EFFECT OF CHAMBER PRESSURE ON BURNING RATE

FOR THE

POTASSIUM NITRATE - DEXTROSE

AND

POTASSIUM NITRATE - SORBITOL

ROCKET PROPELLANTS

By

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Issue 1

Introduction

In the design or analysis of a solid rocket motor (SRM), one of the fundamental parameters is that of the motor *chamber pressure* (P_o). For example, prediction of the chamber pressure is necessary for structural sizing the motor casing. Hoop stress, the predominant stress experienced by the casing walls, is directly proportional to chamber pressure:

$$s_{hoop} = \frac{P_o D}{2 t}$$

where *D* and *t* are the *casing diameter* and *wall thickness*, respectively.

As another example, the *thrust* (F) that the motor develops is directly proportional to chamber pressure:

$$F = C_F A_t P_o$$

where C_F and A_t are the *thrust coefficient* and *nozzle throat area*, respectively.

As well, the *nozzle exhaust velocity* (V_e), from which motor thrust may be alternatively determined (together with mass flow rate), is given by

$$v_e = \sqrt{\frac{2 k R T_o}{k-1}\left[1-\left(\frac{P_e}{P_o}\right)^{k-1/k}\right]}$$

where *k* and *R* are the *effective ratio of specific heats* and the *effective gas constant* of the exhaust products, and T_o and P_e are the *combustion temperature* and *nozzle exit pressure*, respectively.

As can be seen from these examples, it is imperative to be able to predict what chamber pressure will arise from the combustion of the propellant in a particular rocket motor. The pressure that develops in the chamber is the result of a balancing act between the burning of the propellant, which generates combustion gases at a certain rate, and the escaping of these gases through the nozzle opening (throat), also at a certain rate. If the rate of the former process is greater than the rate of the latter, the gases will accumulate in the chamber, resulting in a pressure rise. Interestingly, both processes are a function of the chamber pressure, and at a certain pressure level, an equilibrium situation will occur, where the pressure will remain constant (assuming steady-state conditions).

The rate at which the exhaust products flow through the nozzle is given by

$$m_n = A_t P_o \sqrt{\frac{k}{R T_o}\left(\frac{2}{k+1}\right)^{k+1/k-1}}$$

and the rate at which combustion products are produced by the burning propellant is given by

$$m_c = r_p A_b r$$

where ρ_p, A_b and *r* are the density of the propellant, burning surface area, and propellant burn rate, respectively. As mentioned, the propellant burn rate is a function of chamber pressure and is usually modeled using the *deSt.Robert's burning rate equation*, which is characterized by a straight-line relationship between the log-burning rate and log-pressure as illustrated in Figure 1:

$$r = a P_o^{\,n} + b$$

where *a* and *n* are the *burn rate coefficient* and *burn rate pressure exponent*, respectively.

Introduction (cont.)

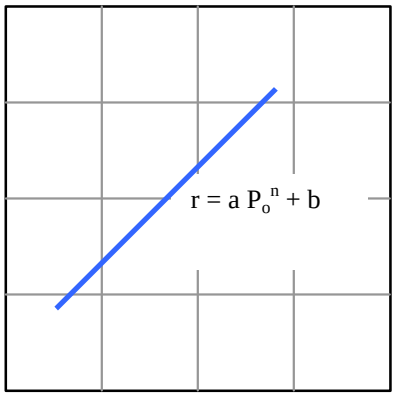


Figure 1 – Pressure – burn rate relationship

The intercept term, *b*, is usually taken as equal to zero, for convenience.

$$r = a P_o^n$$

The values of *a* and *n* are determined empirically, either by the *strand burner* method, or by utilizing a *ballistic evaluation motor* (BEM) specifically designed for this purpose. In the strand burner method, P_o is taken as the pressure within the firing vessel. Once the relationship between burn rate and chamber pressure has been established, it is possible to predict the chamber pressure that a rocket motor will develop, by the following equation, which is derived from the concept described earlier:

$$P_o = \left[\frac{A_b}{A_t} \frac{a\, r_p}{\sqrt{\frac{k}{R\, T_o} \left(\frac{2}{k+1} \right)^{k+1/k-1}}} \right]^{1/1-n}$$

The terms A_b and A_t are simply geometric quantities associated with the propellant grain and the motor nozzle. In fact, the ratio A_b/A_t is an important parameter in rocket motor design and is referred to as *Klemmung*, usually symbolized as K_n. The propellant density is readily determined, either empirically, or idealized from the known densities of the individual constituents. The thermochemical properties R, To and k may be determined with the aid of a chemical equilibrium computer program such as PEP or CET.

Therefore, the only other properties that are required in order to be able to predict chamber pressure are the burn rate coefficient, *a*, and the burn rate pressure exponent, *n*. Therein lies the intent of this exercise . To experimentally determine these important properties for two of the rocket propellants ideal for amateur experimental use: Potassium Nitrate-Dextrose (referred to as KN-Dextrose) and the Potassium Nitrate-Sorbitol (KN-Sorbitol) propellants. The method that was chosen was the *Strand Burner* method, being the most convenient means to achieve accurate results.

Preparation of Propellant Strands

For both propellants tested, the 65/35 oxidizer/fuel ratio was utilized exclusively, being considered as the "standard" ratio that has been proven by experience to be the best compromise in terms of performance and grain castability. Mixtures with a higher fraction of KN have greater viscosity and are thus more difficult to pour. As well, such mixtures have a greater tendency to retain trapped air bubbles. Mixtures with lower O/F ratios deliver reduced performance.

In preparation of the propellant, the sorbitol and KN were proportioned in the "as purchased" form, as prior testing had confirmed that absorbed moisture content was negligible. The dextrose monohydrate, however, was first desiccated by drying in an electric oven at 80°C. for one hour such that the end product was in the anhydrous form. The KN, dextrose, and Sorbitol were separately pulverized using an electric coffee grinder, the type equipped with a single pair of blades that rotate at high speed. Approximately two tablespoons (30 ml) was put into the grinder, then run for about 15-20 seconds. From experience, it was found that the sound made during the grinding process was a good indicator of when the particles had become fully ground. The particles could be heard breaking up initially, the sound of which diminished rapidly. After 20 seconds, it was obvious that no more pulverization was occurring, and that the powder was merely being spun around. Final particle size estimation is given in Appendix A.

After grinding, the constituents were carefully weighed out using a beam-balance scale with an accuracy and resolution estimated to be 0.5 gram. Typical prepared batch size was 400 grams. After weighing, the constituents were placed into a single bowl, then blended lightly. A mortar and pestle was used, if necessary, to break up any lumps that remained after blending. This "dry mixture" was then placed into a plastic tupperware container and secured to an electrical mixer that rotated at 28 RPM. Mixing then occurred for typically 4 to 5 hours. A record was maintained of the details pertaining to the dry mixture batches as well as the propellant batches. This is given in Appendix B.

Strands of propellant were prepared by slowly heating the mixture (typically, in 100 gram lots) in a thermostatically controlled electric "deep fryer" utilizing a paraffin bath. A thermocouple (type K) probe was used to monitor the temperature of the slurry, which was typically between 125-135°C for the KN-Dextrose, and between 110-120°C for the KN-Sorbitol. When the slurry became fully fluid and had no lumps of unmelted mixture remaining, the slurry was scooped into a preheated extruding tool (see Appendix C), and immediately extruded onto a lightly oiled galvanized steel sheet, and allowed to cool. Typically, the "raw" extruded strands were 10-20 cm long. Extruding proved to be quite challenging, as trapped air in the tool formed an occasional bubble in the strand, which made that portion of the strand useless. Usually, about fifty percent of the extruded strand length was discarded due to bubbles or other defects such as necking or discontinuities.

For the KN-Dextrose strands, the process of inspecting, cleaning, cutting, trimming, inhibiting and marking could be done immediately after cooling (one-half hour). The KN-Sorbitol strands, however, had to be allowed to "cure" for 24 hours (minimum) before handling. This is because, after cooling, the strands were still very pliable and would deform if handled. However, after curing, the strands became as rigid as the KN-Dextrose. The physical mechanism of this "curing" behaviour is not yet understood.

Inspection of the raw strands was performed to locate flaws (bubbles, voids, etc.) and subsequently mark off the portions that were acceptable. Inspection was visual, by examining the external surface, and also by using an "illumination" technique to locate hidden voids. This technique involved holding the translucent strand up to a strong light source. Voids were readily detectable as lighter regions. Fully sound regions were nearly opaque.

Cleaning of the KN-Sorbitol strands was done with lacquer thinner to remove any traces of oil. The KN-Dextrose strands, which were somewhat hygroscopic, were scraped with a knife to remove the superficial damp layer. Cutting to length was done utilizing a fine tooth saw, cutting about one-third way through the strand, then fractured by careful bending. Trimming of the strand was done with a sharp Olfa knife (if necessary). Typical finished strand length was 10 cm, and had an approximately oval cross section, typically with a minor diameter of 4 mm and a major diameter of 6 mm. The cross-section of a typical strand is shown in Figure 2.

Preparation of Propellant Strands (cont.)

Inhibiting the surfaces of the strands was found to be necessary. This is because the strands were originally mounted vertically, and liquid products of combustion would drool down the strands (like wax down a candle), causing ignition along the side. Inhibiting was done by painting the strands with heat resistant aluminum spray paint (the type used to paint barbecues). At least two full coats were applied, and allowed to dry for a minimum of twenty-four hours.

Burn rate measurement (in open air) of inhibited versus uninhibited strands confirmed that this coating did not affect burn rate (see Appendix B).

After painting the strands, they were measured, labeled, and notation made of minor flaws. For each lot of strands produced, a sample was burned (in open air) to measure the burn rate, which was then compared to the known burn rate, as a means of "quality control" testing.

Longer length strands tended to be used in the higher pressure tests, due to greater rate of burning at more elevated pressures.

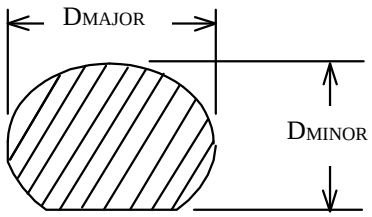


Figure 2 – Cross-section of typical strand

Apparatus

The apparatus (Figure 3) consisted primarily of a *firing vessel* in which the propellant strand was burned under pressure. This consisted of a 4.86 litre, 14 cm. diameter steel cylinder with hemispherical end caps, modified by the addition of a flanged pipe welded to the lower end cap, for attachment of the strand holder (Figure 4). The strand holder consisted of a flanged pipe to which electrical leads in the form of 1/16 inch stainless steel rods were fitted through insulated access holes. This provided electrical connections for the thermocouples and igniter. The strand holder was secured to the firing vessel by means of six ¼-20NC bolts/nuts (SAE grade 8) which joined mating flanges. A fibre gasket was put between the flanges for sealing. The strand holder was also equipped with a flared type fitting for connection to the pressurizing gas supply. The pressurizing gas was nitrogen, supplied from a standard 2200 psi rechargeable cylinder. An orifice of 0.020 inch diameter was installed in the fill line to restrict the flow rate during pressurization.

Measurement of the burning rate was performed with the aid of two thermocouples (T/C), one attached to the strand with its bead near the upper end (nearest the igniter), the other near the bottom end. The T/C was secured to the strand with fine gauge "wire wrap" wire. The T/C's were connected, in parallel, to terminals on the strand holder. These T/C's were replaced after each firing, as they normally became quite scorched. Either of two types of T/C's were used. Type K (chromel-alumel), 0.010 inch diameter, glass-braided insulation, or type E (chromel-constantan), 0.010 inch diameter, teflon coated. The distance between the two thermocouple beads was carefully measured and recorded as the *gauge length*. Ignition of the strand was achieved by use of a nichrome wire filament soldered to a pair of lead wires connected in turn to terminals on the strand holder. The filament was sandwiched between the top surface of the strand and a (split) match head, which was tacked to the strand with small dabs of hot (polyethylene) glue. The use of a match head, which was incorporated after some initial problems with ignition, subsequently resulted in 100% ignition reliability. Power for the igniter was supplied by four AA nicad cells, mounted inside the *ignition box*. The ignition box incorporated a continuity check feature which supplied voltage across the igniter at low current accomplished by means of an LED and resistor connected in series with the igniter filament.

A third thermocouple, mounted onto the strand holder, was utilized for ambient temperature measurement inside the firing vessel.

Prior to conducting any actual experimentation, the entire system, including the firing vessel, was hydrostatically tested to 2500 psi, by first filling the vessel with water, bleeding the system of all air, then utilizing a hydraulic jack to pressurize the system with oil. The maximum operational pressure was taken to be 1700 psi, thus the test pressure represents a safety margin of 1.5.

Measurement of the firing vessel pressure was done with a 0-5000 psi bourdon "test" gauge, rated at 0.25% (full scale) accuracy. Low pressure (< 200 psi) measurements were taken with a high quality 0-300 psi bourdon gauge. Comparison testing showed only a small discrepancy in reading between the two gauges over the range 100-300 psi.

The thermocouples were connected to a Micronta 22-168A digital volt meter (DVM) that was interfaced to a 80286 PC. A software routine was written (Appendix E) which sampled the DVM output emf (mV) at the maximum available sample rate (3.3 samples/sec). This data was stored in an array in memory, then written to a text file for permanent storage.

Apparatus (cont)

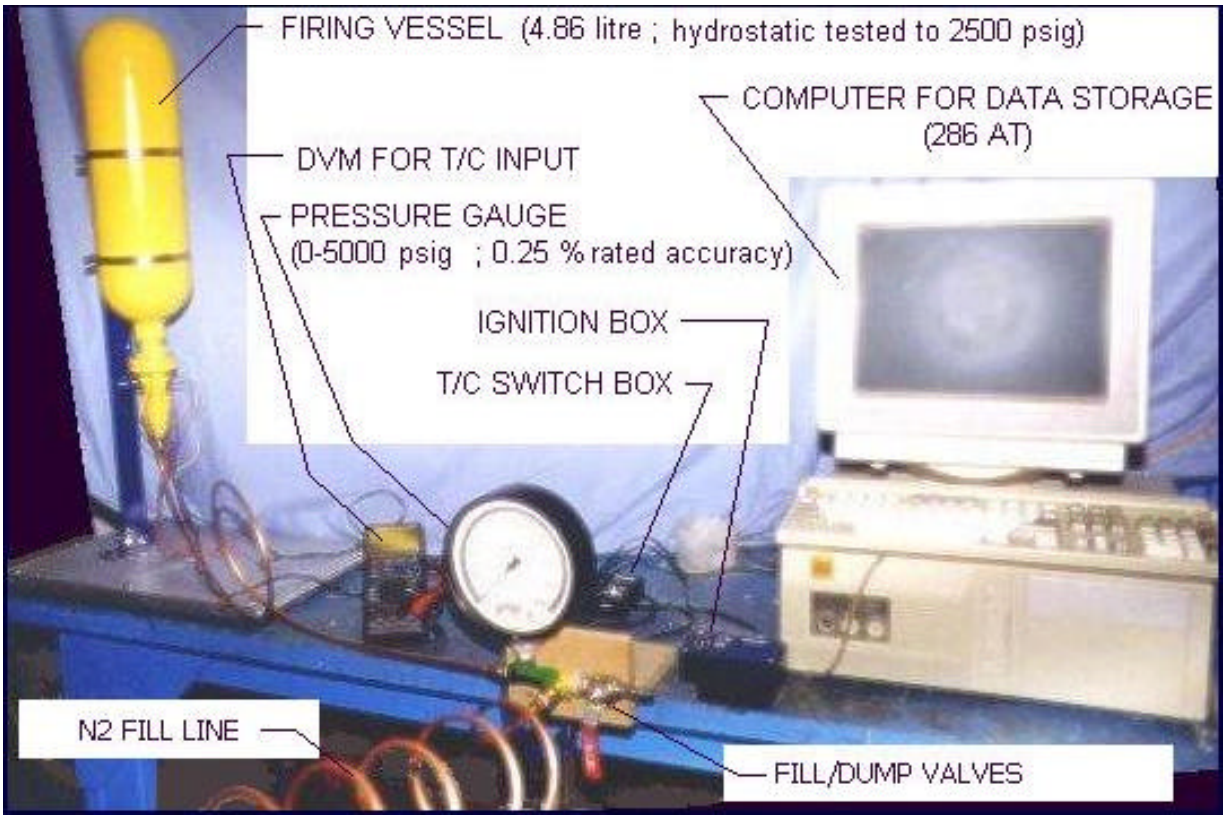


Figure 3 – Experimental apparatus

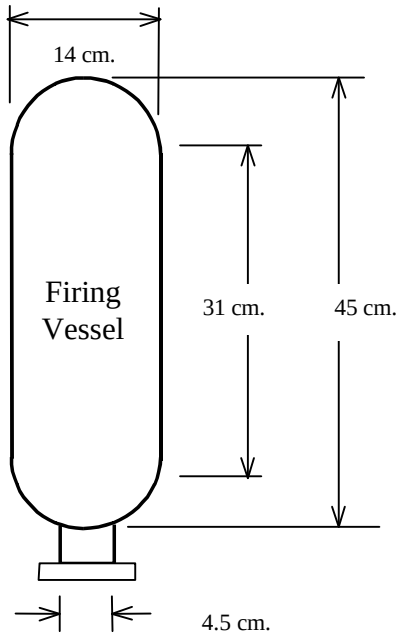


Figure 4 – Dimensions of Firing Vessel

Experimental Technique

A total of 37 burns were conducted. Of this total, 18 were of the KN-Dextrose propellant, of which 14 produced useable data, over a pressure range of 0 psig to 1610 psig (11.1 MPa). For the KN-Sorbitol propellant, a total of 19 tests were conducted, of which 13 produced useable data, over the pressure range 0 psig to 1533 psig (10.6 MPa).
For each burn conducted, the experimental technique involved performing the following series of steps. Mounting of the strand in the holder, attachment of thermocouples and igniter, joining the strand holder to the firing vessel, connecting the N2 filling line at the strand holder inlet port, connection of the N2 supply tank to the fill valve. The firing vessel was then purged by pressurizing to 30 psig, dumping, then repeating this sequence twice more. This effectively reduced residual O_2 content to less than 1%. Pressurization of the system was accomplished next. Upon completion of the pressurization, the thermocouple reading was taken to record the vessel ambient pressure, and the initial pressure was recorded. Data recording was initiated, then the firing button pressed to ignite the strand. The pressure rise due to the burning strand was then observed and the maximum pressure recorded.
Most of the burns were conducted with the strand mounted vertically, as it was originally felt that this would assure minimal influence of the flame upon the rate of burning. There were occasional problems with drooling molten products of combustion rolling down the strand resulting in false voltage spikes if the lower T/C burn sensor was contacted. It was later decided to investigate mounting the firing vessel (and thus the strand) horizontally to avoid this problem. Burn rate testing of horizontally mounted strands (in the open air, for convenience) was conducted to measure the burn rate. It was found that the burning rate was not detrimentally affected and thus all the subsequent tests were conducted with the firing vessel mounted horizontally.

Analysis

The T/C voltage output data was read into an Excel spreadsheet and plotted in the form of a line graph, an example of which is shown in Figure 5. Nominal results would be in the form of two voltage spikes, which represent the flame front reaching the first, then second T/C (see Figure 6). Both spikes were usually positive, although not necessarily. The time period between spikes was taken as the time required to burn the gauge length. The first data point, at which the slope of the curve sharply increased, at each spike, was taken as the two reference points defining this time period. In the example, the beginning data points are #24 and #64. Judgement was occasionally required to estimate this point when the slope did not rise rapidly or when secondary spikes were present. The pressure at which burning was considered to occur was taken as the average of the initial pressure and the maximum pressure (delta was typically 30-50 psi**). Burn rate was taken as gauge length divided by burn time**, and thus represents the average burn rate at the average vessel pressure over the duration of the burn.

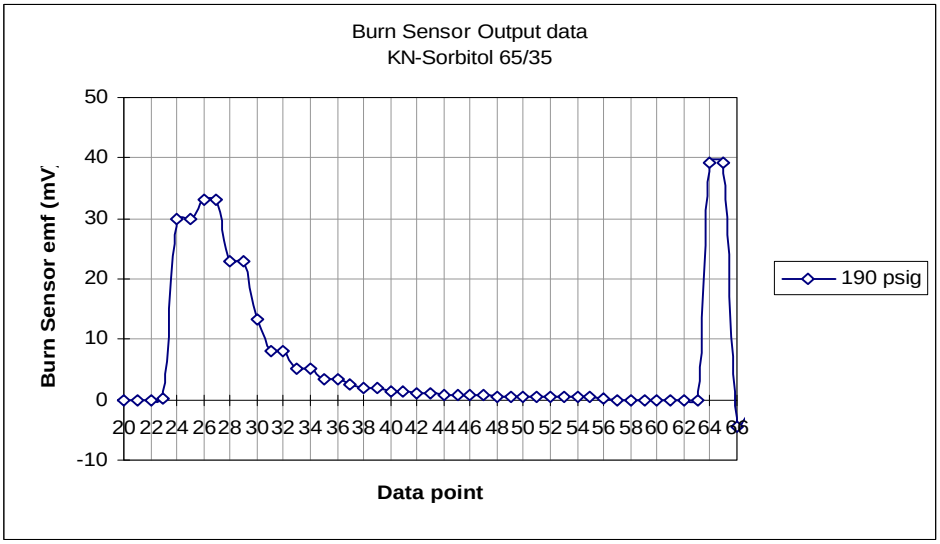


Figure 5 – Example of thermocouple output plotted to show voltage spikes

Experimental Technique (cont)

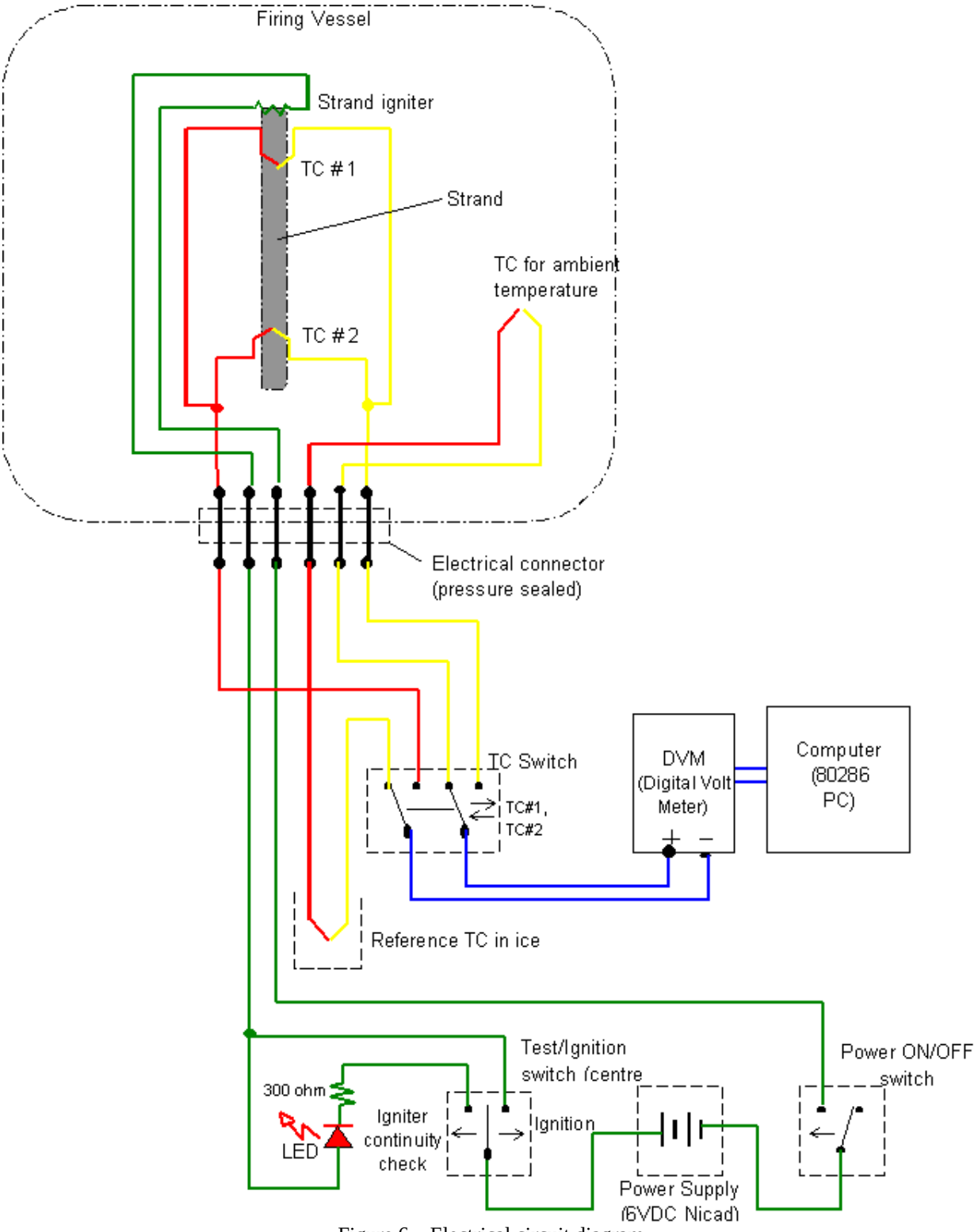


Figure 6 – Electrical circuit diagram

Results

A summary of the experimental burn rate results (excluding invalidated results) are given in Table 1. Note that the units given are those of the measuring instruments (psig and centimetres).

In Table 2 and Table 3, the results are reproduced in both English and SI units, with pressure converted to absolute units. A plot of the results for KN-Dextrose is given in Figure 7, and for KN-Sorbitol in Figure 8, in English units. A plot of the results for KN-Dextrose is given in Figure 9, and for KN-Sorbitol in Figure 10, in SI units.

A comparison of experimental results for both of these propellants with the results for KN-Sucrose is given in Figure 11. The KN-Sucrose results were obtained from a similar burn rate investigation conducted several years prior. Note that the amount of scatter in the earlier data was significantly greater than with recent testing. The reduced scatter with the recent investigation is attributed to much improved experimental technique.

Some of the results obtained were deemed invalid, and the data was not used. In these, burning of the strand did not proceed in a normal "cigarette" manner, rather, burning of the strand (as indicated by the lower burn sensor) was rapid. This event was almost certainly the result of liquid combustion product "drooling" down the side of the strand, causing either combustion to occur along the side, or the liquid product coming into contact with the lower burn sensor, falsely indicating the burn time. It was therefore decided, commencing with burn PB-25, to mount the firing vessel horizontally, rather than vertically, to eliminate drooling and thus avoid uncontrolled burning. This seemed to solve the problem, as in the twelve subsequent burns, only once did an uncontrolled burning occur. Burn rate testing to validate this had demonstrated that, contrary to earlier thought, that mounting the strand horizontally did *not* adversely effect the burn rate.

Experimental Results			
KN-Dextrose		KN-Sorbitol	
Vessel pressure	Burn rate	Vessel pressure	Burn rate
psig	cm/sec	psig	cm/sec
0	0.215	0	0.256
98	0.759	95	0.898
148	0.751	103	0.937
224	0.754	192	0.784
325	0.798	203	0.781
425	0.830	301	0.765
523	0.932	401	0.792
651	1.100	535	0.765
845	1.308	659	0.952
953	1.314	830	0.977
1144	1.285	1005	1.102
1218	1.232	1194	1.091
1405	1.300	1533	1.129
1610	1.392		

Table 1 – Summary of experimental results

Results (cont.)

KN-Dextrose				
Vessel pressure			Burn rate	
psig	psia	Mpaa	cm/sec	in/sec.
0	14.7	0.101	0.215	0.085
98	113	0.777	0.759	0.299
148	162	1.12	0.751	0.296
224	238	1.64	0.754	0.297
325	340	2.34	0.798	0.314
425	440	3.03	0.830	0.327
523	537	3.70	0.932	0.367
651	666	4.59	1.100	0.433
845	860	5.93	1.308	0.515
953	968	6.67	1.314	0.517
1144	1159	7.99	1.285	0.506
1218	1233	8.50	1.232	0.485
1405	1420	9.79	1.300	0.512
1610	1625	11.20	1.392	0.548

Table 2 – Experimental results for KN-Dextrose, English and SI units

KN-Sorbitol				
Vessel pressure			Burn rate	
psig	psia	Mpaa	cm/sec	in/sec.
0	14.7	0.101	0.256	0.101
95	110	0.756	0.898	0.354
103	117	0.808	0.937	0.369
192	207	1.43	0.784	0.309
203	218	1.50	0.781	0.307
301	316	2.18	0.765	0.301
401	416	2.87	0.792	0.312
535	549	3.79	0.765	0.301
659	674	4.65	0.952	0.375
830	845	5.83	0.977	0.385
1005	1020	7.03	1.102	0.434
1194	1209	8.33	1.091	0.430
1533	1548	10.67	1.129	0.444

Table 3 – Experimental results for KN-Sorbitol, English and Metric units

Results (cont.)

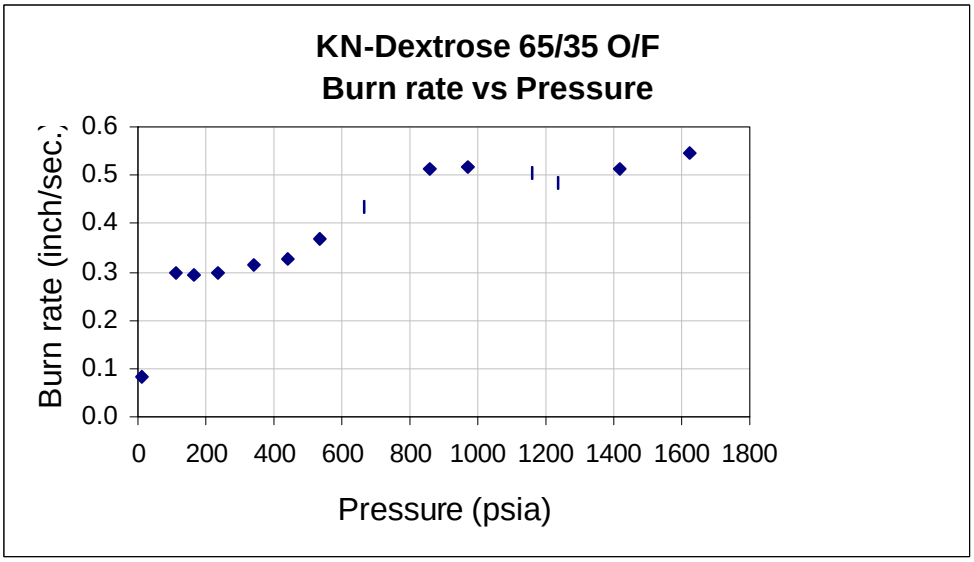


Figure 7 – Experimental results for KN-Dextrose, plotted (English units)

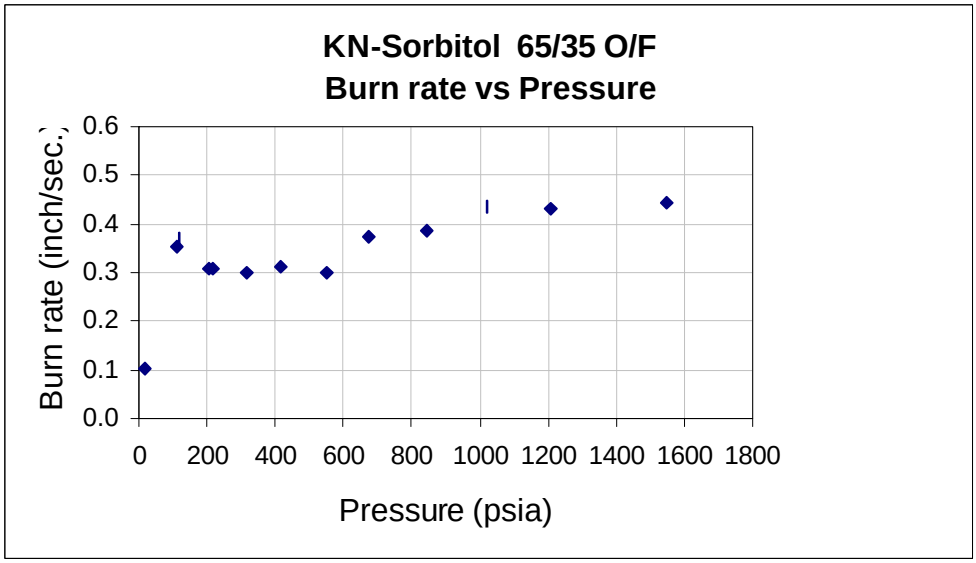


Figure 8 – Experimental results for KN-Sorbitol, plotted (English units)

Results (cont.)

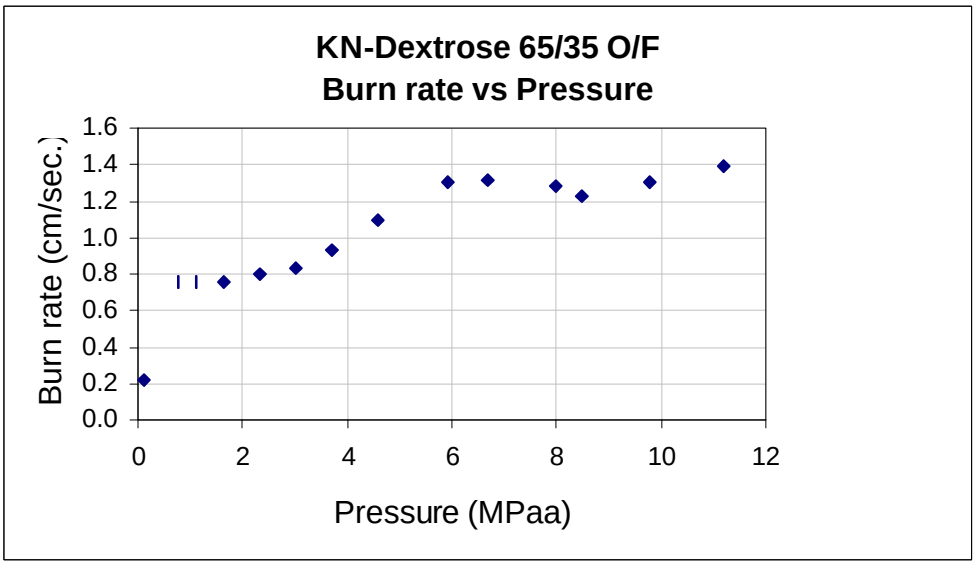


Figure 9 – Experimental results for KN-Dextrose, plotted (SI units)

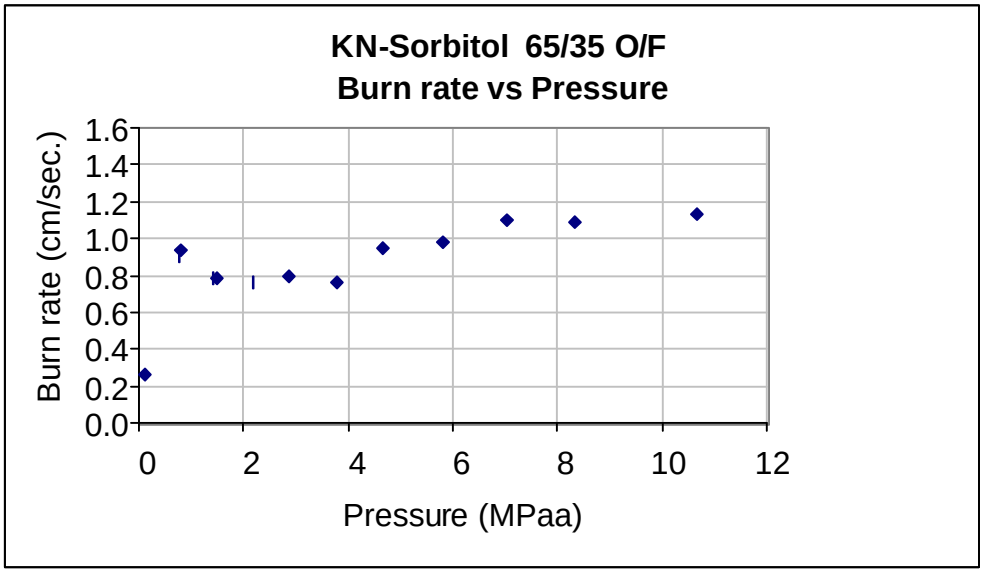


Figure 10 – Experimental results for KN-Sorbitol, plotted (SI units)

Results (cont.)

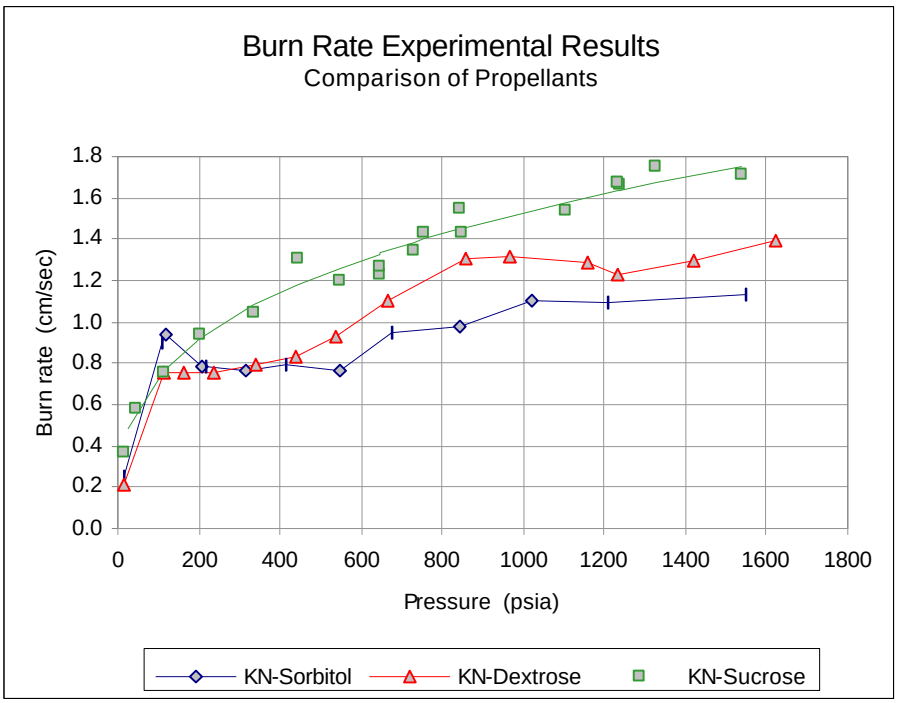


Figure 11 – Comparison of experimental results for KN-Dextrose, KN-Sorbitol, and KN-Sucrose

Discussion:

It was originally planned to conduct burn rate measurements at about six different pressure levels (for each propellant) over the range of 100 to 1600 psi. It was felt that this may be sufficient to apply a “least squares fit”, using regression techniques, through the data points to obtain representative values for the pressure exponent *n* and pressure coefficient *a* as applicable to the *de St.Robert* model of burn rate behaviour. However, after conducting a number of burn rate measurements over this pressure range, it was clear that the burn rate behaviour was too complex to fit the data to a single curve of this form. In the end, about twice as many data points were collected.

The most striking feature of the results for both the KN-Dextrose and KN-Sorbitol propellants is the marked difference in the burn rate behaviour compared with the KN-Sucrose propellant, as illustrated in Figure 11. The latter propellant clearly follows the classic *de Saint Robert* model of burn rate behaviour. However, the two recently tested propellants deviate significantly from this behaviour. Indeed, for many rocket propellants, the value of *n* deviates greatly through various pressure regimes. Propellants showing a markedly reduced *n* are known as *plateau* propellants. Propellants that show negative values of *n* over short pressure ranges are known as *mesa* propellants. This concept is illustrated in Figure 12.

In order to better comprehend the behaviour of the KN-Dextrose and KN-Sorbitol propellants, the experimental burn rate results were each plotted on a Log pressure-Log burn rate graph, as shown in Figures 13 and 14.

A straight line was drawn through those points which best represent the various regimes where the pressure exponent may be considered to be constant, that is , linear on the log-log plot.

Based on this analysis approach, KN-Dextrose would appear to be a plateau propellant, and KN-Sorbitol would appear to be a mesa (or rather, inverted-mesa) propellant.

As such, it is possible to isolate the various pressure regimes and to obtain values for the pressure coefficient *a* and the pressure exponent *n* for each of these regimes. Indeed, this was performed, and the results are presented in Tables 4 and 5. The tables are split into English units (left half) where burn rate is given in inch/sec with pressure given in psi (absolute), and in SI units (right half) where burn rate is given in mm/sec with pressure given in Mpa (absolute).

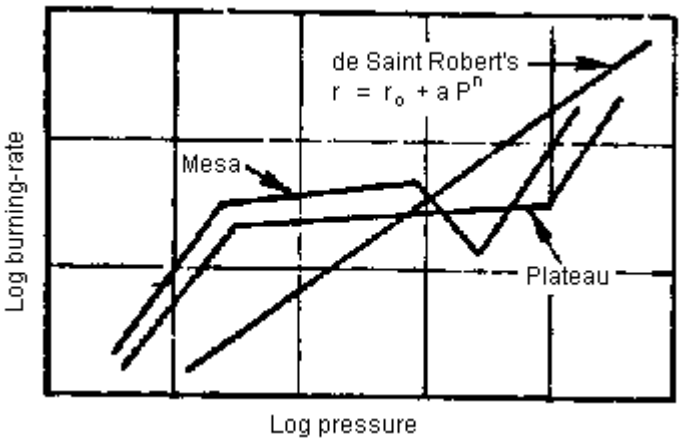


Figure 12 – Various concepts of propellant burn rate behaviour
(ref. NASA SP–8039 Solid Rocket Motor Performance Analysis and Prediction)

Discussion (cont.)

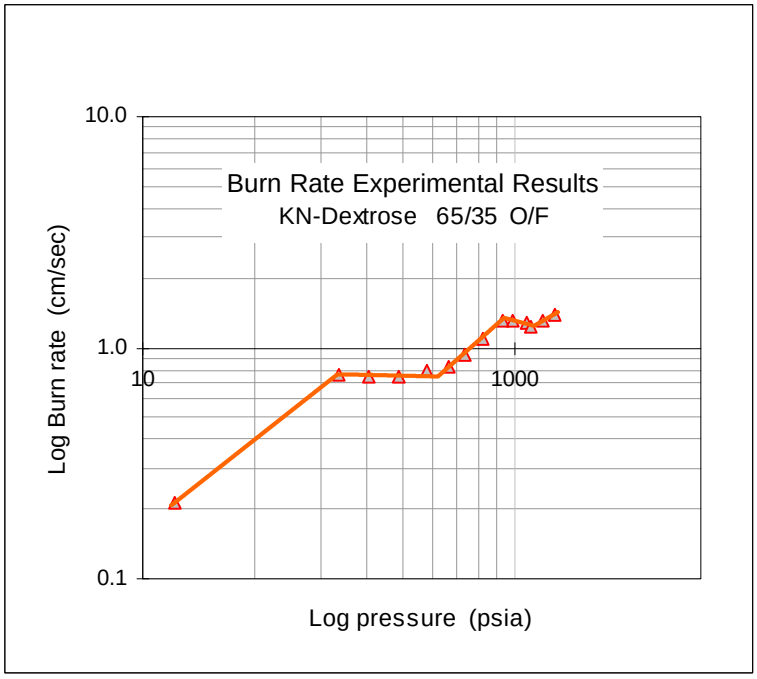


Figure 13 – Defining linear pressure regimes, KN-Dextrose

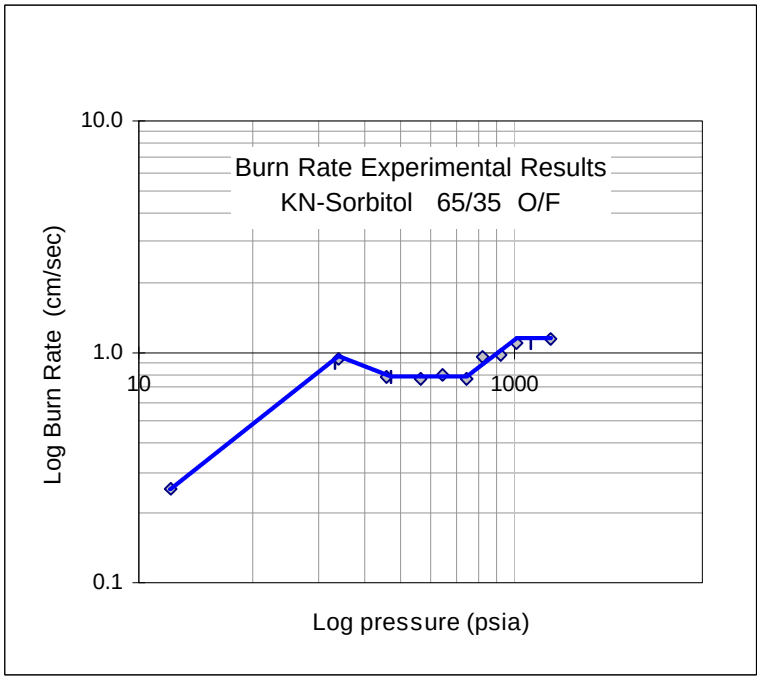


Figure 14 – Defining linear pressure regimes, KN-Sorbitol

Discussion (cont.)

KN-Dextrose									
Pressure range			a	n	Pressure range			a	n
psia			in/sec, (psia)		Mpa			mm/sec, (Mpa)	
15	to	113	0.016	0.619	0.103	to	0.779	8.88	0.619
113	to	373	0.311	-0.009	0.779	to	2.57	7.55	-0.009
373	to	860	0.005	0.688	2.57	to	5.93	3.84	0.688
860	to	1233	1.416	-0.148	5.93	to	8.50	17.2	-0.148
1233	to	1625	0.021	0.442	8.50	to	11.20	4.78	0.442

Table 4 – Burn rate coefficients and exponents for KN-Dextrose propellant

KN-Sorbitol									
Pressure range			a	n	Pressure range			a	n
psia			in/sec, (psia)		Mpa			mm/sec, (Mpa)	
15	to	117	0.019	0.625	0.103	to	0.807	10.71	0.625
117	to	218	1.648	-0.314	0.807	to	1.50	8.763	-0.314
218	to	550	0.330	-0.013	1.50	to	3.79	7.852	-0.013
550	to	1020	0.011	0.535	3.79	to	7.03	3.907	0.535
1020	to	1548	0.277	0.064	7.03	to	10.67	9.653	0.064

Table 5 – Burn rate coefficients and exponents KN-Sorbitol propellant

Conclusion

Values for the pressure coefficient *a* and pressure exponent *n* over specified pressure regimes, have been determined for the KN-Dextrose and KN-Sorbitol propellants, and are suitable for use in design and analysis of rocket motors utilizing either of these propellants.

Since most rocket motors are designed, for optimum performance, to operate over a fairly narrow pressure range, often only a single value for *a* and *n* need be utilized, applicable to that pressure range.

Note that the results obtained in this experimentation do not reflect the effects of erosive burning phenomenon. However, if a motor is designed with a sufficiently large port area to nozzle throat area ratio (typically greater than 6), the consquence of erosive burning in augmenting burn rate is not significant.

Appendices

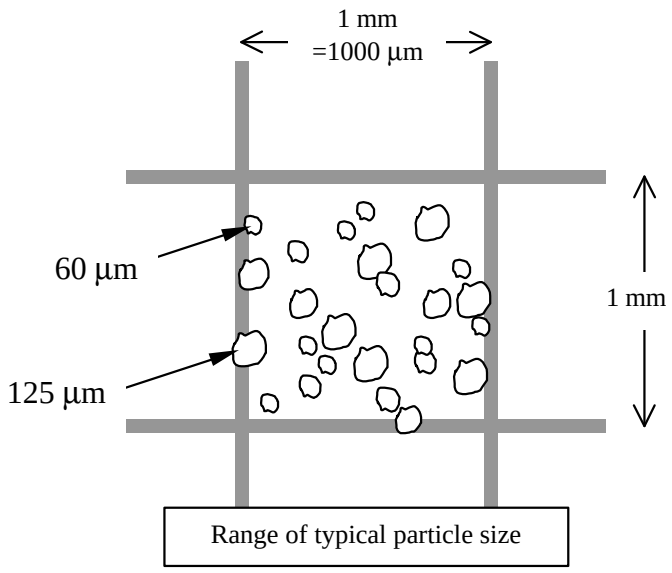
Appendix A

Oxidizer Particle Size Estimation

A simple method was used to obtain an estimate of the typical oxidizer particle size. A tiny, random sample of ground oxidizer was placed on piece of standard graphing paper, with one millimetre minor grid lines. Using a 20x eyepiece magnifier, the sample was observed and the particles were compared in size to the 1 mm grid spacing. The 1 mm grid spacing represents a distance of 1000 microns (1000×10^{-6} metres). One tenth of this spacing, therefore, represents a distance of 100 microns. Using this method, it is relatively easy to judge particles that are of this order of size. This concept is illustrated in the figure below.

From this examination, it was found that the vast majority of the particles were of the range of $1/8^{th}$ to $1/15^{th}$ of the grid spacing, consistently, for all of the batches prepared for this series of burn rate tests. This places the oxidizer particle size mainly in the range of about **60 to 125 micron**.

A sample of oxidizer from each propellant batch was retained for more accurate determination of particle size and distribution at a future date.



Appendix B

Dry Mixture and Propellant Batch Particulars

Dry Mix Batch # KNAD-240199

Particulars
140 g. Anhydrous Dextrose (AD), consumer grade
260 g. Potassium Nitrate (KN), Veterinarian grade
400 g. Total dry mix
Both constituents ground finely using electric coffee grinder (approx. 20 sec.)
Both constituents accurately weighed using balance beam scale; rated 0.5 gram accuracy
Blended in rotation mixer (28 RPM) for 6 hours.

Propellant Batch # KNAD-240199-290199-1

Particulars
Prepared using paraffin bath. Bath temperature 150-155 C.; Slurry temperature 130 C.
Extruded into strands (1/4"nominal dia.) for burnrate testing
Colour was light tan; some caramelization was apparent
Hygroscopic. Immediately after cooling to room temp, surfaces were damp.

Strands
Initially, strands were left bare (not painted)
Trial test at 200 psig indicated problem with bare strands. Dribbling of liquid at flame front caused entire strand to become engulfed.
Subsequently, strands were painted using aluminum hi-heat spray paint (damp surfaces on strands did not pose a problem. Paint adhered well.)
Atmospheric burnrate test conducted on bare strand:

L1=	2.28 cm
L2=	4.95 cm
t1=	10.64 sec
t2=	22.6 sec
r1=	0.214 cm/sec
r2=	0.219 cm/sec
P_{atm}=	30.85 in.Hg.
$T_{ambient}$=	20 C

Atmospheric burnrate test conducted on painted strand:

L1=	1.55 cm
L2=	3.11 cm
t1=	7.12 sec
t2=	14.13 sec
r1=	0.218 cm/sec
r2=	0.220 cm/sec
P_{atm}=	31.05 in.Hg.
$T_{ambient}$=	20 C

Propellant Batch # KNAD-240199-310199-1

Particulars

Extruded into strands (3/16"nominal dia.) for burnrate testing
Colour was ivory; slight caramelization was apparent
Hygroscopic. Immediately after cooling to room temp, surfaces were damp.

Strands

All strands were painted with hi-heat aluminum paint.
Atmospheric burnrate test conducted (for quality test) on 2 bare strands, 1st extruded strand and last extruded strand:
1st strand:

L1=	2.45 cm
L2=	4.19 cm
t1=	11.71 sec
t2=	19.84 sec
r1=	0.209 cm/sec
r2=	0.211 cm/sec
P_{atm}=	31.125 in.Hg.
$T_{ambient}$ =	20 C approx.

Last strand:

L1=	2.09 cm
L2=	4.95 cm
t1=	* sec
t2=	23.75 sec
r1=	n.a. cm/sec
r2=	0.208 cm/sec

* not recorded

Dry Mix Batch # KNSB-060299

Particulars

105 g. Sorbitol (less than 0.5% absorbed moisture), consumer grade
194 g. Potassium Nitrate (KN), Veterinarian grade
299 g. Total dry mix
Both constituents ground finely using electric coffee grinder (approx. 20 sec.)
Both constituents accurately weighed using balance beam scale; rated 0.5 gram accuracy
Blended in rotation mixer (28 RPM) for 5 hours.

Propellant Batch # KNSB-060299-060299-1

Particulars

Slurry cast temperature recorded at 113 C. (with T.C.).
Ambient conditions: temperature 20.8 C. ; R.H. 60%

Extruded into strands (3/16"nominal dia.) for burn rate testing. Extruded easily.

Colour was pure white
Hygroscopic. Immediately after cooling to room temp, surfaces were damp.
Strand were soft and plastic, easily deformable after cooling to ambient

Strands After curing for 24 hours, strands were rigid and brittle.
All strands were painted with hi-heat aluminum paint.
An atmospheric burn rate test was conducted on an extruded strand, but data was lost.

Propellant Batch # KNSB-060299-060399-1

Particulars

Extruded into strands (3/16"nominal dia.) for burn rate testing. Extruded easily.
Colour was pure white
Hygroscopic. Immediately after cooling to room temp, surfaces were damp.
Strand were soft and plastic, easily deformable after cooling to ambient

Strands After curing for 24 hours, strands were rigid and brittle.
All strands were painted with hi-heat aluminum paint.
An atmospheric burn rate test was conducted on an extruded strand:

T_{amb}: 22 C.
B.P.: 30.47 in.Hg.

L1 = 2.29 cm.
t1 = 9.31 sec.
r1 = **0.246** cm/sec

Comment: Inhibitor paint was scraped off of one side of strand to allow for better visual of flame front for more accurate gauge time measurement.

Dry Mix Batch # KNAD-110399

Particulars 105 g. Anhydrous Dextrose (AD), consumer grade
195g. Potassium Nitrate (KN), Veterinarian grade
300 g. Total dry mix
Both constituents ground finely using electric coffee grinder (approx. 20 sec.)
Both constituents accurately weighed using balance beam scale; rated 0.5 gram accuracy
Blended in rotation mixer (28 RPM) for 6 hours.

Propellant Batch # KNAD-110399-120399-2

Particulars Extruded into strands (3/16"nominal dia.) for burn rate testing
Colour was ivory; slight caramelization was apparent
Hygroscopic. Immediately after cooling to room temp, surfaces were damp.

Strands All strands were painted with hi-heat aluminum paint.
Atmospheric burn rate test not conducted.

Propellant Batch # KNSB-060299-180399-1

Particulars

Extruded into strands (3/16"nominal dia.) for burnrate testing. Extruded easily.
Colour was pure white
Hygroscopic. Immediately after cooling to room temp, surfaces were damp.
Strand were soft and plastic, easily deformable after cooling to ambient

Strands After curing for 24 hours, strands were somewhat flexible.
All strands were painted with hi-heat aluminum paint.
Atmospheric burn rate testing conducted on two strands:

T_{amb}: 19.4 C.
B.P.: 30.61 in.Hg.

Strand #1	L1 =	4.18 cm.	t1 =	16.73 sec.	r1 =	0.250 cm/sec
	L2 =	8.00 cm.	t2 =	32.06 sec.	r2 =	**0.250** cm/sec
Strand #2	L1 =	1.95 cm.	t1 =	7.93 sec.	r1 =	0.246
	L2 =	4.38 cm.	t2 =	17.66 sec.	r2 =	**0.248**

Comment: Strands were unpainted. Tested 24 hours after extruding. Strands were still somewhat flexible.

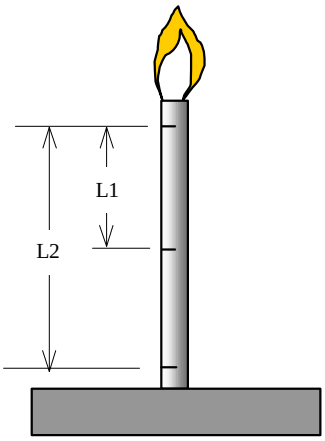


Figure B-1 – Atmospheric strand burning test setup showing gauge lengths

Appendix C

Strand Extruding Tool

The propellant *strand extruding tool* is shown in the figure below. It consists of a barrel into which the molten propellant slurry is loaded, a nozzle containing a circular orifice from which the propellant is extruded into the form of strands, and a handle. The plunger, which is a sliding fit (loose enough to help trapped air to escape), is pushed into the barrel as the tool is slowly moved along the recipient surface.

Prior to loading, the extruding tool was preheated in an oven at 80°C.

Insulated gloves were required to be worn when using this tool.

Three significant difficulties were encountered when using the extruding tool

1. Even with insulated gloves, the tool quickly became uncomfortable to hold
2. Trapped air in the barrel resulted in occasional bubbles forming in the strands, which rendered that portion of the strand worthless.
3. Even though the tool was preheated, it was often a race to extrude the material before it began to "freeze", when significant force would have been required to extrude the strands.

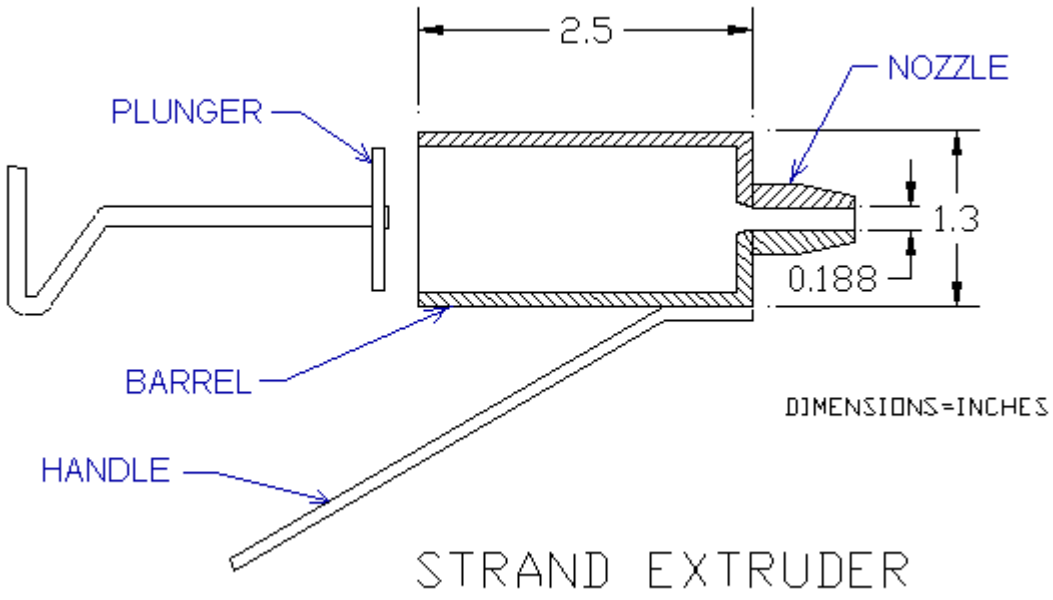


Figure C-1 – Diagram of Strand Extruding tool

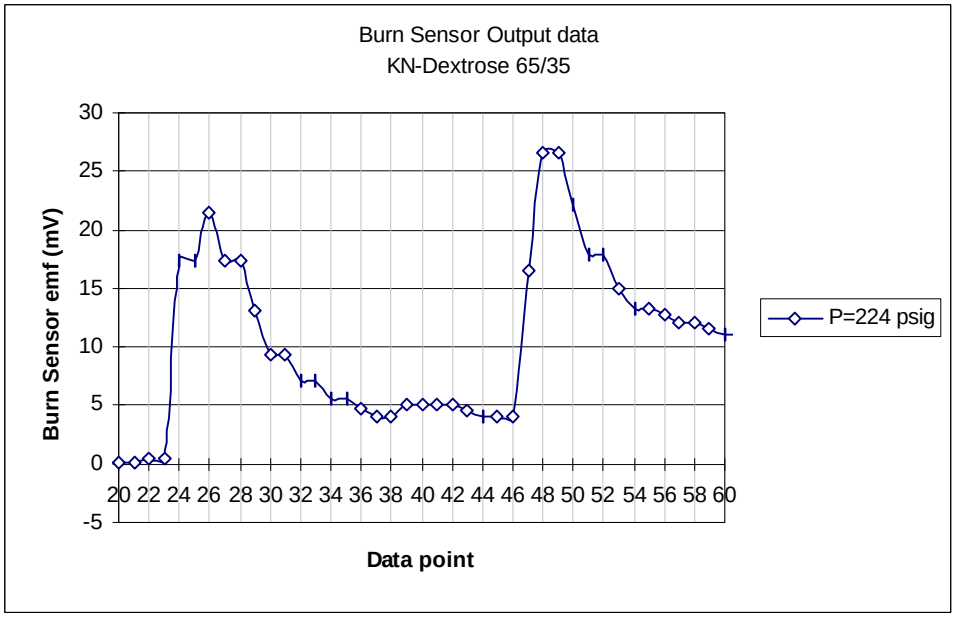
Appendix D

Strand Burn Rate Trials

PB-1
Test DX300199-1 Strand Burning Test
KN-Dextrose (anhydrous) propellant
65/35 O/F ratio
Batch no. KNAD-240199-290199-1

$P_{initial}$ =	202 psig
P_{max} =	245 psig
	43 psig
$P_{average}$ =	223.5 psig
Spike 1	24 (start pt.)
Spike 2	47 (start pt.)
23	Samples between spikes
3.333	Sample/sec. rate
Δt =	6.90 sec.
L_{gauge} =	5.2 cm
r =	**0.754 cm/sec.**
(r =	0.297 in/sec.')

Notes:
1. Strand had slight flaw about 1/2 way down, an oval shallow concavity.



PB-2
Test DX300199-2 Strand Burning Test
KN-Dextrose (anhydrous) propellant
65/35 O/F ratio
Batch no. KNAD-240199-290199-1

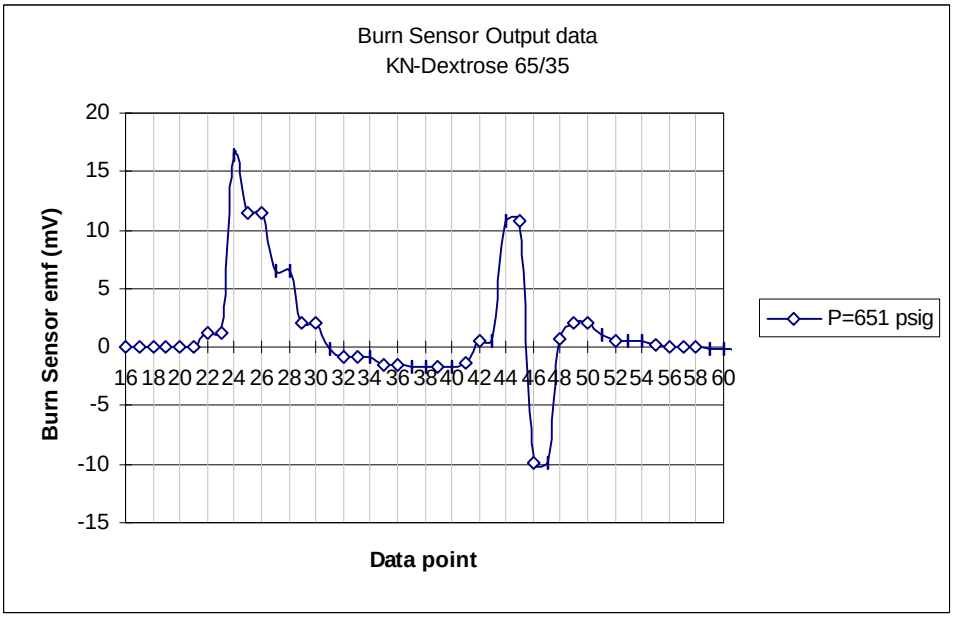
$P_{initial}$ =	602 psig
P_{max} =	700 psig
	98 psig
$P_{average}$ =	651 psig

Spike 1	24 (start pt.)
Spike 2	44 (start pt.)
20	Samples between spikes
3.333	Sample/sec. rate
Δt =	6.00 sec.
L_{gauge} =	6.6 cm
r =	**1.100 cm/sec.**
(r =	0.433 in/sec.')

Notes:
1.Lab thermometer placed on side of tank recorded T_{amb}=21.6 C. prior to test
2.Strand dimensions:

L_{total} =	8.3 cm.
D_{maj} =	0.80 cm.
D_{min} =	0.55 cm.

3.Strand had no apparent defects



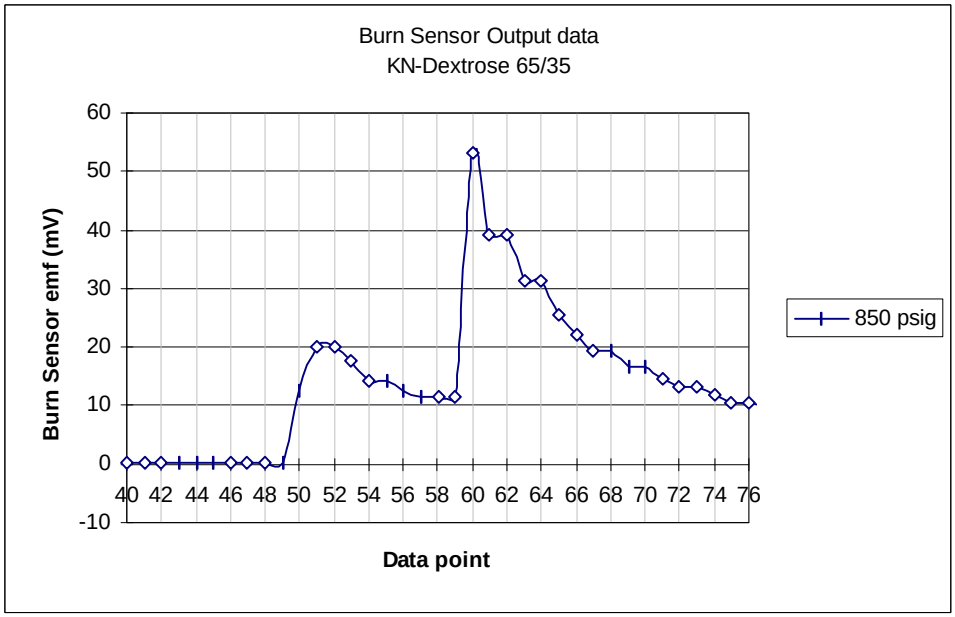
PB-3
Test DX310199-1 Strand Burning Test
KN-Dextrose (anhydrous) propellant
65/35 O/F ratio
Batch no. KNAD-240199-310199-1

$P_{initial}$ =	820 psig
P_{max} =	880 psig
	60 psig
$P_{average}$ =	850 psig

Spike 1	50 (start pt.)
Spike 2	60 (start pt.)
10	Samples between spikes
3.333	Sample/sec. rate
Δt =	3.00 sec.
L_{gauge} =	7.25 cm
r =	~~**2.417 cm/sec.**~~
(r =	0.951 in/sec.')

Note: Result invalidated --uncontrolled combustion occured

Notes:
1.Strand had no apparent defects
2. Burning was initially even, then suddenly rate appeared to increase dramatically (based on pressure rise).



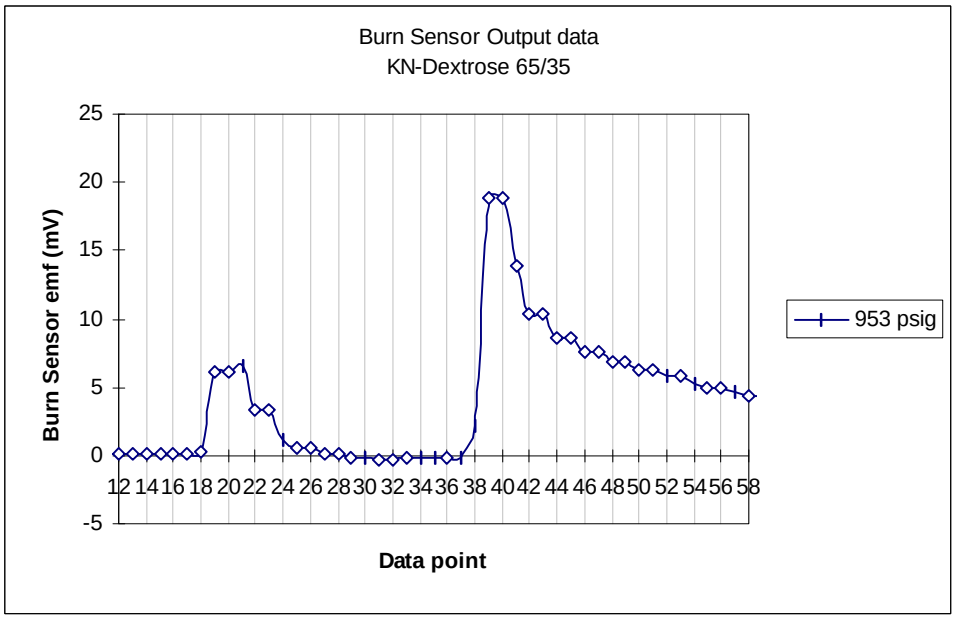
PB-4
Test DX020299-1 Strand Burning Test
KN-Dextrose (anhydrous) propellant
65/35 O/F ratio
Batch no. KNAD-240199-310199-1

$P_{initial}$ =	915 psig
P_{max} =	990 psig
	75 psig
$P_{average}$ =	952.5 psig

Spike 1	19 (start pt.)
Spike 2	38 (start pt.)
19	Samples between spikes
3.333	Sample/sec. rate
Δt =	5.70 sec.
L_{gauge} =	7.49 cm
r =	**1.314 cm/sec.**
(r =	0.517 in/sec.')

Notes:

1.Strand painted with hi-heat paint, two coats, allowed to dry 24 hours.
2.Strand had a minor defect at mid length.
3.Failed to ignite at first attempt. Igniter was replaced with a shorter length nichrome wire.
4. Appeared to burn evenly, judging by sound and pressure rise.

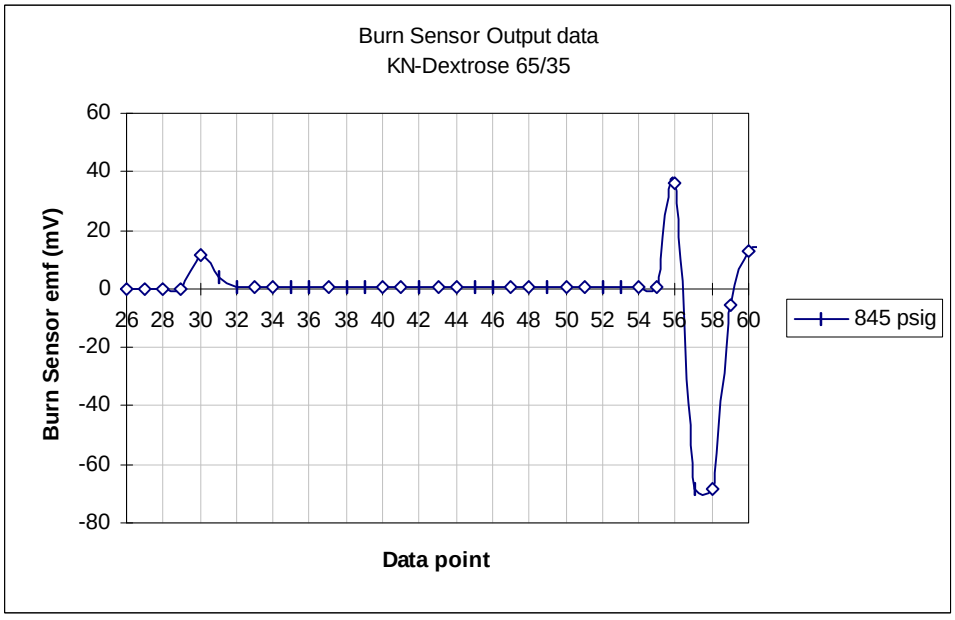


PB-5
Test DX050299-1 Strand Burning Test
KN-Dextrose (anhydrous) propellant
65/35 O/F ratio
Batch no. KNAD-240199-310199-1

$P_{initial}$ =	796 psig
P_{max} =	893 psig
	97 psig
$P_{average}$ =	844.5 psig

Spike 1	30 (start pt.)
Spike 2	56 (start pt.)
26	Samples between spikes
3.333	Sample/sec. rate
Δt =	7.80 sec.
L_{gauge} =	10.2 cm
r =	**1.308 cm/sec.**
(r =	0.515 in/sec.')

Notes:
1.Strand had no apparent defects
2.Strand painted with hi-heat paint
3. Strand nominal dimensions:
L_{TOT} = 12.45 cm
D_{MIN} = 0.37 cm
D_{MAJ} = 0.65 cm

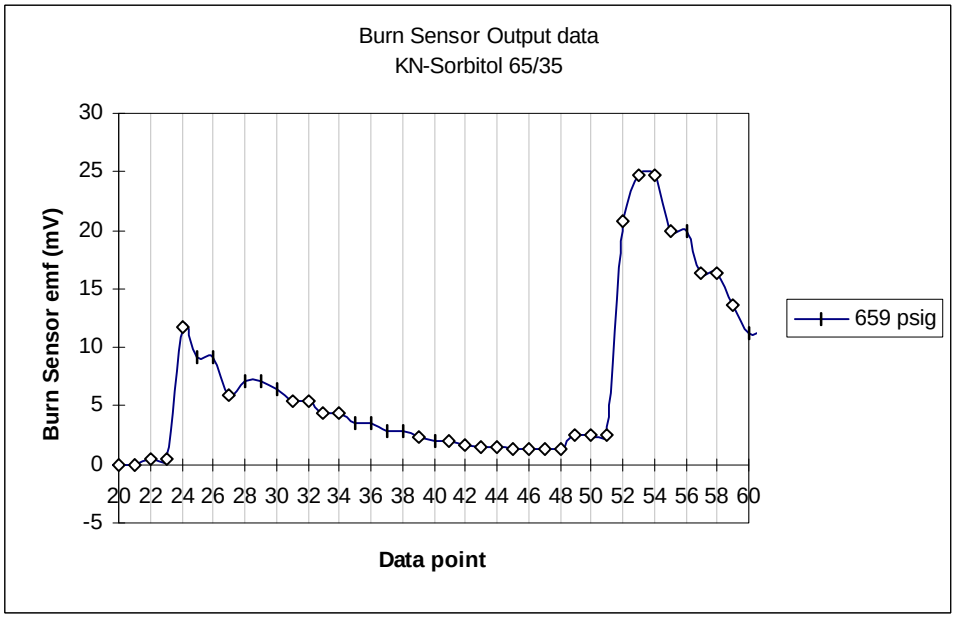


PB-6
Test SB090299-1 Strand Burning Test
KN-Sorbitol propellant
65/35 O/F ratio
Batch no. KNSB-060299-060299-1

$P_{initial}$ =	630 psig
P_{max} =	688 psig
	58 psig
$P_{average}$ =	659 psig

Spike 1	24 (start pt.)
Spike 2	52 (start pt.)
28	Samples between spikes
3.333	Sample/sec. rate
Δt =	8.40 sec.
L_{gauge} =	8.00 cm
r =	**0.952 cm/sec.**
(r =	0.375 in/sec.')

Notes:
1.Strand had no apparent defects
2.Strand painted with hi-heat paint
3. Strand nominal dimensions:
L_{TOT} = 9.9 cm
D_{MIN} = 0.38 cm
D_{MAJ} = 0.54 cm

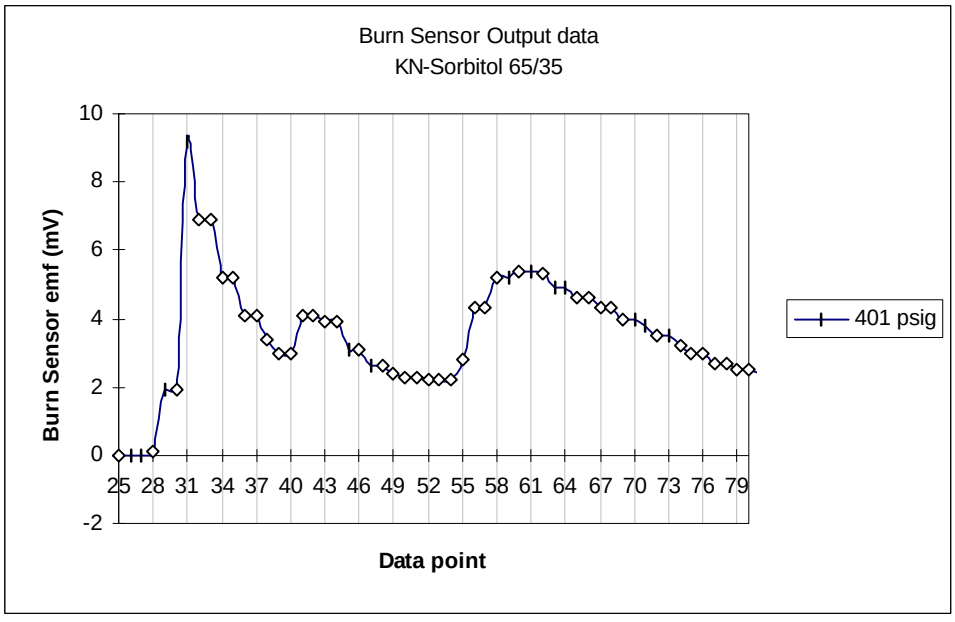


PB-7
Test SB100299-1 Strand Burning Test
KN-Sorbitol propellant
65/35 O/F ratio
Batch no. KNSB-060299-060299-1

$P_{initial}$ =	380 psig
P_{max} =	422 psig
	42 psig
$P_{average}$ =	401 psig

Spike 1	29 (start pt.)
Spike 2	55 (start pt.)
26	Samples between spikes
3.333	Sample/sec. rate
Δt =	7.80 sec.
L_{gauge} =	6.18 cm
r =	**0.792 cm/sec.**
(r =	0.312 in/sec.')

Notes:
1.Strand had no apparent defects
2.Strand painted with hi-heat paint
3. Strand nominal dimensions:
L_{TOT} = 7.5 cm
D_{MIN} = 0.37 cm
D_{MAJ} = 0.63 cm
4. Ambient room temp 18.9 C.

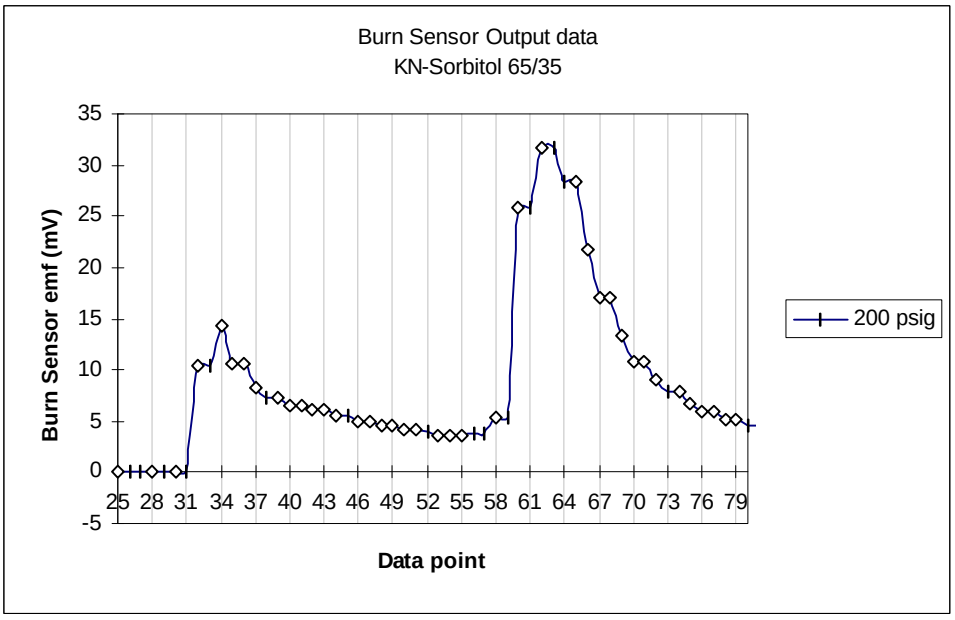


PB-8
Test SB110299-1 Strand Burning Test
KN-Sorbitol propellant
65/35 O/F ratio
Batch no. KNSB-060299-060299-1

$P_{initial}$ =	180 psig
P_{max} =	220 psig
	40 psig
$P_{average}$ =	200 psig

Spike 1	32 (start pt.)
Spike 2	60 (start pt.)
28	Samples between spikes
3.333	Sample/sec. rate
Δt =	8.40 sec.
L_{gauge} =	6.60 cm
r =	**0.786 cm/sec.**
(r =	0.309 in/sec.')

Notes:
1.Strand had no apparent defects
2.Strand painted with hi-heat paint
3. Strand nominal dimensions:
L_{TOT} = 8.5 cm
D_{MIN} = 0.45 cm
D_{MAJ} = 0.64 cm
4. Ambient room temp 19.6 C.

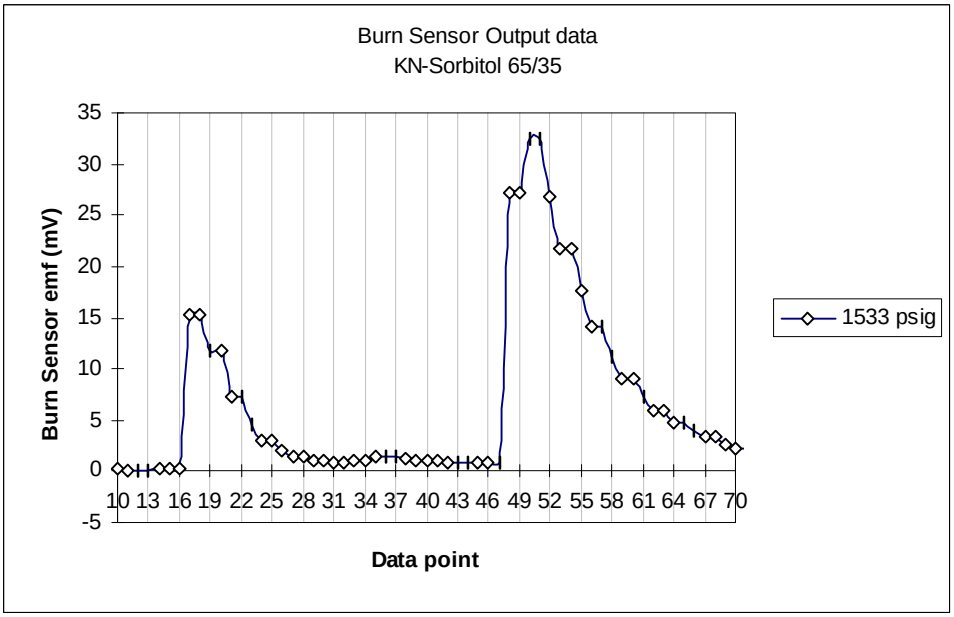


PB-9
Test SB120299-1 Strand Burning Test
KN-Sorbitol propellant
65/35 O/F ratio
Batch no. KNSB-060299-060299-1

$P_{initial}$ =	1500 psig
P_{max} =	1565 psig
	65 psig
$P_{average}$ =	1532.5 psig

Spike 1	17 (start pt.)
Spike 2	48 (start pt.)
31	Samples between spikes
3.333	Sample/sec. rate
Δt =	9.30 sec.
L_{gauge} =	10.50 cm
r =	**1.129 cm/sec.**
(r =	0.445 in/sec.')

Notes:
1.Strand had no apparent defects
2.Strand painted with hi-heat paint
3. Strand nominal dimensions:
L_{TOT} = 12.3 cm
D_{MIN} = 0.36 cm
D_{MAJ} = 0.56 cm
4. Ambient room temp 20.5 C.

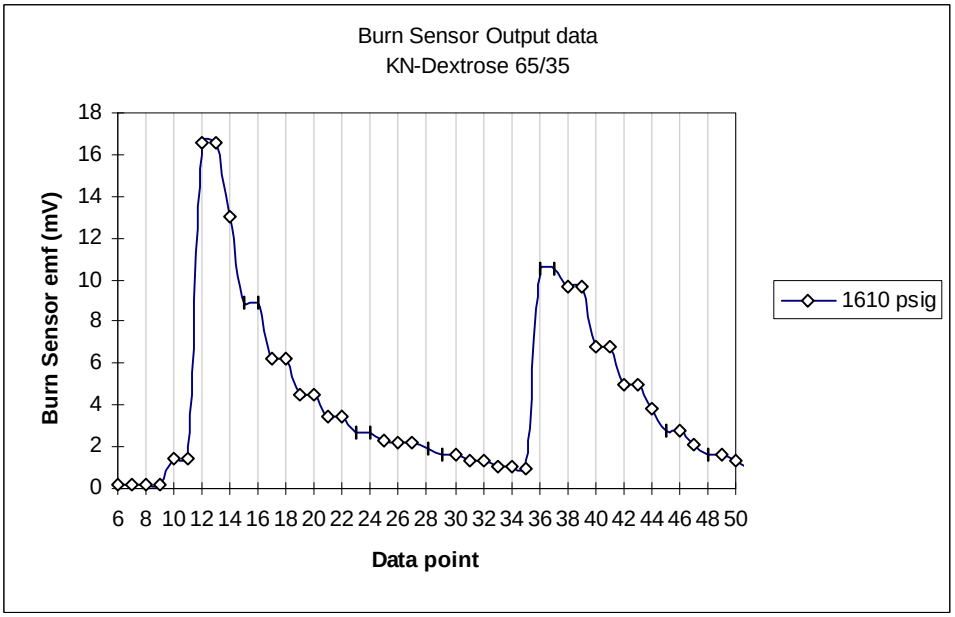


PB-10
Test DX130299-1 Strand Burning Test
KN-Dextrose (anhydrous) propellant
65/35 O/F ratio
Batch no. KNAD-240199-310199-1

$P_{initial}$ =	1570 psig
P_{max} =	1650 psig
	80 psig
$P_{average}$ =	1610 psig

Spike 1	12 (start pt.)
Spike 2	36 (start pt.)
24	Samples between spikes
3.333	Sample/sec. rate
Δt =	7.20 sec.
L_{gauge} =	10.02 cm
r =	**1.392 cm/sec.**
(r =	0.548 in/sec.')

Notes:
1.Strand had no apparent defects
2.Strand painted with hi-heat paint
3. Strand nominal dimensions:
L_{TOT} = 11.75 cm
D_{MIN} = 0.39 cm
D_{MAJ} = 0.65 cm
4. Ambient room temp 21.2C.



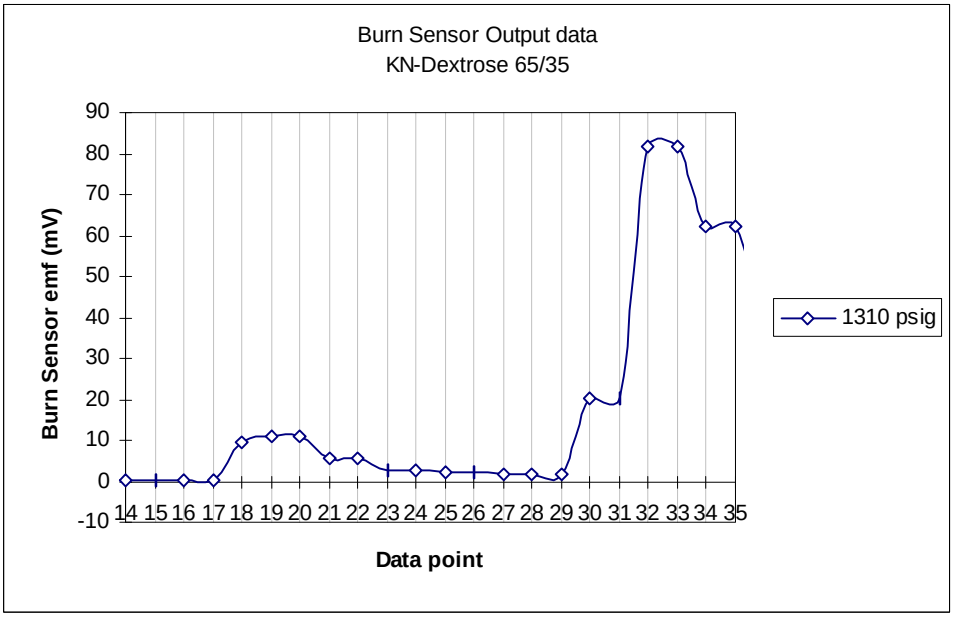
PB-11
Test DX130299-2 Strand Burning Test
KN-Dextrose (anhydrous) propellant
65/35 O/F ratio
Batch no. KNAD-240199-310199-1

$P_{initial}$ =	1230 psig
P_{max} =	1390 psig
	160 psig
$P_{average}$ =	1310 psig

Spike 1	18 (start pt.)
Spike 2	30 (start pt.)
12	Samples between spikes
3.333	Sample/sec. rate
Δt =	3.60 sec.
L_{gauge} =	8.23 cm
r =	~~**2.286 cm/sec.**~~
(r =	0.900 in/sec.')

Note: Result invalidated --uncontrolled combustion occured

Notes:
1.Strand had two minor blemishes (concavities)
2.Strand painted with hi-heat paint
3. Strand nominal dimensions:
L_{TOT} = 9.50 cm
D_{MIN} = 0.60 cm
D_{MAJ} = 0.89 cm
4. Strand began burning normally, then a sudden pressure rise was observed, and the sound eminating from the Firing Vessel grew briefly louder. This effect had been observed in earlier test that had premature ignition of the strand due to "drooling" of molten product. At Pmax, a slight metallic "crack" sound was heard eminating from the Firing Vessel. Later inspection revealed nothing unusual. Note that the strand used in this test was significantly "fatter" than typical (see dimensions).

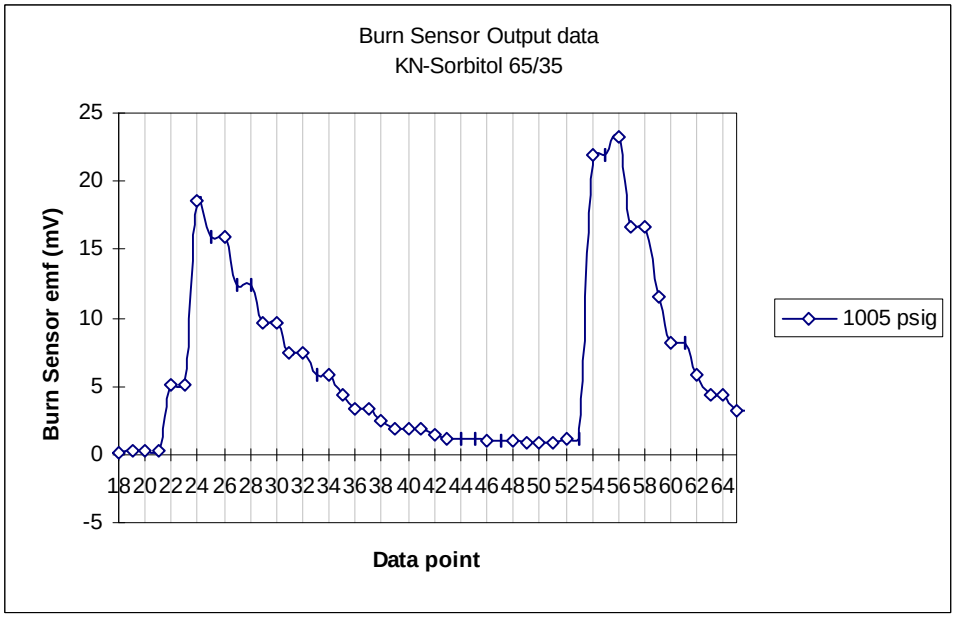


PB-12
Test SB130299-1 Strand Burning Test
KN-Sorbitol propellant
65/35 O/F ratio
Batch no. KNSB-060299-060299-1

$P_{initial}$ =	975 psig
P_{max} =	1035 psig
	60 psig
$P_{average}$ =	1005 psig

Spike 1	22 (start pt.)
Spike 2	54 (start pt.)
32	Samples between spikes
3.333	Sample/sec. rate
Δt =	9.60 sec.
L_{gauge} =	10.58 cm
r =	**1.102 cm/sec.**
(r =	0.434 in/sec.')

Notes:
1.Strand had no apparent defects
2.Strand painted with hi-heat paint
3. Strand nominal dimensions:
L_{TOT} = 12.05 cm
D_{MIN} = 0.39 cm
D_{MAJ} = 0.55 cm
4. Appeared to burn well. Pressure rise was even. Sound from the Firing Vessel was slight.

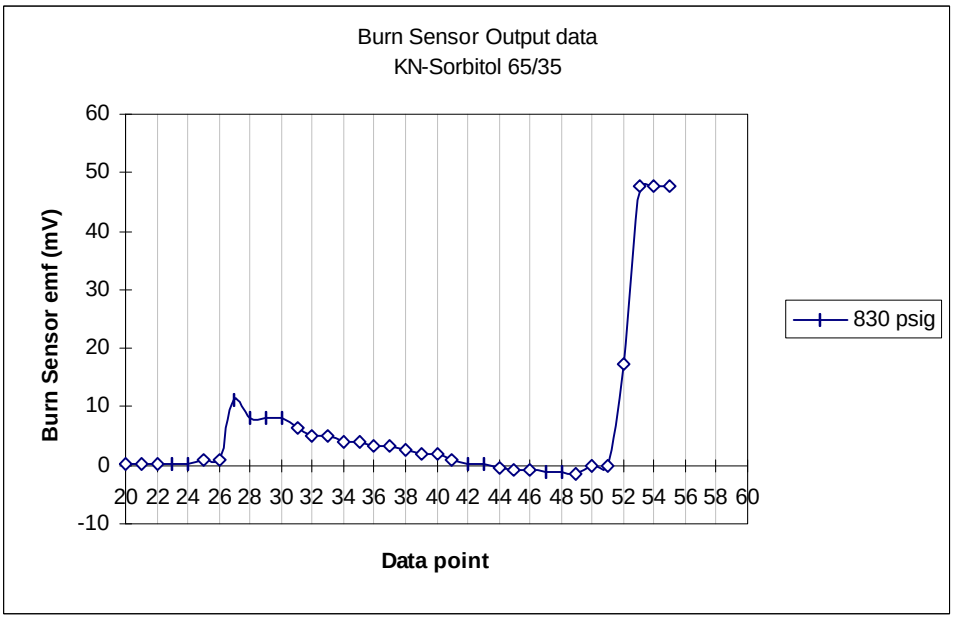


PB-13
Test SB060399-1 Strand Burning Test
KN-Sorbitol propellant
65/35 O/F ratio
Batch no. KNSB-060299-060399-1

$P_{initial}$ =	800 psig
P_{max} =	860 psig
	60 psig
$P_{average}$ =	830 psig

Spike 1	27 (start pt.)
Spike 2	52 (start pt.)
25	Samples between spikes
3.333	Sample/sec. rate
Δt =	7.50 sec.
L_{gauge} =	7.33 cm
r =	**0.977 cm/sec.**
(r =	0.385 in/sec.')

Notes:
1.Strand had no apparent defects
2.Strand painted with hi-heat paint
3. Strand nominal dimensions:
L_{TOT} = 9.15 cm
D_{MIN} = 0.35 cm
D_{MAJ} = 0.70 cm
4. Appeared to burn well. Pressure rise was even. Sound from the Firing Vessel was very slight.
5. Thermocouple reading went to OL (out of range) after sample # 55.

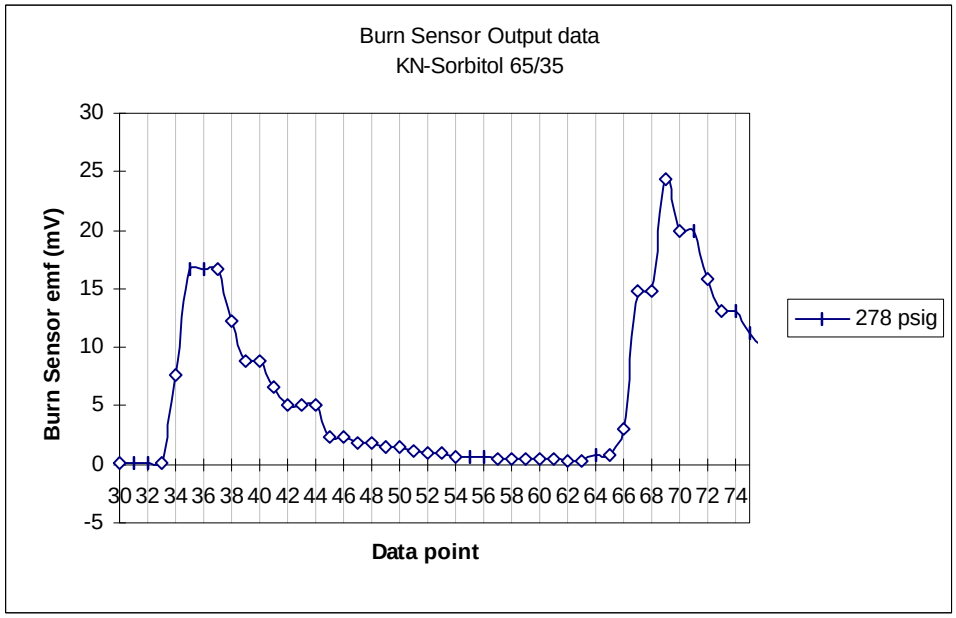


PB-14
Test SB060399-2 Strand Burning Test
KN-Sorbitol propellant
65/35 O/F ratio
Batch no. KNSB-060299-060399-1

$P_{initial}$ =	260 psig
P_{max} =	295 psig
	35 psig
$P_{average}$ =	277.5 psig

Spike 1	34 (start pt.)
Spike 2	67 (start pt.)
33	Samples between spikes
3.333	Sample/sec. rate
Δt =	9.90 sec.
L_{gauge} =	8.40 cm
r =	**~~0.848~~ cm/sec.**
(r =	0.334 in/sec.')

Note: Result invalidated --flawed strand resulted in uncontrolled burn

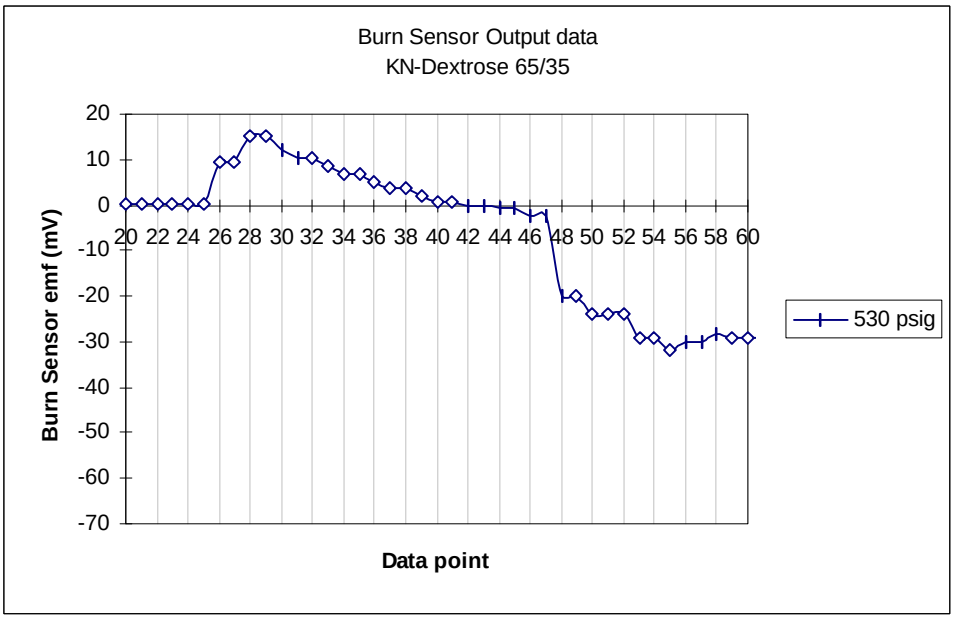


PB-15
Test DX070399-1 Strand Burning Test
KN-Dextrose propellant
65/35 O/F ratio
Batch no. KNAD-060299-060399-1

$P_{initial}$ =	502 psig
P_{max} =	558 psig
	56 psig
$P_{average}$ =	530 psig

Spike 1	26 (start pt.)
Spike 2	48 (start pt.)
22	Samples between spikes
3.333	Sample/sec. rate
Δt =	6.60 sec.
L_{gauge} =	8.10 cm
r =	~~**1.227**~~ **cm/sec.**
(r =	0.483 in/sec.')

Result invalidated - see note 5.

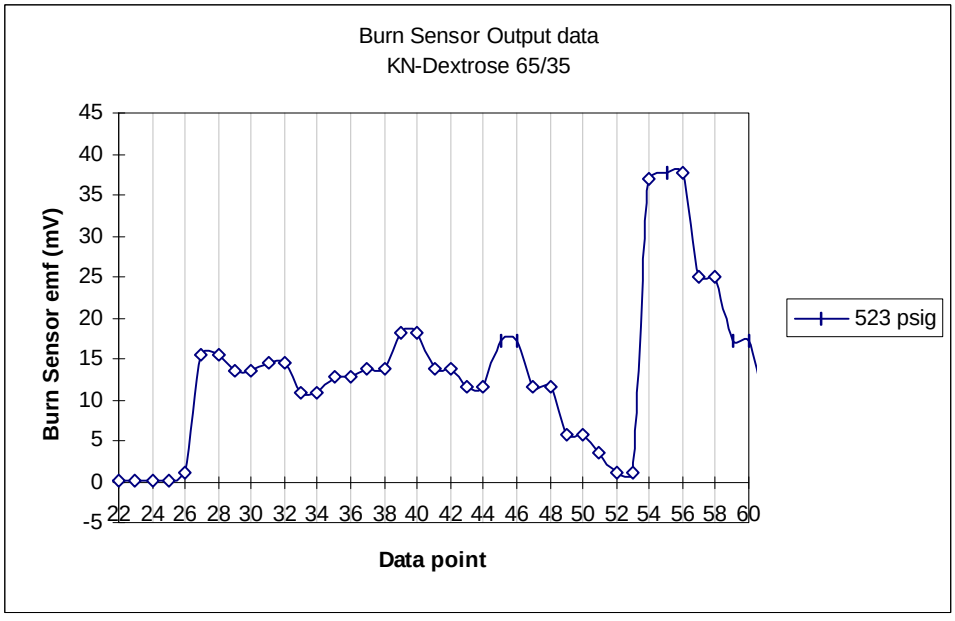


PB-16
Test DX070399-2 Strand Burning Test
KN-Dextrose propellant
65/35 O/F ratio
Batch no. KNAD-060299-060399-1

$P_{initial}$ =	500 psig
P_{max} =	545 psig
	45 psig
$P_{average}$ =	522.5 psig

Spike 1	27 (start pt.)
Spike 2	54 (start pt.)
27	Samples between spikes
3.333	Sample/sec. rate
Δt =	8.10 sec.
L_{gauge} =	7.55 cm
r =	**0.932 cm/sec.**
(r =	0.367 in/sec.')

Notes:
1.Strand had no discernible flaws.
2.Strand painted with hi-heat paint
3. Strand nominal dimensions:
L_{TOT} = 9.6 cm
D_{MIN} = 0.54 cm
D_{MAJ} = 0.38 cm
4. Appeared to burn well. Pressure rise was even, as was the sound from the Firing Vessel.

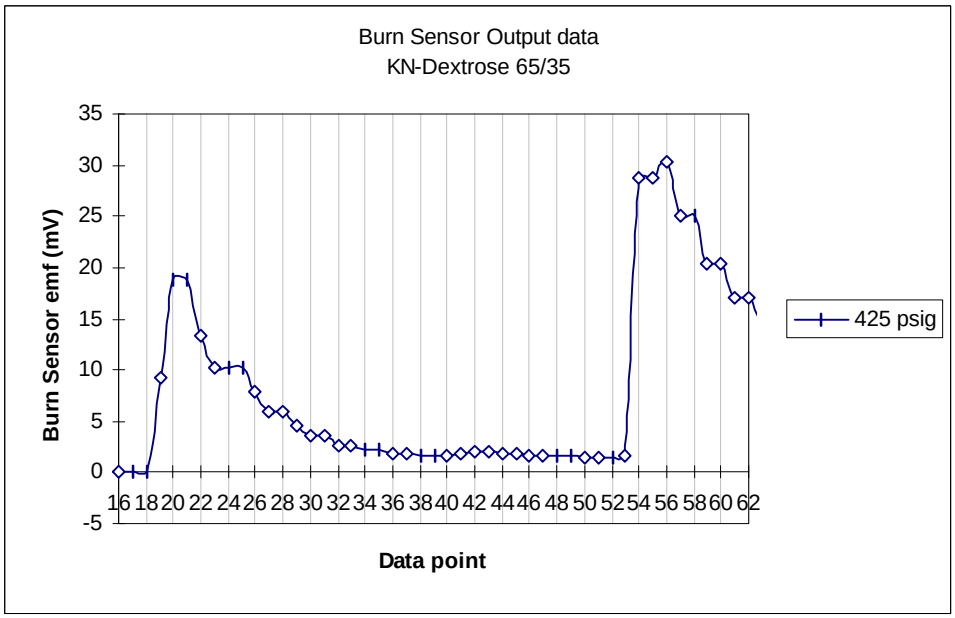


PB-17
Test DX140399-1 Strand Burning Test
KN-Dextrose propellant
65/35 O/F ratio
Batch no. KNAD-110399-120399-2

$P_{initial}$ =	400 psig
P_{max} =	450 psig
	50 psig
$P_{average}$ =	425 psig

Spike 1	19 (start pt.)
Spike 2	54 (start pt.)
35	Samples between spikes
3.333	Sample/sec. rate
Δt =	10.50 sec.
L_{gauge} =	8.72 cm
r =	**0.830 cm/sec.**
(r =	0.327 in/sec.')

Notes:
1.Strand had no discernible flaws.
2.Strand painted with hi-heat paint
3. Strand (#7) nominal dimensions:
L_{TOT} = 10.4 cm
D_{MIN} = 0.37 cm
D_{MAJ} = 0.60 cm
4. Appeared to burn well. Pressure rise was even, almost no sound
5. Apparatus modified by the addition of an adjustable pressure release valve.
The valve was set to vent at 405 psi. Provided some venting, but could not eliminate pressure rise.

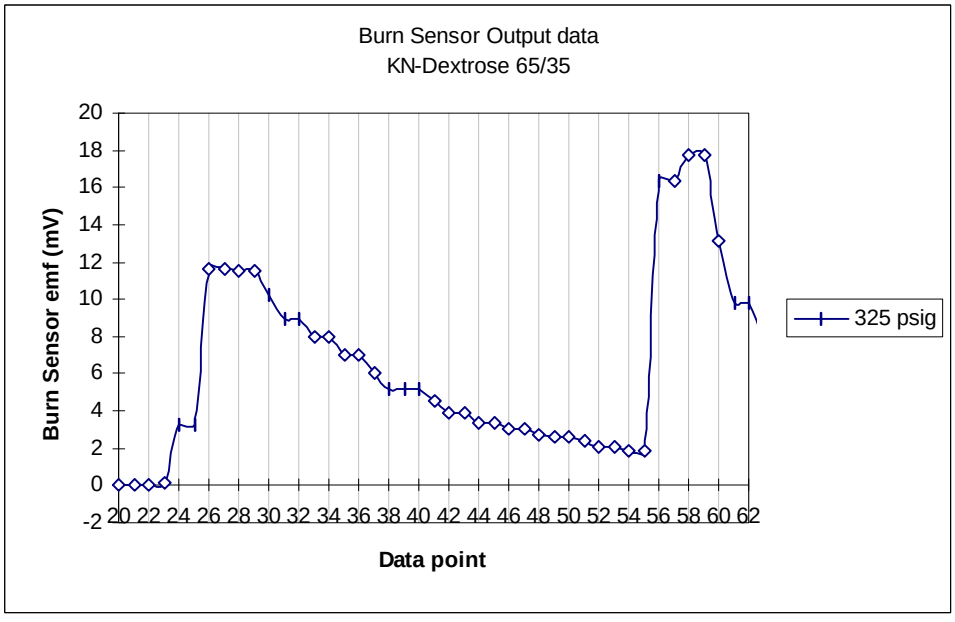


PB-18
Test DX160399-1 Strand Burning Test
KN-Dextrose propellant
65/35 O/F ratio
Batch no. KNAD-110399-120399-2

$P_{initial}$ =	305 psig
P_{max} =	345 psig
	40 psig
$P_{average}$ =	325 psig

Spike 1	24 (start pt.)
Spike 2	56 (start pt.)
32	Samples between spikes
3.333	Sample/sec. rate
Δt =	9.60 sec.
L_{gauge} =	7.66 cm
r =	**0.798 cm/sec.**
(r =	0.314 in/sec.')

Notes:
1.Strand had no discernible flaws.
2.Strand painted with hi-heat paint
3. Strand (#8) nominal dimensions:
L_{TOT} = 8.75 cm
D_{MIN} = 0.35 cm
D_{MAJ} = 0.58 cm
4. Appeared to burn well. Pressure rise was even, almost no sound
5. Apparatus modified by the addition of an adjustable pressure release valve.
The valve was set to vent at 305 psi. Provided some venting, but could not eliminate pressure rise.

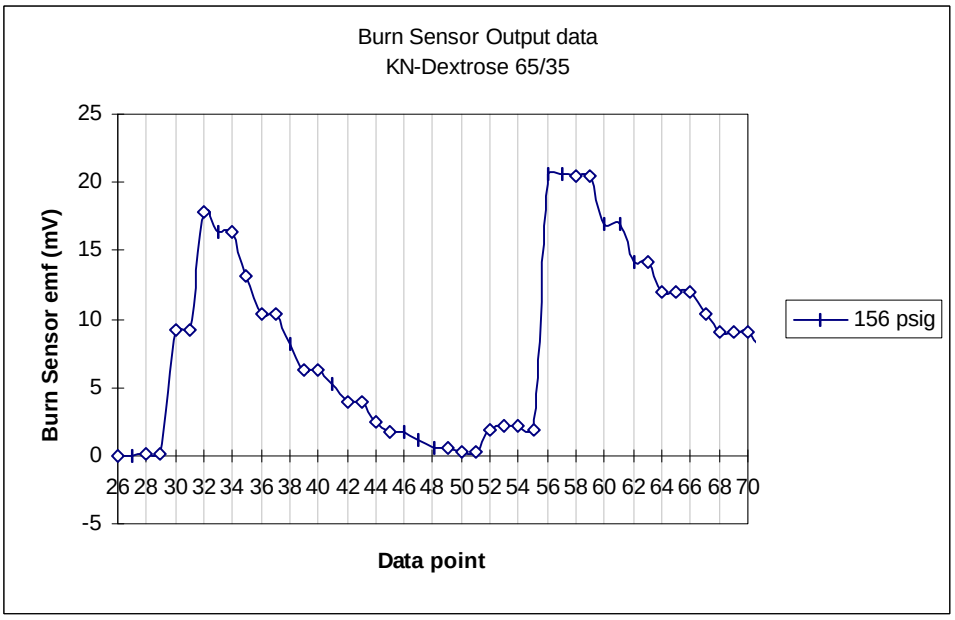


PB-19
Test DX170399-1 Strand Burning Test
KN-Dextrose propellant
65/35 O/F ratio
Batch no. KNAD-110399-120399-2

$P_{initial}$ =	142 psig
P_{max} =	170 psig
	28 psig
$P_{average}$ =	156 psig

Spike 1	30 (start pt.)
Spike 2	56 (start pt.)
26	Samples between spikes
3.333	Sample/sec. rate
Δt =	7.80 sec.
L_{gauge} =	6.40 cm
r =	**~~0.821~~ cm/sec.**
(r =	0.323 in/sec.')

Result invalidated. Foothill indicates 2nd sensor caught drool...premature ignition?

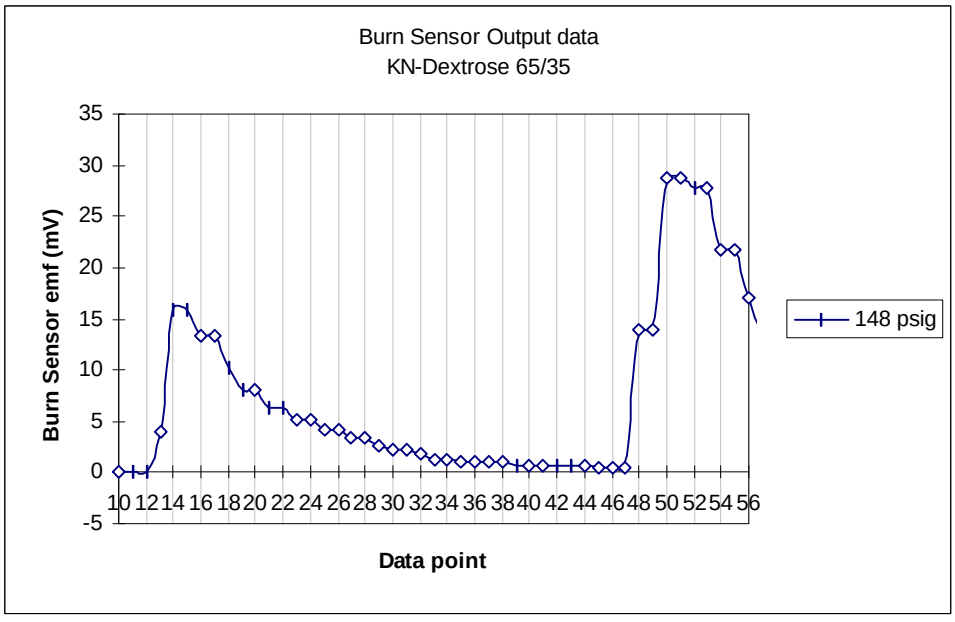


PB-20
Test DX180399-1 Strand Burning Test
KN-Dextrose propellant
65/35 O/F ratio
Batch no. KNAD-110399-120399-2

$P_{initial}$ =	130 psig
P_{max} =	165 psig
	35 psig
$P_{average}$ =	147.5 psig

Spike 1	13 (start pt.)
Spike 2	48 (start pt.)
35	Samples between spikes
3.333	Sample/sec. rate
Δt =	10.50 sec.
L_{gauge} =	7.89 cm
r =	**0.751 cm/sec.**
(r =	0.296 in/sec.')

Notes:
1.Strand had no discernible flaws.
2.Strand painted with hi-heat paint
3. Strand (#6) nominal dimensions:
L_{TOT} = 9.65 cm
D_{MIN} = 0.38 cm
D_{MAJ} = 0.61 cm
4. Appeared to burn well. Pressure rise was even, almost no sound

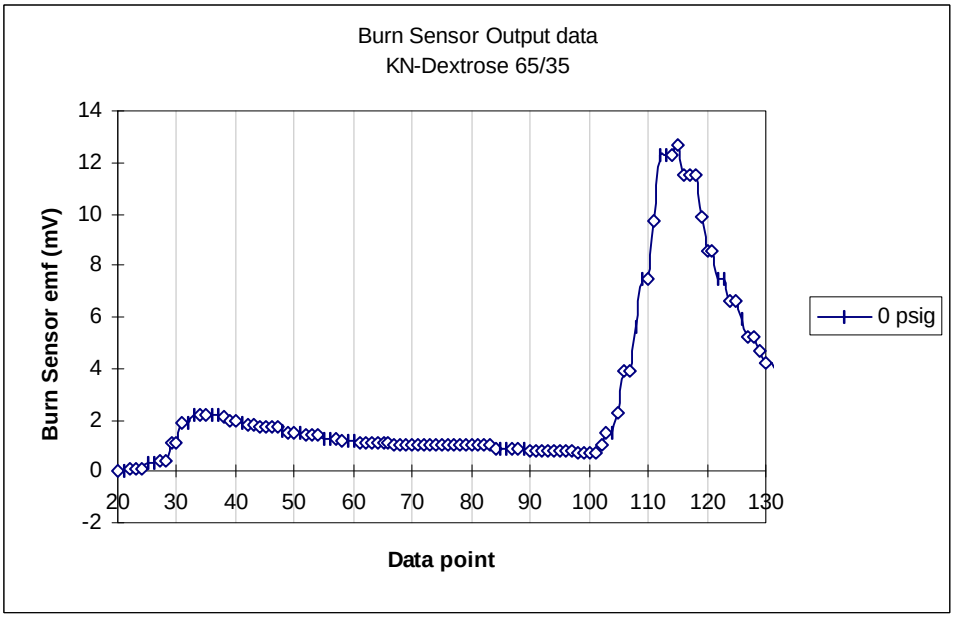


PB-21
Test DX180399-2 Strand Burning Test
KN-Dextrose propellant
65/35 O/F ratio
Batch no. KNAD-060299-060399-1

$P_{initial}$ =	0 psig
P_{max} =	0 psig
	0 psig
$P_{average}$ =	0 psig

Spike 1	29 (start pt.)
Spike 2	106 (start pt.)
77	Samples between spikes
3.333	Sample/sec. rate
Δt =	23.10 sec.
L_{gauge} =	4.96 cm
r =	**0.215 cm/sec.**
(r =	0.085 in/sec.')

Notes:
1.Strand had a cavity, but was not located in the gauge length
2.Strand painted with hi-heat paint
3. Strand was from previous batch, with nominal dimensions:
L_{TOT} = 6.75 cm
D_{MIN} = 0.42 cm
D_{MAJ} = 0.55 cm
4. This test was conducted at atmospheric pressure, inside the strand burner (fill tube disconnected and attach bolts were loosened to allow a gap. Vessel was purged prior to firing.
5. Appeared to burn well. Some smoke issued from the port, less than expected.



PB-22
Test SB200399-1 Strand Burning Test
KN-Sorbitol propellant
65/35 O/F ratio
Batch no. KNSB-060299-180399-1

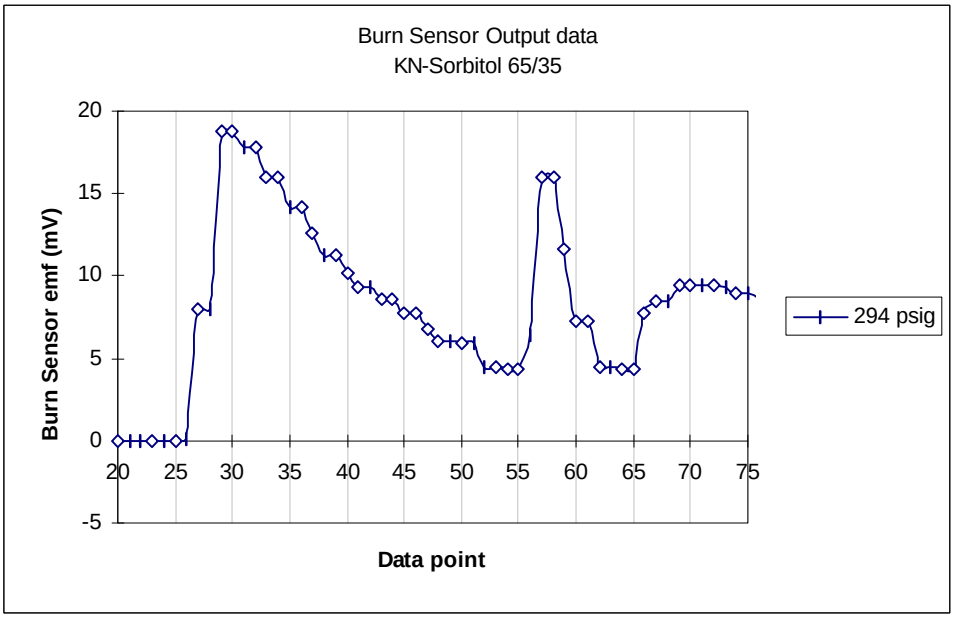
$P_{initial}$ =	280 psig
P_{max} =	308 psig
	28 psig
$P_{average}$ =	294 psig

Spike 1	27 (start pt.)
Spike 2	66 (start pt.)
39	Samples between spikes
3.333	Sample/sec. rate
Δt =	11.70 sec.
L_{gauge} =	8.53 cm
r =	**0.729 cm/sec.**
(r =	0.287 in/sec.')

Notes:
1. Strand had no apparent defects
2. Strand painted with hi-heat aluminum paint
3. Strand nominal dimensions:

L_{TOT} =	9.55 cm
D_{MIN} =	0.30 cm
D_{MAJ} =	0.50 cm

4. Appeared to burn well.
5. On the graph, the spike that occurs at data pt.55 is considered to be a result of a ball of molten product dribbling onto the second TC sensor. The flame front is considered to reach the second TC sensor at data pt.66, at the start of the next spike.



PB-23
Test SB210399-1 Strand Burning Test
KN-Sorbitol propellant
65/35 O/F ratio
Batch no. KNSB-060299-180399-1

$P_{initial}$ =	180 psig
P_{max} =	208 psig
	28 psig
$P_{average}$ =	194 psig

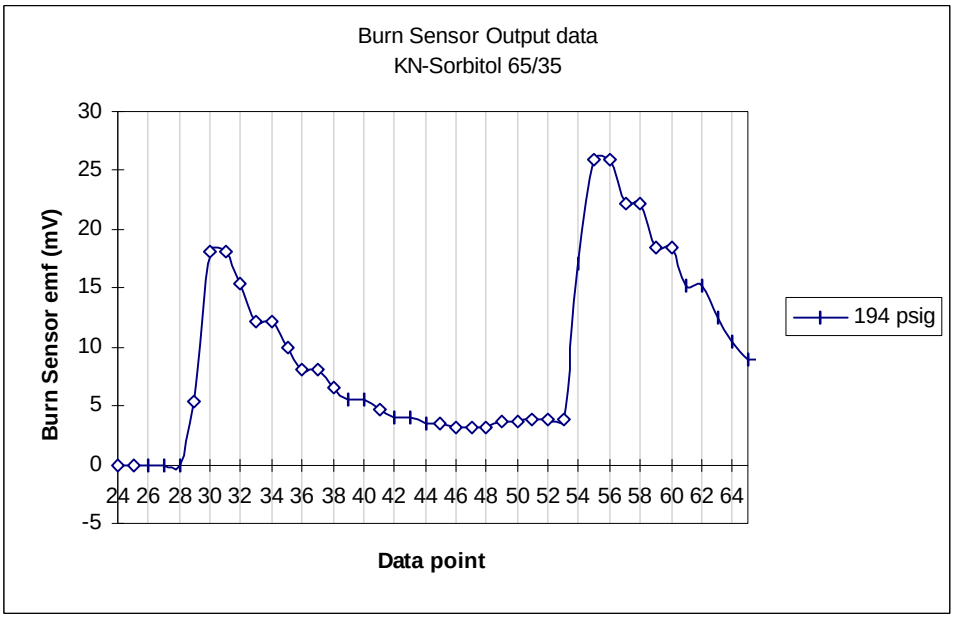
Spike 1	29 (start pt.)
Spike 2	54 (start pt.)
25	Samples between spikes
3.333	Sample/sec. rate
Δt =	7.50 sec.
L_{gauge} =	6.41 cm
r =	***0.855*** **cm/sec.**
(r =	0.336 in/sec.')

Result valid?. Strand flaws may have caused rapid burn.

Notes:
1. Strand had a number of surface defects. However, all blemishes were well coated with the hi-heat paint.
2. Strand painted with hi-heat aluminum paint
3. Strand nominal dimensions:

L_{TOT} =	7.6 cm
D_{MIN} =	0.39 cm
D_{MAJ} =	0.55 cm

4. Appeared to burn well.

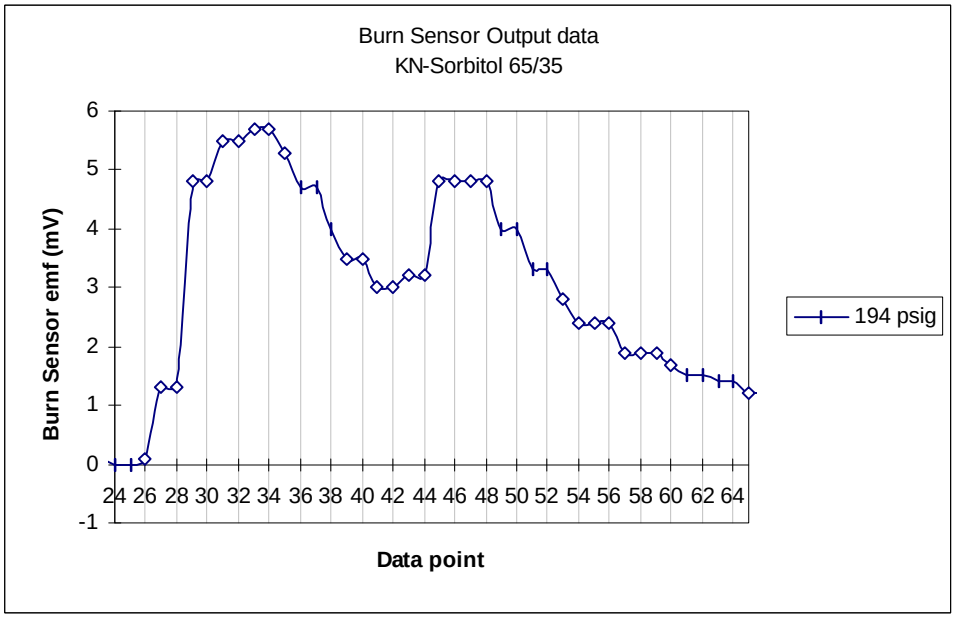


PB-24
Test SB220399-1 Strand Burning Test
KN-Sorbitol propellant
65/35 O/F ratio
Batch no. KNSB-060299-180399-1

$P_{initial}$ =	180 psig
P_{max} =	209 psig
	29 psig
$P_{average}$ =	194.5 psig

Spike 1	27 (start pt.)
Spike 2	45 (start pt.)
18	Samples between spikes
3.333	Sample/sec. rate
Δt =	5.40 sec.
L_{gauge} =	6.60 cm
r =	~~***1.222***~~ **cm/sec.**
(r =	0.481 in/sec.')

Result valid? Uncontrolled burned appears to have occured.



PB-25
Test SB260399-1 Strand Burning Test
KN-Sorbitol propellant
65/35 O/F ratio
Batch no. KNSB-060299-180399-1

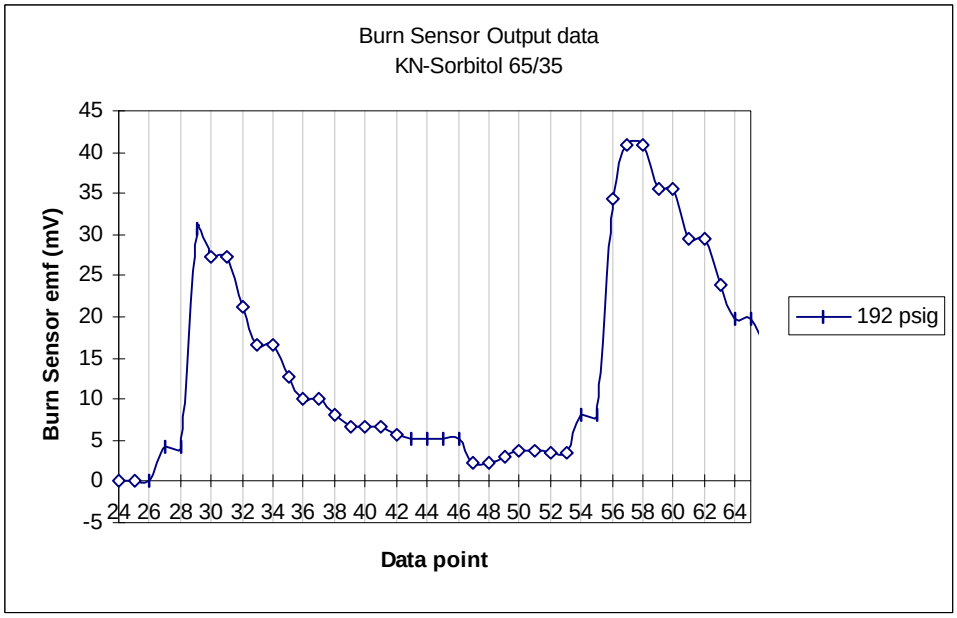
$P_{initial}$ =	180 psig
P_{max} =	204 psig
	24 psig
$P_{average}$ =	192 psig

Spike 1	29 (start pt.)
Spike 2	56 (start pt.)
27	Samples between spikes
3.333	Sample/sec. rate
Δt =	8.10 sec.
L_{gauge} =	6.37 cm
r =	**0.786 cm/sec.**
(r =	0.310 in/sec.')

Notes:
1. Strand had a small cavity near centre, but was well painted
2. Strand painted with hi-heat aluminum paint. Paint scraped away at gauge marks
3. Strand nominal dimensions:

L_{TOT} =	7.55 cm
D_{MIN} =	0.36 cm
D_{MAJ} =	0.45 cm

4. Appeared to burn well
5. Strand burner vessel was mounted horizontally, rather than vertical as in previous tests, to avoid the dribbling problem.



PB-26
Test SB290399-1 Strand Burning Test
KN-Sorbitol propellant
65/35 O/F ratio
Batch no. KNSB-060299-180399-1

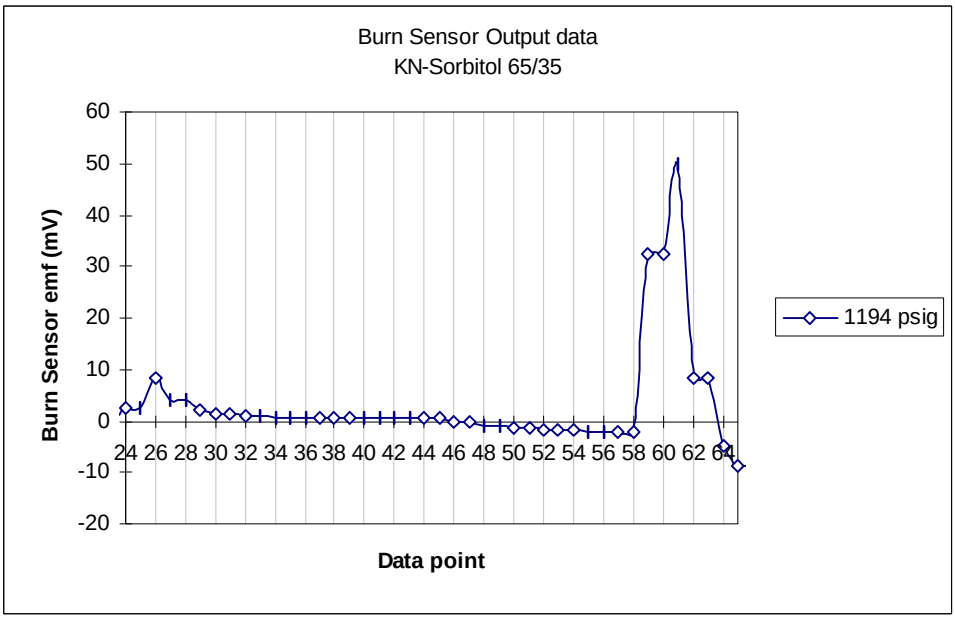
$P_{initial}$ =	1170 psig
P_{max} =	1218 psig
	48 psig
$P_{average}$ =	1194 psig

Spike 1	26 (start pt.)
Spike 2	59 (start pt.)
33	Samples between spikes
3.333	Sample/sec. rate
Δt =	9.90 sec.
L_{gauge} =	10.80 cm
r =	**1.091 cm/sec.**
(r =	0.429 in/sec.')

Notes:
1. Strand had no apparent flaws
2. Strand painted with hi-heat aluminum paint. Paint scraped away at gauge marks
3. Strand nominal dimensions:

L_{TOT} =	12.1 cm
D_{MIN} =	0.35 cm
D_{MAJ} =	0.48 cm

4. Appeared to burn well
5. Strand burner vessel was mounted horizontally, rather than vertical as in most previous tests, to avoid the drooling problem.



PB-27
Test DX300399-1 Strand Burning Test
KN-Dextrose propellant
65/35 O/F ratio
Batch no. KNAD-110399-120399-2

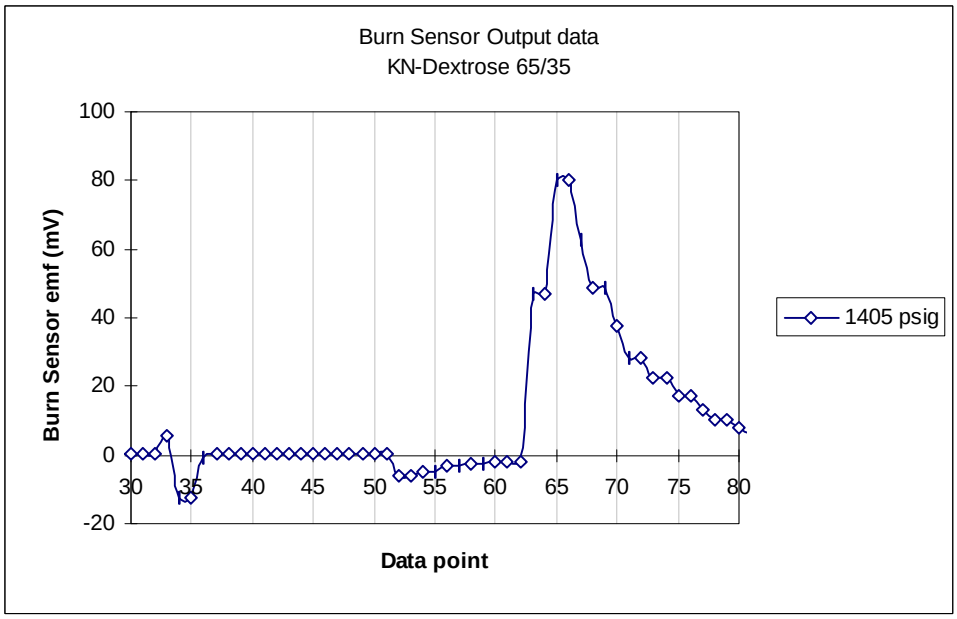
$P_{initial}$ =	1370 psig
P_{max} =	1440 psig
	70 psig
$P_{average}$ =	1405 psig

Spike 1	33 (start pt.)
Spike 2	63 (start pt.)
30	Samples between spikes
3.333	Sample/sec. rate
Δt =	9.00 sec.
L_{gauge} =	11.70 cm
r =	**1.300 cm/sec.**
(r =	0.512 in/sec.')

Notes:
1.Strand had no apparent flaws
2.Strand painted with hi-heat paint, but was scraped away at gauge marks
3. Strand (#3) with nominal dimensions:

L_{TOT} =	12.95 cm
D_{MIN} =	0.35 cm
D_{MAJ} =	0.50 cm

4. Appeared to burn well, although quite quickly
5. Vessel mounted horizontally.



PB-28
Test DX310399-1 Strand Burning Test
KN-Dextrose propellant
65/35 O/F ratio
Batch no. KNAD-110399-120399-2

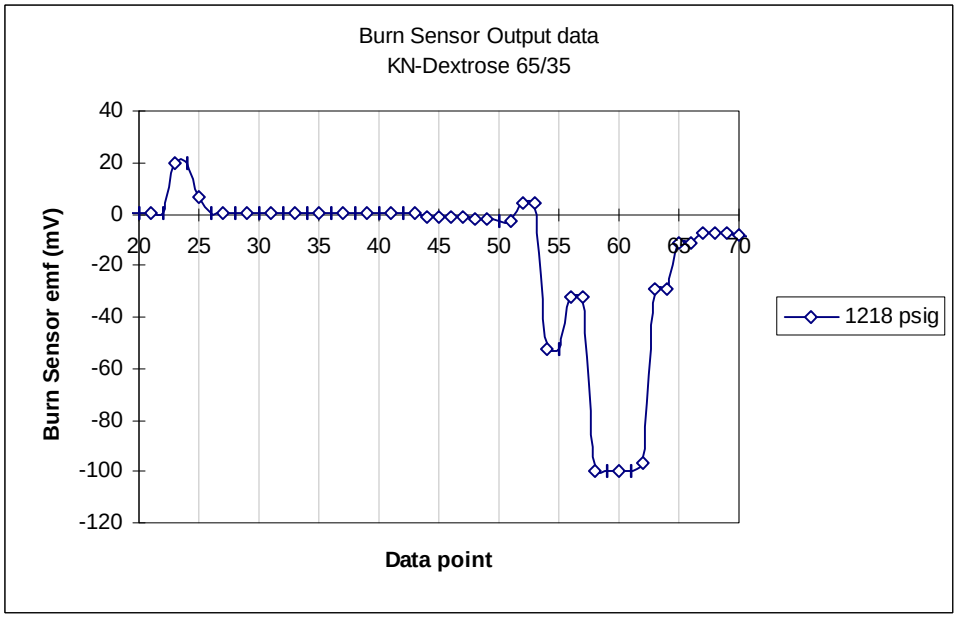
$P_{initial}$ =	1178 psig
P_{max} =	1258 psig
	80 psig
$P_{average}$ =	1218 psig

Spike 1	23 (start pt.)
Spike 2	52 (start pt.)
29	Samples between spikes
3.333	Sample/sec. rate
Δt =	8.70 sec.
L_{gauge} =	10.72 cm
r =	**1.232 cm/sec.**
(r =	0.485 in/sec.')

Notes:
1.Strand had a minor imperfection near each end
2.Strand painted with hi-heat paint, but was scraped away at gauge marks
3. Strand (#4) with nominal dimensions:

L_{TOT} =	12.4 cm
D_{MIN} =	0.39 cm
D_{MAJ} =	0.58 cm

4. Appeared to burn well, although quite quickly
5. Vessel mounted horizontally.



PB-29
Test DX020499-1 Strand Burning Test
KN-Dextrose propellant
65/35 O/F ratio
Batch no. KNAD-110399-120399-2

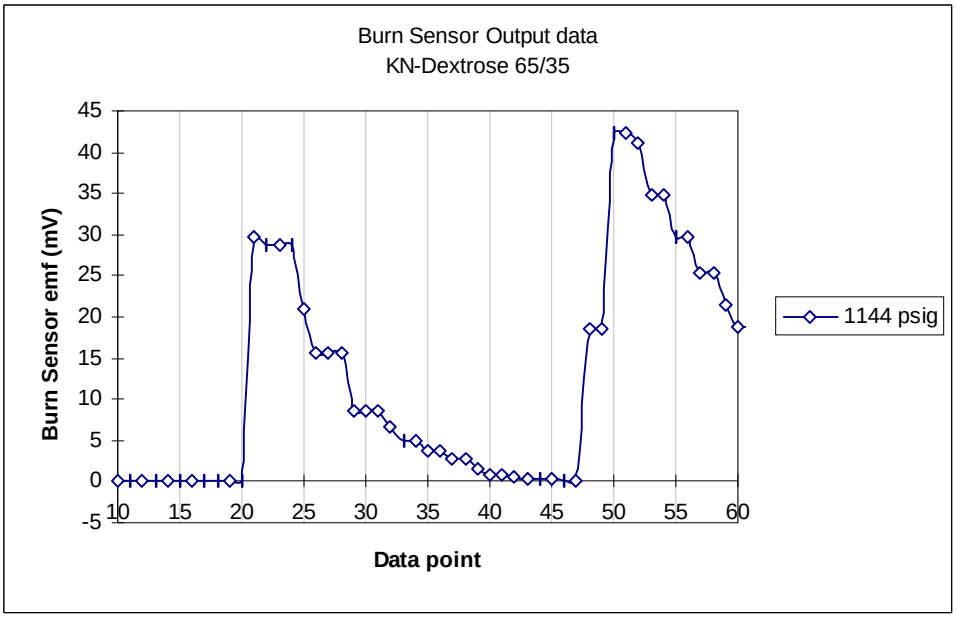
$P_{initial}$ =	1110 psig
P_{max} =	1178 psig
	68 psig
$P_{average}$ =	1144 psig

Spike 1	21 (start pt.)
Spike 2	48 (start pt.)
27	Samples between spikes
3.333	Sample/sec. rate
Δt =	8.10 sec.
L_{gauge} =	10.41 cm
r =	**1.285 cm/sec.**
(r =	0.506 in/sec.')

Notes:
1.Strand had no apparent flaws
2.Strand painted with hi-heat paint, but was scraped away at gauge marks
3. Strand (#2) with nominal dimensions:

L_{TOT} =	11.4 cm
D_{MIN} =	0.38 cm
D_{MAJ} =	0.61 cm

4. Appeared to burn well, although quite quickly
5. Vessel mounted horizontally.



PB-30
Test DX020499-2 Strand Burning Test
KN-Dextrose propellant
65/35 O/F ratio
Batch no. KNAD-110399-120399-2

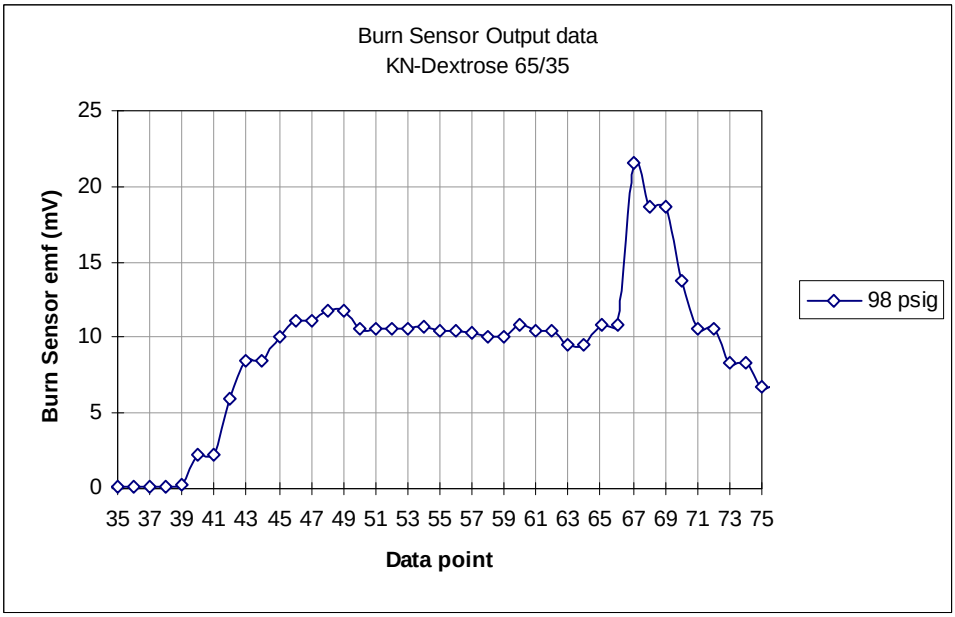
$P_{initial}$ =	90 psig
P_{max} =	106 psig
	16 psig
$P_{average}$ =	98 psig

Spike 1	40 (start pt.)
Spike 2	67 (start pt.)
27	Samples between spikes
3.333	Sample/sec. rate
Δt =	8.10 sec.
L_{gauge} =	6.15 cm
r =	**0.759 cm/sec.**
(r =	0.299 in/sec.')

Notes:
1.Strand had no apparent flaws
2.Strand painted with hi-heat paint, but was scraped away at gauge marks
3. Strand (#1) (cut into two pieces) with nominal dimensions:

L_{TOT} =	6.95 cm
D_{MIN} =	0.35 cm
D_{MAJ} =	0.54 cm

4. Appeared to burn well.
5. Vessel mounted horizontally.



PB-31
Test SB020499-1 Strand Burning Test
KN-Sorbitol propellant
65/35 O/F ratio
Batch no. KNSB-060299-180399-1

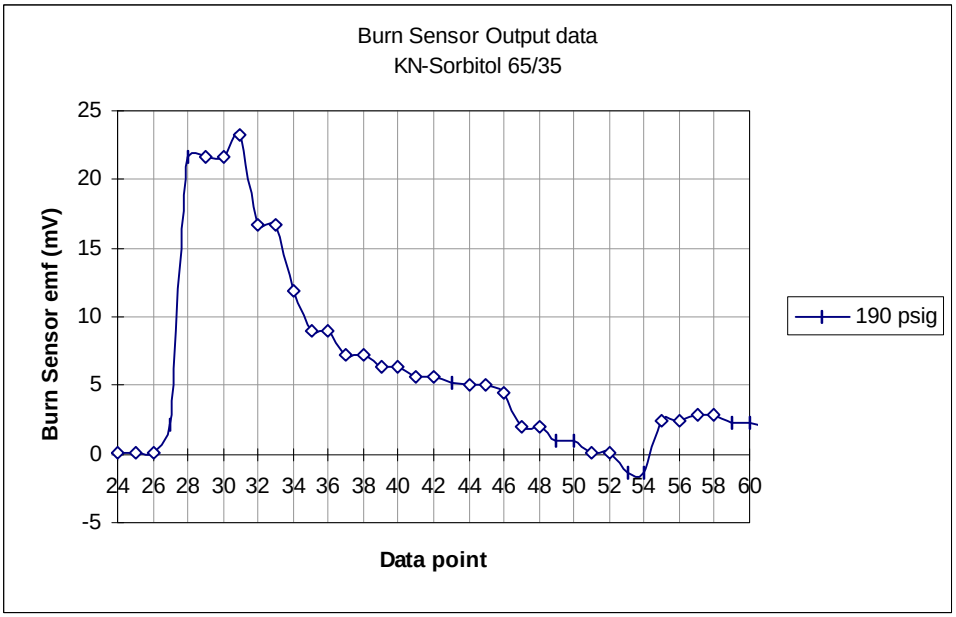
$P_{initial}$ =	178 psig
P_{max} =	202 psig
	24 psig
$P_{average}$ =	190 psig

Spike 1	27 (start pt.)
Spike 2	55 (start pt.)
28	Samples between spikes
3.333	Sample/sec. rate
Δt =	8.40 sec.
L_{gauge} =	6.56 cm
r =	**0.781 cm/sec.**
(r =	0.307 in/sec.')

Notes:
1.Strand had a minor blemish about 1/3 from bottom
2.Strand painted with hi-heat paint, but was scraped away at gauge marks
3. Strand nominal dimensions:

L_{TOT} =	7.4 cm
D_{MIN} =	0.35 cm
D_{MAJ} =	0.50 cm

4. Appeared to burn well.



PB-32
Test SB020499-2 Strand Burning Test
KN-Sorbitol propellant
65/35 O/F ratio
Batch no. KNSB-060299-180399-1

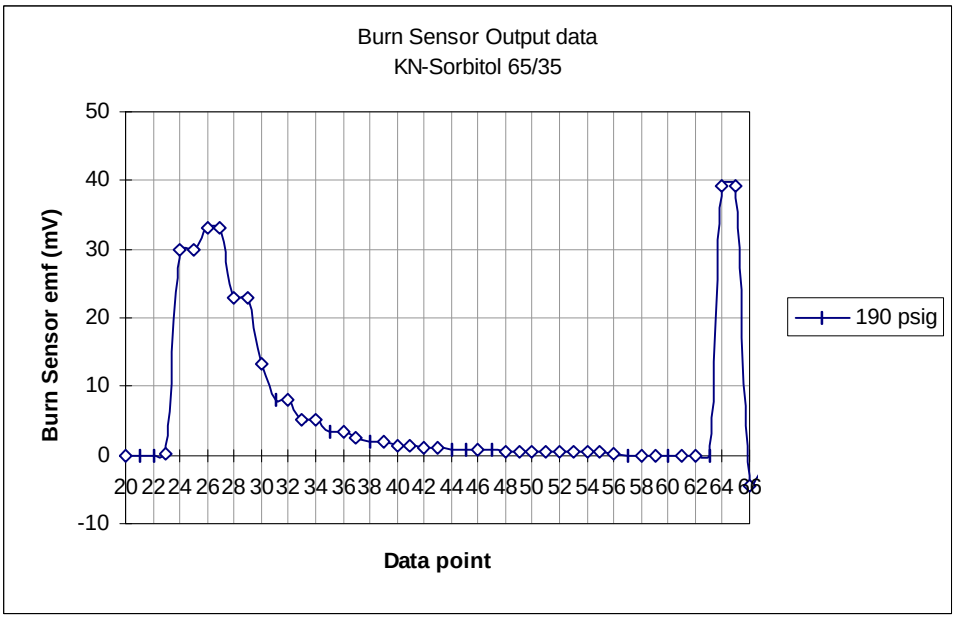
$P_{initial}$ =	290 psig
P_{max} =	312 psig
	22 psig
$P_{average}$ =	301 psig

Spike 1	24 (start pt.)
Spike 2	64 (start pt.)
40	Samples between spikes
3.333	Sample/sec. rate
Δt =	12.00 sec.
L_{gauge} =	9.18 cm
r =	**0.765 cm/sec.**
(r =	0.301 in/sec.')

Notes:
1.Strand had a number of minor blemishes
2.Strand painted with hi-heat paint, but was scraped away at gauge marks
3. Strand nominal dimensions:

L_{TOT} =	10.2 cm
D_{MIN} =	0.34 cm
D_{MAJ} =	0.41 cm

4. Appeared to burn well (slowly).



PB-33
Test SB030499-1 Strand Burning Test
KN-Sorbitol propellant
65/35 O/F ratio
Batch no. KNSB-060299-180399-1

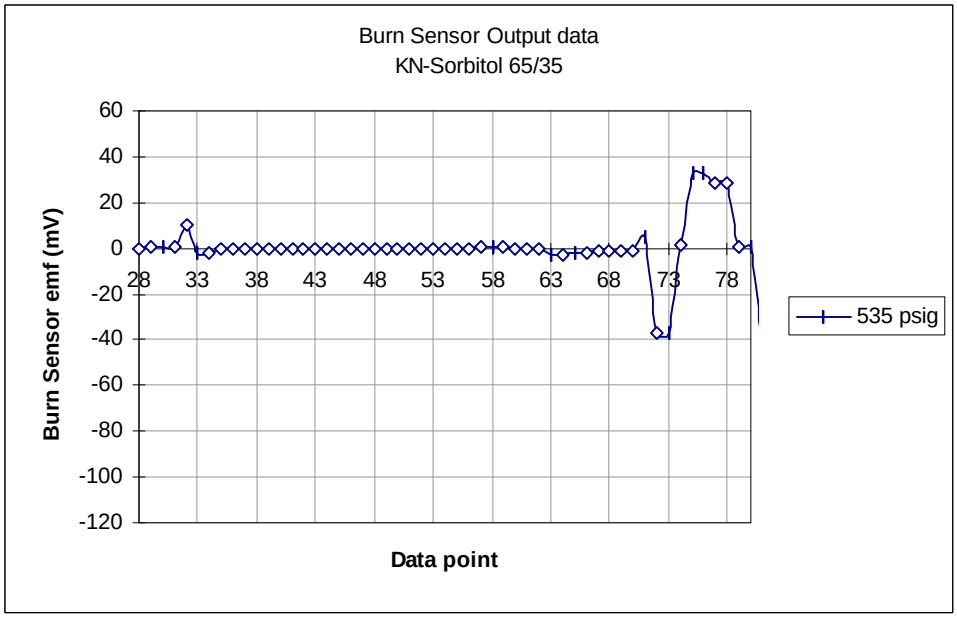
$P_{initial}$ =	519 psig
P_{max} =	550 psig
	31 psig
$P_{average}$ =	534.5 psig

Spike 1	32 (start pt.)
Spike 2	71 (start pt.)
39	Samples between spikes
3.333	Sample/sec. rate
Δt =	11.70 sec.
L_{gauge} =	8.95 cm
r =	**0.765 cm/sec.**
(r =	0.301 in/sec.')

Notes:
1.Strand had a number of minor blemishes
2.Strand painted with hi-heat paint, but was scraped away at gauge marks
3. Strand nominal dimensions:

L_{TOT} =	10 cm
D_{MIN} =	0.29 cm
D_{MAJ} =	0.55 cm

4. Appeared to burn well (quite slowly).



PB-34
Test SB030499-2 Strand Burning Test
KN-Sorbitol propellant
65/35 O/F ratio
Batch no. KNSB-060299-180399-1

$P_{initial}$ =	86 psig
P_{max} =	103 psig
	17 psig
$P_{average}$ =	94.5 psig

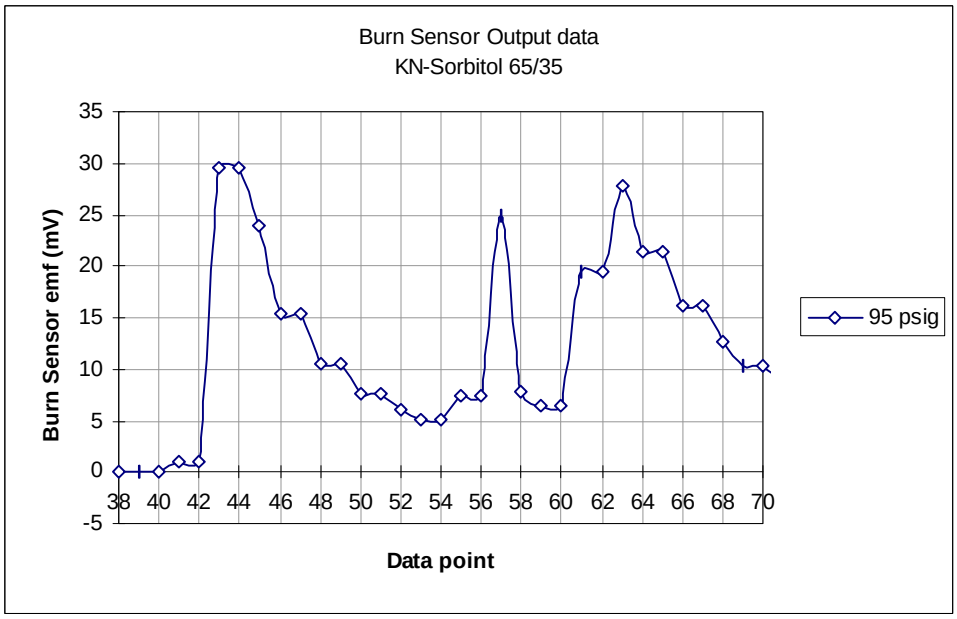
Spike 1	43 (start pt.)
Spike 2	57 (start pt.)
14	Samples between spikes
3.333	Sample/sec. rate
Δt =	4.20 sec.
L_{gauge} =	5.54 cm
r =	**~~1.319~~ cm/sec.**
(r =	0.519 in/sec.')

Invalid result. Uncontrolled burn?

Notes:
1.Strand had a number of minor blemishes and irregularities.
2.Strand painted with hi-heat paint, but was scraped away at gauge marks
3. Strand nominal dimensions:

L_{TOT} =	6.25 cm
D_{MIN} =	0.37 cm
D_{MAJ} =	0.44 cm

4. Appeared to burn well (quite slowly).



PB-35
Test SB030499-3 Strand Burning Test
KN-Sorbitol propellant
65/35 O/F ratio
Batch no. KNSB-060299-180399-1

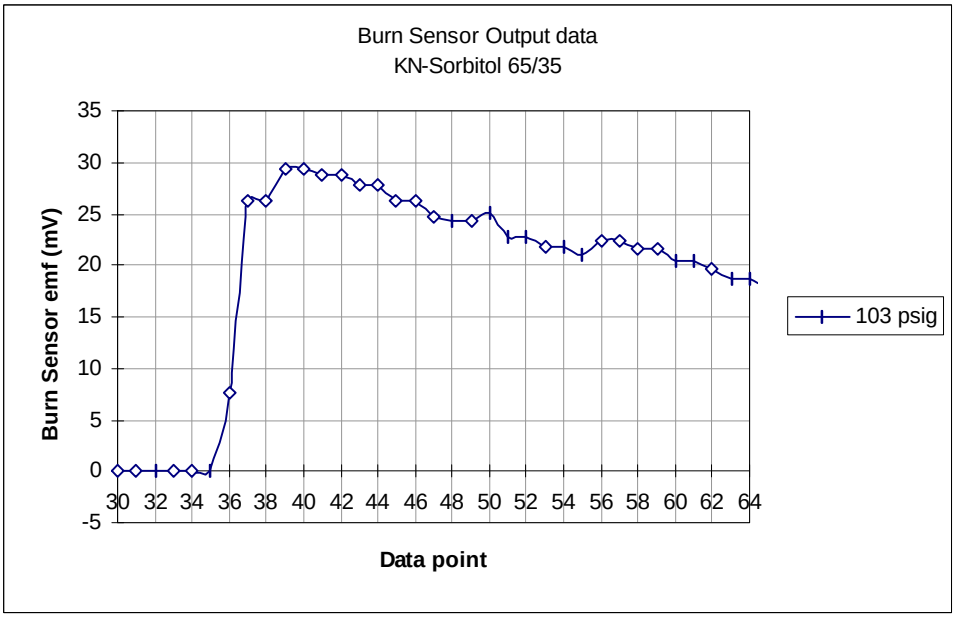
$P_{initial}$ =	90 psig
P_{max} =	115 psig
	25 psig
$P_{average}$ =	102.5 psig

Spike 1	36 (start pt.)
Spike 2	56 (start pt.)
20	Samples between spikes
3.333	Sample/sec. rate
Δt =	6.00 sec.
L_{gauge} =	5.62 cm
r =	**0.937 cm/sec.**
(r =	0.369 in/sec.')

Notes:
1.Strand had minor blemishes
2.Strand painted with hi-heat paint, but was scraped away at gauge marks
3. Strand nominal dimensions:

L_{TOT} =	6.3 cm
D_{MIN} =	0.35 cm
D_{MAJ} =	0.60 cm

4. Appeared to burn well



PB-36
Test SB040499-1 Strand Burning Test
KN-Sorbitol propellant
65/35 O/F ratio
Batch no. KNSB-060299-180399-1

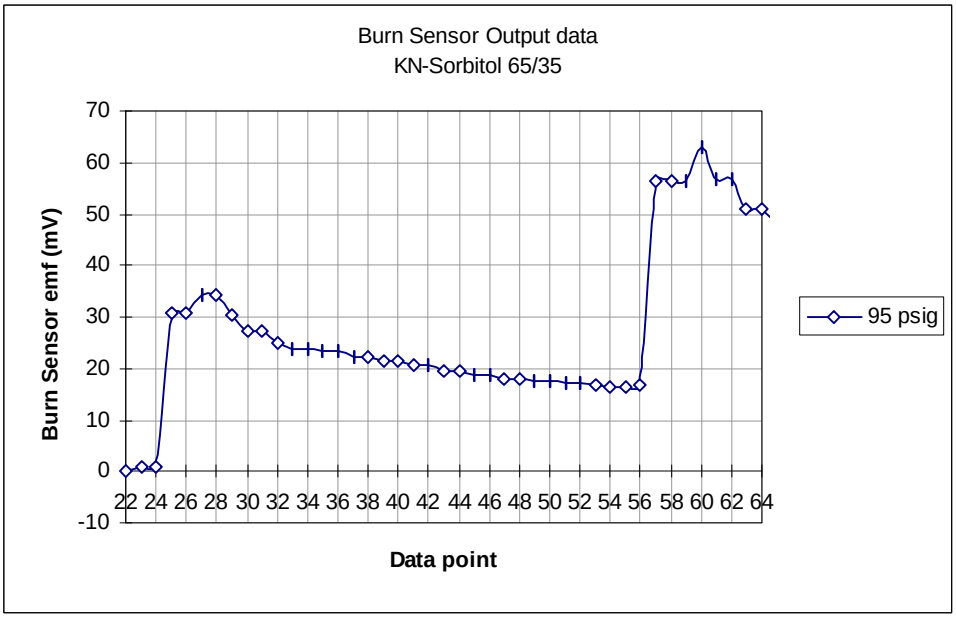
$P_{initial}$ =	82 psig
P_{max} =	108 psig
	26 psig
$P_{average}$ =	95 psig

Spike 1	25 (start pt.)
Spike 2	57 (start pt.)
32	Samples between spikes
3.333	Sample/sec. rate
Δt =	9.60 sec.
L_{gauge} =	8.62 cm
r =	**0.898 cm/sec.**
(r =	0.354 in/sec.')

Notes:
1.Strand had no apparent flaws
2.Strand painted with hi-heat paint, but was scraped away at gauge marks
3. Strand nominal dimensions:

L_{TOT} =	9.86 cm
D_{MIN} =	0.31 cm
D_{MAJ} =	0.52 cm

4. Appeared to burn well (quite slowly, but quicker at first).



PB-37
Test SB040499-2 Strand Burning Test
KN-Sorbitol propellant
65/35 O/F ratio
Batch no. KNSB-060299-180399-1

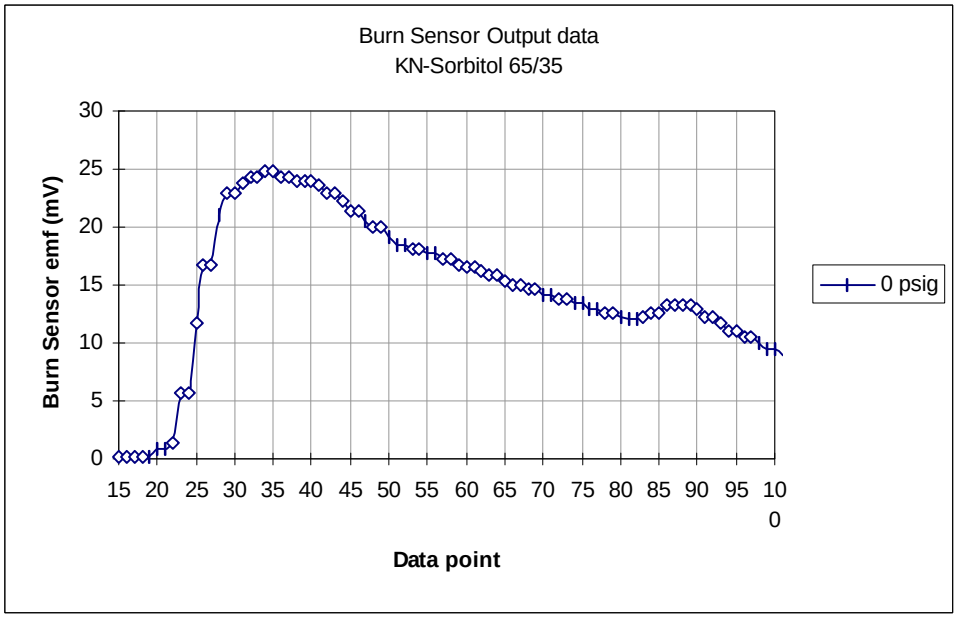
$P_{initial}$ =	0 psig
P_{max} =	0 psig
	0 psig
$P_{average}$ =	0 psig

Spike 1	20 (start pt.)
Spike 2	83 (start pt.)
63	Samples between spikes
3.333	Sample/sec. rate
Δt =	18.90 sec.
L_{gauge} =	4.83 cm
r =	**0.256 cm/sec.**
(r =	0.101 in/sec.')

Notes:
1.Strand had no apparent flaws
2.Strand painted with hi-heat paint, but was scraped away at gauge marks
3. Strand nominal dimensions:

L_{TOT} =	5.6 cm
D_{MIN} =	0.38 cm
D_{MAJ} =	0.59 cm

4. Appeared to burn well (quite slowly).
5. Test conducted at atmospheric pressure in firing vessel (purged).



Appendix E

Thermocouple Sampling Computer Program

```
'Program SAMP written by R.Nakka, Jan. 1999 (QuickBasic 4.5)
' The purpose of this program is to sample data from the Micronta 22-168A
' Digital Volt Meter that interfaces to a PC. The data sampled is for Strand
' Burn rate testing.
CLS
OPTION BASE 1
DIM valu$(1000)
COLOR 2
PRINT "Sampling Program for Propellant Burnrate Testing"
PRINT "**********************************************"
PRINT
INPUT "Enter a name for output file:  ", fout$
OPEN fout$ FOR OUTPUT AS #1
PRINT
COLOR 14
PRINT "Set Thermocouple selector switch to TEMPERATURE"
PRINT
PRINT "Then PURGE and PRESSURIZE system before continuing..."
COLOR 2
PRINT
PRINT "After pressurizing, hit any key to record vessel ambient TC reading..."
PRINT
dum$ = INPUT$(1)

OPEN "com1:1200,N,7,2,RS,CS,DS,CD" FOR RANDOM AS #2   'meter port
getsamp$ = "D"                                        'signal to get data
PRINT #2, "getsamp$"
Temp$ = INPUT$(14, #2)
PRINT "Vessel ambient TC reading =", Temp$
PRINT #1, Temp$
PRINT
COLOR 14
PRINT "Select Thermocouple selector switch to SENSOR"
COLOR 2
PRINT
INPUT "Enter number of data points to record (1000 max.)", Npts%
PRINT
PRINT "Hit any key to begin recording data..."

PRINT
dum$ = INPUT$(1)
PRINT "Recording..."
FOR count% = 1 TO Npts%                          'record sensor data
  PRINT #2, "getsamp$"
  valu$(count%) = INPUT$(14, #2)
NEXT count%
PRINT "Recording stopped. Data written to output file."
FOR count% = 1 TO Npts%                        'print data to output file
  PRINT #1, valu$(count%)
  PRINT , valu$(count%)
NEXT count%
CLOSE #1
CLOSE #2
END
```