

High-pressure combustion of composite propellants

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Abstract

A typical AP/HTPB non-aluminized propellant combustion was investigated at a wide range of pressures. By changing the throat diameter and keeping all other parameters constant we've obtained a large set of pressure charts and checked the results for the compatibility with the $r=aP^n$ model. Two combustion modes were obtained, defining a change in the n exponent referred in the literature as "n-jump" or "slope break".

In the next step the propellant grains were pre-heated and fired at elevated temperatures. The same phenomenon was found, but it occurred at lower pressures. Efforts to predict the pressure curves for the high exponent combustion were unsuccessful.

1. Introduction

Composite propellants are usually cast in motors designed to operate at a relatively low to medium pressures, namely up to 15MPa. In some special cases and elevated temperatures one can "push the limits", but this is not an advisable strategy. If a "Low Smoke" performance is required, a non-aluminized propellant is used. Combination of these two requirements (high combustion pressure and non aluminized composition) creates unique conditions that may lead to a catastrophic system failure. One of the dangers of use of non-aluminized propellants is combustion instability. To overcome this problem a low amount of a solid additive is added to the propellant to create an oscillation damping effect, supplied by the alumina particles in an aluminized propellant. The other, less well-known and researched problem, is a sudden jump in the pressure exponent ($r = aP^n$) that may lead to a violent increase in the burning rate. This "n-jump" (also referred to as "slope break") is the research subject presented in this paper.

2. Literature survey

The scientific development of composite propellants started in earnest about 60 years ago. New compositions, more energetic than the "old" homogeneous propellants, were developed and tested. An obvious way to increase the propellant burn rate was to burn it at progressively increasing pressures. Solid propellant burning rate is proportional to the chamber pressure, but it was soon found that this relation works well up to a pressure limit, above which "the propellant charge seems to burn in a violent and unpredictable manner" [1]. This 1963 reference cites pressure limits of 12,000 Psi for a double-base and 3,000 Psi (~21 MPa) for composite propellants. As a result, a proper warning for the SRM designers was included in design manuals. In a 1966 research [2], homogeneous and composite propellants burn rates were measured at pressures up to 140 MPa. This research cites a 1963 article in which a pure Ammonium Perchlorate deflagration process was examined. It was found that pure AP exhibited an abrupt transition of the exponent n at ~35 MPa. In a 1975 article [3] authors define a "break point" criteria by comparing the solid phase thermal depth with the size of an individual oxidizer particle: when their dimensions are comparable, a break point in combustion is observed and the burn model changes. A 1991 research [4] describes a combustion model development for an AP-inert binder propellant, which includes burn rate dependence on pressure with strong influence of the AP particle size. However, the model cannot follow a sharp exponent break that occurs "above 300 to 400 atm". Another 1991 study [5] found no evidence that the slope break phenomena is related to combustion instability. A reduced smoke HTPB propellant exhibited a slope break above 28 MPa, without inducing combustion instability. In a 1999 study [6] propellant burn rates were measured at pressures up to 140 MPa. All of the propellants experienced a change in burning rate pressure exponent at pressures less than or equal to the AP monopropellant brake point pressure (~35 MPa). A recently published work [7] describes testing AP based propellants in a closed bomb at pressures between 20 to 300 MPa. The propellants "burn in a well behaved, laminar fashion", but with exponent $n= 1.05$! A follow-up paper by authors of ref.4 that deals with AP based propellants combustion includes more data on the n jump subject [8].

It should be noted that in most, if not all studies, the propellant combustion was performed in Strand burners or closed bombs, while in our study we have used a full size rocket motor.

3. Ballistic Evaluation Motor

The Ballistic Evaluation Motor (BEM) is a standard tool used by IMI/RSD for evaluation of solid propellant ballistic properties of. A reusable heavy wall casing contains a 150 mm long cylindrical case bonded propellant grain. The grain outer diameter is 90 mm and the inner bore diameter is 40 mm. Propellant grain weight is 1.3 to 1.5 kg,

depending on its density. The aft dome includes a graphite/metal nozzle insert. The chamber pressure gage is located in the front dome. A 7-gram bag of pyrotechnical composition is used to ignite the propellant.

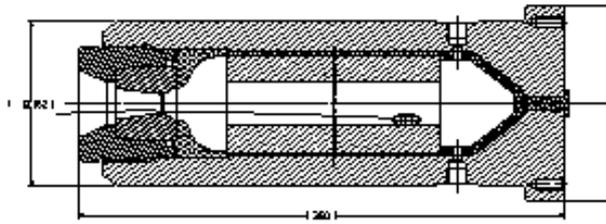


Figure 1: BEM cutout



Figure 2: BEM on a test stand

Thousands of BEMs have been fired with highly reproducible results, supplying the necessary data for the evaluation of burning rate coefficients. The grain design (internal combustion with both ends uninhibited) creates a nearly constant burning area and in most cases a nearly neutral burning is achieved.

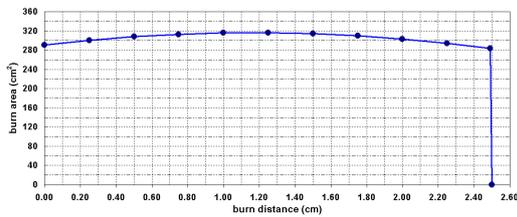


Figure 3: BEM Burn area vs. burn distance

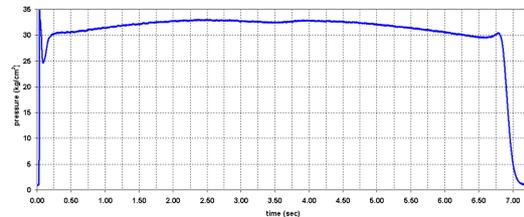


Figure 4: Typical BEM pressure chart

4. Preliminary tests

Several BEM grains were casted and test-fired using progressively smaller throat diameters. The propellant composition was: 75% Ammonium Perchlorate (1/3 coarse 2/3 fine), 2% Ferric Oxide burning rate catalyst, 0.5% Silicon Carbide and 22.5% of an HTPB binder and other processing additives. The pressures vs. time curves from the preliminary set of firings are presented in figure 5.

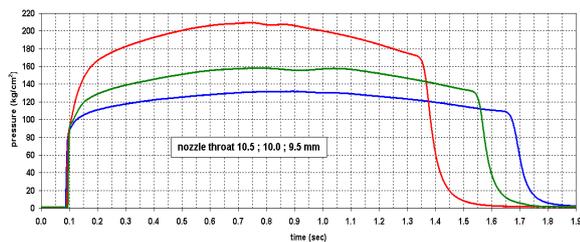


Figure 5: Pressure vs. time chart for preliminary BEM firings (9.5, 10.0 and 10.5 mm throats)

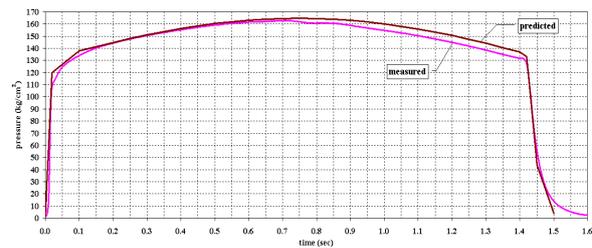


Figure 6: BEM predicted vs. measured pressure chart

The motors performed well at relatively high pressures and the pressure curves gave no indication to any combustion peculiarity. The “wave” at the mid-web burn time is a well-known feature referred to as a “mid-web anomaly” that results from the motor casting technique (plunging the casting pin into the liquid propellant). Curiously, a “Friedman curl”, a small pressure increase just before web burnout (see figure 4) was missing. A simple one-dimensional prediction gives a reasonable fit, as presented in figure 6 for the 10 mm throat test.

Next set of tests included firings of the same propellant with smaller nozzle diameters (9.5 to 8.5 mm).

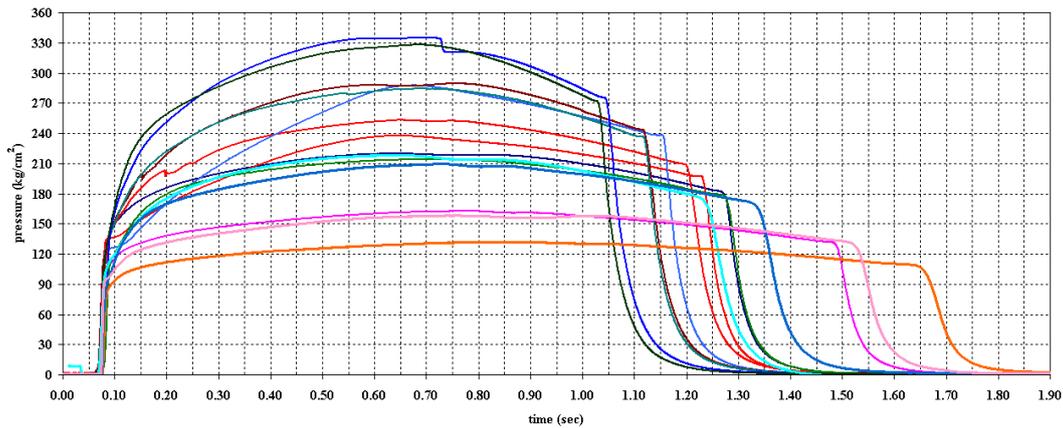


Figure 7: Pressure vs. time charts for the second set of BEM firings

Some minor irregularities appeared in two or three firings, but none of them was found to be related to the high combustion pressure. Nozzle inserts used in this test set were made from tungsten and no throat erosion was observed.

A closer look at the curves revealed that at least two of them (and not those with the highest maximum pressure) have a distinctly higher slope immediately after the grain ignition.

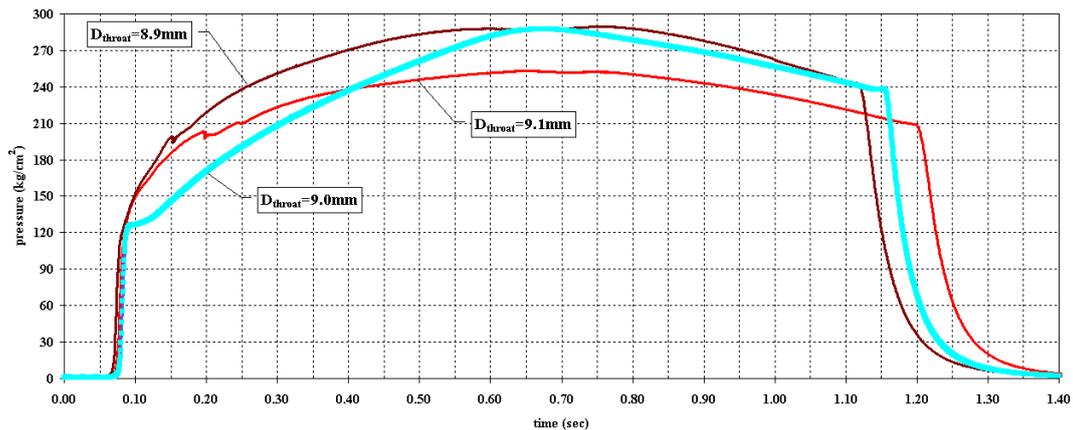


Figure 8: Pressure vs. time chart for three throat diameters

One would expect the 9.0 mm throat pressure curve to be located in between the two others. The ignition pressure rise is similar for all three firings, but instead of a gradual rise that follows the increase of the propellant burning area, a steep slope develops. This slope is inconsistent with other pressure curves and could not be simulated using constant values for burning rate equation parameters.

A basic internal ballistics relationship between chamber combustion pressure and nozzle throat diameter is presented by equation (1).

$$\frac{P_1}{P_2} = \left[\frac{D_2}{D_1} \right]^{2/1-n} \quad (1)$$

The calculated value of the n exponent is >0.8 using the average pressure of the two “normal” firings. This is a very high value for a composite propellant (and even for a homogeneous one), which results in high combustion sensitivity to small changes in grain and throat dimensions. Such a high-pressure exponent renders the propellant useless for most if not all practical purposes. Use of the same relationship for the first set of tests resulted in n values of ~ 0.5 . This inconsistency prompted a further research of the propellant behavior at a wide pressure range.

5. High-pressure combustion tests

In the next set of tests (figure 9), ever smaller nozzles were used, and the results were surprising, to say the least.

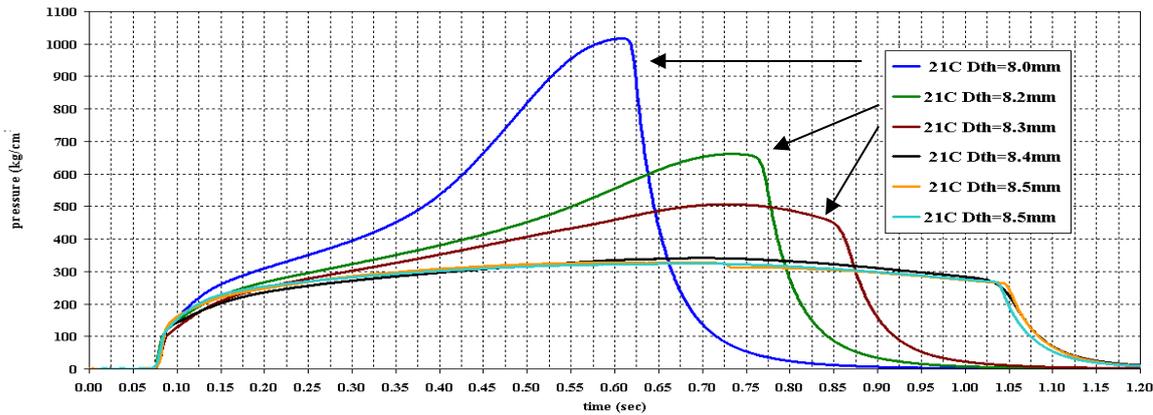


Figure 9:
Pressure vs.
time chart for
BEM firings
with small
diameter
nozzles

No doubt a
significant
change in the
propellant
behavior
occurred. A
small decrease

of ~2.4% in throat area (diameter change from 8.4 to 8.3 mm) dramatically changed the propellant combustion behavior. The ignition pressure rise is similar in all firings, but while the use of 8.5 and 8.4 mm diameter nozzles resulted in a high but fairly neutral pressure curves, motors with smaller throat diameters “take off” and their pressure curves rise with an exponentially increasing slope. Clearly, the concept of “average pressure” for these firings is not easily defined, and the propellant combustion cannot be described as “at constant pressure”. Ignoring the pressure curves progressivity, the average chamber pressure of all firings was calculated by dividing the pressure integral by the motor action time. A log-log chart of Burn Rate vs. Chamber Pressure was drawn to check the linearity of the propellant burning model as described by the Vieille law, $r = aP^n$.

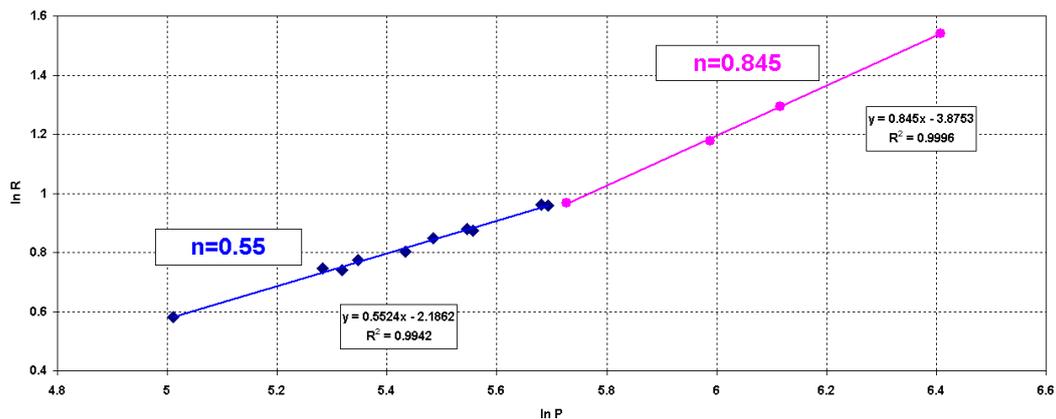


Figure 10: Log-Log linear regression of BEM burn rate vs. pressure

Two well-defined linear dependencies were found, both with a high linearity coefficient (>0.99). The exponent n values (the line slopes) were in the range of the examples described above. The “ n jump” occurred at a pressure of ~300 kg/cm².

Repeated series of tests from two different propellant batches resulted in good repeatability for pressures < 300 kg/cm². In all three set of firings the line slope remained fairly constant (0.53, 0.54, and 0.55).

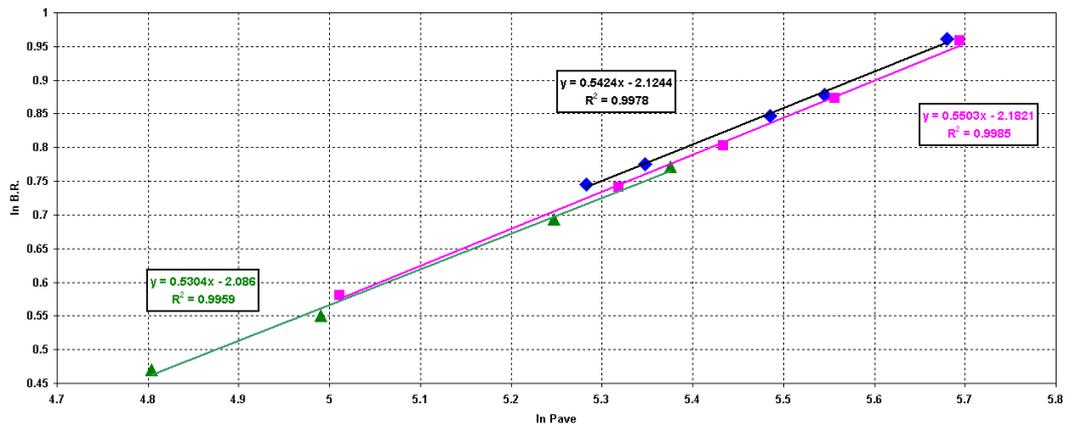


Figure 11: log-log linear regression of three BEM test sets

All attempts to simulate the propellant combustion with diameter nozzle smaller than 8.4 mm failed. The ballistic simulation program used a “low burn rate” set of coefficients for pressures up to 300 kg/cm² and a “high burn rate” set for higher pressures.

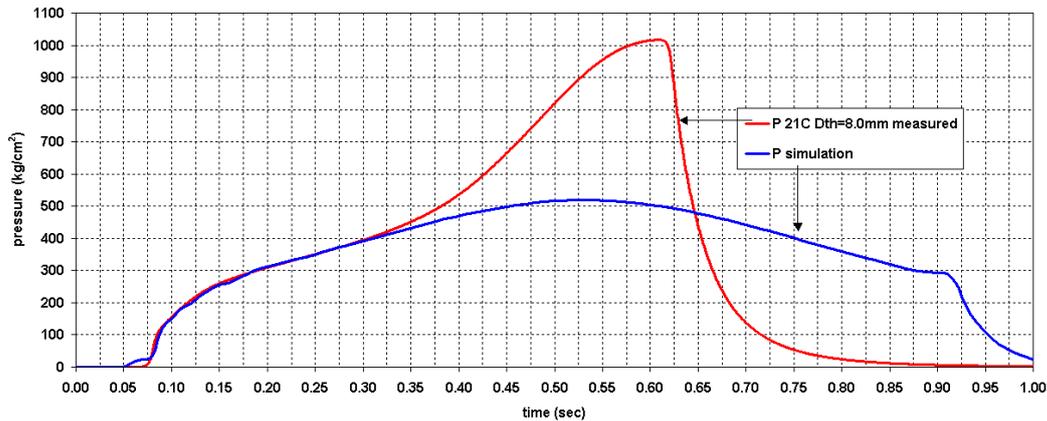


Figure 12: measured vs. predicted BEM pressure chart with 8.0 mm nozzle

As explained in paragraph 3 above, the BEM burn area gradually decreases after a mid-web distance. The high n exponent emphasizes the effect of burn area decrease and the program cannot account for the steep pressure rise. At ~400 kg/cm² the measured curve raises steeply, a probable evidence of additional burn rate increase. The only way to account for the measured pressure increase is to introduce an n exponent as an increasing function of pressure and to allow it to reach values >1. This mathematical “trick” is still waiting for a physical explanation.

6. Propellant temperature influence

All the above tests were performed after conditioning the propellant grains at 21°C for 24 hours. Propellant temperature change influences the propellant burn rate. The sensitivity of the burn rate to temperature change is evaluated by performing a series of firings of propellant grains at different temperatures with a constant nozzle throat. The firings were performed using an 8.8 mm throat. The propellant grains were conditioned at 0, 10, 21, 35 and 50 deg. C.

Most of the pressure charts followed a more or less neutral burning pattern. Two of the curves (35° and 50°C) progressed with a higher slope than others, but it was decided to include these results in the calculations.

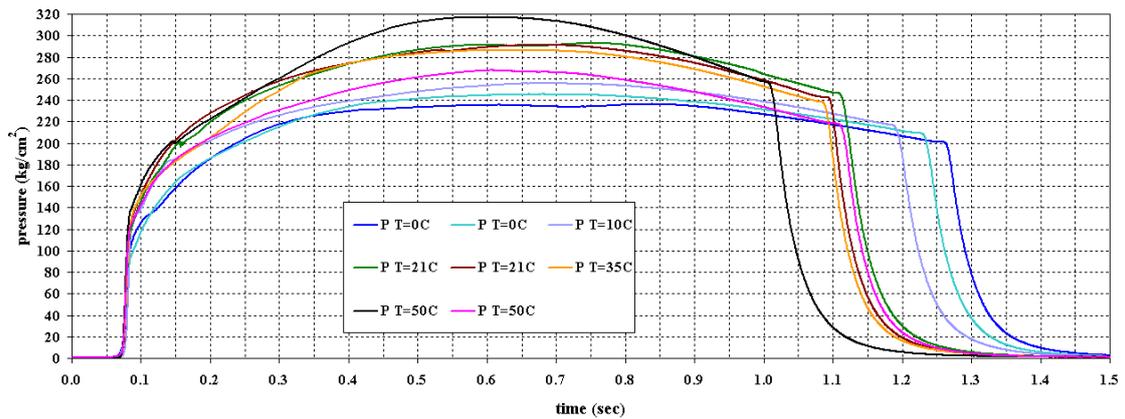


Figure 13: 8.8 mm throat BEM firings at different propellant temperatures

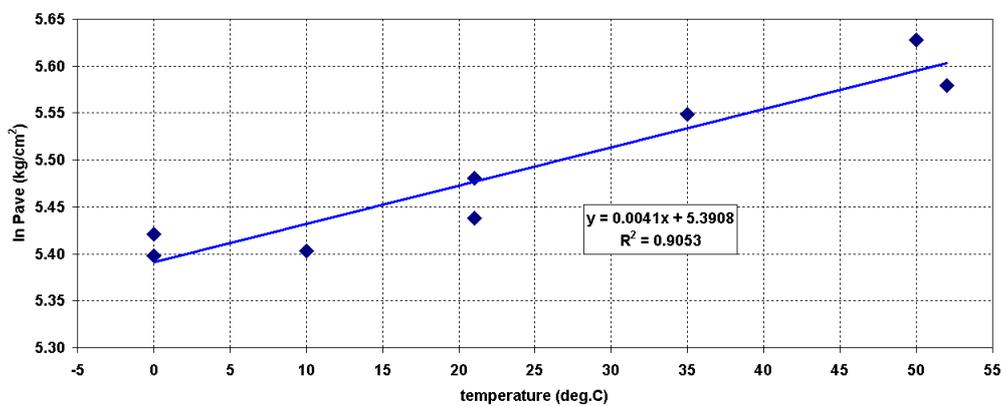


Figure 14: π_k evaluation chart (based on figure 13 data reduction)

The resulting temperature sensitivity coefficient π_k is relatively high – 0.4 %/degree vs. the more familiar value of 0.20 to 0.25 %/degree.

The next set of firings tested the impact of initial propellant temperature on the n -jump phenomena. Propellant grains acclimatized at 50°C were fired using nozzles with throat diameters of 8.5 and 8.4 mm. In the 21°C tests, nozzles with throat diameters 8.3 mm and lower created the violent progressive burning attributed to the n -jump effect.

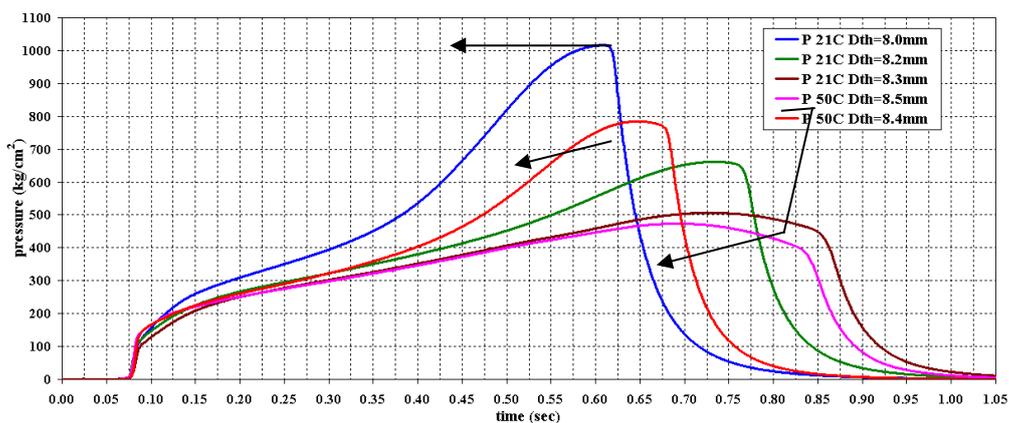


Figure 15: 21°C and 50°C BEM firings with small nozzle throats

Higher propellant temperature created the n -jump in firings with “large” nozzle throats – as seen in figure 16. The n -jump transition point is “pushed back” to larger throat diameters. Due to the unpredictable increase in pressure, no attempt was made to fire a 50°C grain with throat diameter less than 8.4 mm.

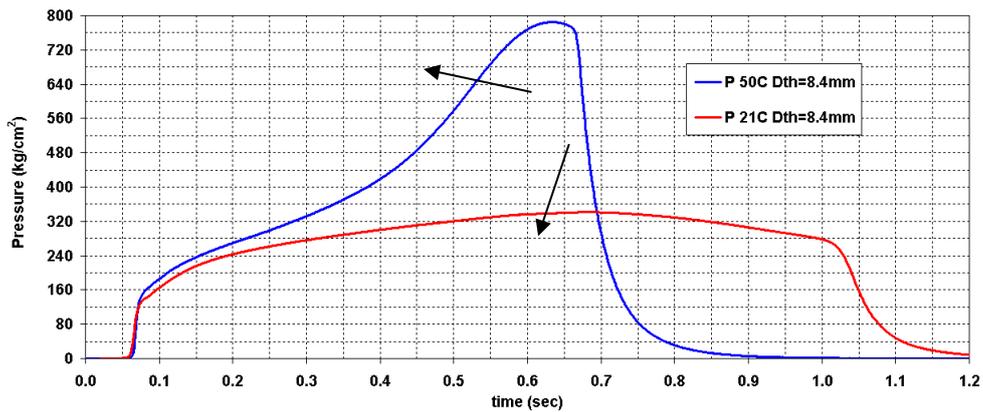


Figure 16: Propellant temperature influence on pressure curves

As in the case of the 21⁰C tests, some unpredictable results were obtained. Equal propellant grains fired with equal nozzles burned with different burn rates.

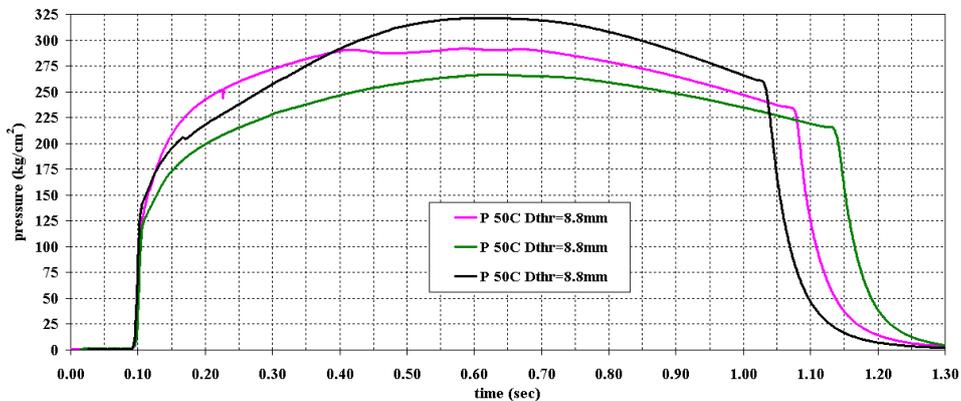


Figure 17: Pressure vs. time chart for three BEM firings at 50⁰C and 8.8 mm throat

It is interesting to try and explain the pressure curves development after the ignition pressure rise. One of the curves starts with a relatively low slope and burns at the lowest average pressure for the longest action time. The two other curves develop a similar (and higher) pressure gradient up to 0.01 sec, but part after 0.03 seconds, one of them “curving down” on a path parallel to the lower pressure curve while the other, moving at a lower slope for a longer time, overtakes the other curve and reaches the highest pressure of the three. Propellant temperature variations (assuming that the 50⁰C has a dispersion of several degrees) cannot account for the curves slope differences. Stating the question in human terms, how does the propellant “know” at a pressure of ~200 kg/cm² to choose a different pressure increase slope? Is this phenomena related to the *n*-jump effect that occurs “in the future” at ~300 kg/cm²? A similar phenomenon was described in reference [7]: “...burns that begin at lower pressures follow one burn law and burns that begin at higher pressure follow a different burn law. Curiously, the lower pressure burn will follow this burn law even if it moves into the high pressure regime.”

7. Conclusion

Ballistic Evaluation Motors with non-aluminized composite propellant grains were fired with progressively smaller throat diameters. Data reduction of the firings has shown that the propellant combustion mode changes at ~300 kg/cm². Calculation of the burning rate model parameters resulted in two exponent *n* values – 0.55 for pressures <300 kg/cm² and 0.845 for pressures >300 kg/cm². This combustion mode change is known as the *n*-jump or slope break effect. Increase in propellant temperature resulted in sharp pressure rise (attributed to the *n*-jump effect) with nozzle diameters that behaved “normally” at ambient temperature. An attempt to simulate the *n*-jump using different burning rate model parameters (*a*, *n*) for low and high pressures was unsuccessful. To account for the violent pressure increase, the *n* exponent had to be increased progressively, a mathematical solution, so far without a sound physical basis.

Several explanations were proposed in the literature by combustion modeling experts, describing a change in combustion pattern as the chemical reaction zone is pushed closer to the propellant surface by the increasing pressure. Others prefer blaming micro cracks that develop at such pressures and increase the burning area.

More questions than answers remained. As a practical conclusion it is advised for those who intend to use AP based propellants to check the n -jump break point (in our case $\sim 300 \text{ kg/cm}^2$) at elevated temperatures and to keep the motor designed MEOP within a safe distance from this pressure.

8. References

- 1) AMPC pamphlet, 1963. Elements of Armament Engineering, Part Two: Ballistics. AMPC 706-107 chapter 2-8.4, page 2-15.
- 2) Cole, R.B. Burning rates of solid composite propellants at pressures up to 20,000 psig. Rhom and Haas report S-80, September 15, 1996 AD375686
- 3) Kumar, R.N., Strand, L.D., Combustion problems of nitramine propellants. AIAA Paper 75-239, 1975
- 4) Lengelle, G., Duterque, J.R., Godon, J.C. and Trubert, J.F. 1991. Solid Propellant Steady Combustion – Physical Aspects. In: Combustion of Solid Propellants. AGARD Report LS-180. Chapter 3 pp. 3-20 – 3- 22, 1991
- 5) Raun, R.L., Butcher, A.G., Beckstead, M.W. Slope break and high pressure combustion instability, 28th JANNAF Combustion Meeting, 1991
- 6) Atwood, A.I., Curran, P.O., Price, C.F., Boggs, T.L., Booth, D. High pressure burning rate studies of AP based propellants. RTO AVT Symposium, RTO MP-23, 1999
- 7) Glascoe, E.A., Tan, N. High Pressure Burn Rate Measurements on an Ammonium Perchlorate Propellant, Lawrence Livermore National Laboratory Energetic Materials Center, LLNL-TR-428515, April 23, 2010
- 8) Lengell, G., Duterque, J., Trubert, J.F. Combustion of Solid Propellants. NATO RTO-EN-023, 2002