Defence Science Journal, Vol. 56, No. 3, July 2006, pp. 353-367

Burn-rate Measurement on Small-scale Rocket Motors

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ABSTRACT

Small-scale rocket motors are widely used by propulsion industries to carry out burn rate measurement for a variety of needs. Several automated data-reduction procedures have been implemented to derive burn rate from pressure-time profiles resulting from experimentation. Even if these are easy and fast to use, these procedures are not completely reliable in that these measure only the average behaviour of a motor. A new model has recently been proposed to overcome this problem. However, it was soon noticed that the results depend on the propellant grain production and forming processes even if the motor hardware is the same. A series of propellant grains has been produced to be sampled to map the local ballistic behaviour and changes introduced by the manufacturing process. In this study, sampling and testing procedures are reported and the results of an almost complete grain mapping are discussed.

Keywords: Burn-rate measurement, rocket motors, small-scale rocket motors, data reduction, ballistic behaviour, ballistics

NOMENCLATURE

AP	Ammonium perchlorate
BC	Bayern chemie
CV	Coefficient of variation
MB	Mass balance
PW	Pratt and Whitney
S 1	Segment 1
SRM	Solid rocket motor
SSTM	Small-scale test motor
TK	Thiokol
TOT	Thickness over time
A	Surface Area
a	Coefficient of Vieille law
c^*	Characteristic velocity
HF	Hump factor
$K(w)$	Burn-rate model function
n	Pressure exponent of Vieille law
p	Pressure
t	Time
w	Propellant web thickness
ρ	Density
η_t	Correction coefficient of throat area

Revised 29 December 2005

c	Combustion
E	End of propellant burning
end	Final value
ext	External
G	End of motor operation
Int	Internal
p	Propellant
t	Throat

1. INTRODUCTION

Solid rocket motors (SRMs) are widely used in space propulsion. Implementation of theoretical and numerical modelling in solid rocket propulsion has made impressive progress during the last decade, mainly due to more powerful computing capabilities. Yet, the lack of complete understanding of several aspects and phenomena still require the support of wide experimentation. Data so collected are important to validate new theories, refine existing modelling, and characterise propellants.

Burn rate is the main parameter in the SRM design, development, and setup. It is important to know its precise dependence on pressure in particular, because this affects the prediction accuracy of flight performance. New propellant formulations are mainly evaluated upon their ballistic properties. Quality control on motor production is based on burn-rate measurement of cast propellant samples.

The wide variety of experimental techniques currently used in international facilities have been recently summarised and discussed in the NATO RTO-TR-43[1-2]. In an industrial environment, small-scale test motors (SSTM) are used to test propellant, both for development and quality control purposes. Being more expensive than strand burner tests, these tests are performed only after a final propellant formulation has been established and these give a better correlation to full-scale rocket motor performance. The optimisation of time and cost is important for an industry so that the analysis of SSTM fire results can be automated, simple and fast to perform. Different kinds of data reduction procedures are adopted by the industry.

Both numerical analyses and experimental procedures can introduce errors. Sources of uncertainty are the SSTM manufacturing (including hardware and propellant charge), testing (including equipment and the actual test conduction), and data-reduction procedures. It was shown in previous works[3-4] that data-reduction procedures often introduce a lower scatter level in the final results than the experimental setup. Besides, a more refined but also complex data-reduction procedure[5-6] revealed that propellant grains may not follow a homogeneous burning law. In fact, the production of a solid rocket motor is a complex sequence of actions (mixing of ingredients, casting process, curing, storage, assembling, etc). A modification of any single aspect in manufacturing process can produce local changes of performance (ballistic, mechanical, ageing, etc).

In this work, SSTM grains have been analysed to detect possible variations of ballistic properties. All data reported here refer to the Baria SSTM (Fig. 1) used in Ariane-5 solid booster production.

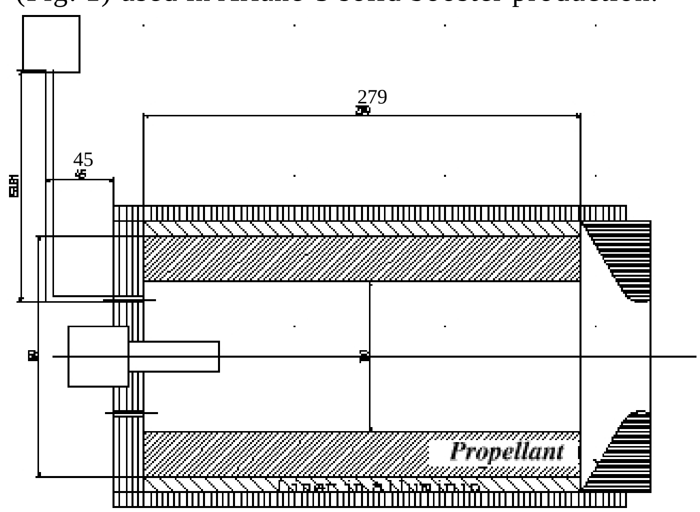

Figure 1. Baria small-scale test motor

2. BURN-RATE MEASUREMENT

The steady burn rate pressure dependence of ammonium perchlorate (AP)-based composite propellants is conveniently fitted by the Vieille - St. Robert law (Eqn. 1), if working pressure of rocket motor is below 2000 psi (138 bar) and for a given initial temperature

$$r_b = ap^n \tag{1}$$

Experiments were carried out to evaluate the pair of ballistic parameters *a* and *n*. Fire tests were performed using multiple SSTM's with different throat diameters. Each test produces a recorded pressure-time profile, yielding effective burn rate and pressure by an appropriate data-reduction procedure. The propellant ballistic properties are defined by fitting at least three different pressure levels and the corresponding burn-rate values.

Two main approaches are in use to obtain the ballistic properties from the experimental motor pressure profiles: the mass balance (MB) approach and the thickness over time (TOT) approach. Both approaches include a variety of specific procedures differing in details of the implementation.

The TOT approach is very simple and it consists of fixing a conventional burning beginning and end in the neighborhood of the pressure transients. The burn rate is obtained dividing the grain web thickness by the burning time

$$r_{TOT} = \frac{web\,thickness}{burning\,time} = \frac{w_E - w_B}{t_E - t_B} = \frac{w_b}{t_b} \qquad (2)$$

Several TOT procedures from international industries have been analysed in the past (BC from Bayern Chemie[3-8], BPD1 and BPD2 from FiatAvio, SNPE from SNPE/Onera, TK1 from Thiokol, HG by Hessler and Glick). Each one follows its own criterion to perform the choice of the instants t_E and t_B. The MB approach is based on an approximation of the mass balance equation. Under the hypotheses of zero-dimensional, quasi-steady behaviour and neglecting the gas storage inside the combustion chamber, one can write

$$r_b = \frac{p_c \eta_t A_t}{c^* \rho_p A_b} \qquad (3)$$

The Eqn (3) can be recast as

$$r_{MB} = \frac{w_A - w_G}{t_E - t_B} \frac{\int_B^E p_c\, dt}{\int_A^G p_c\, dt} \qquad (4)$$

Some MB procedures from international industries and from the university have been analysed in the past (PM and PMn from Politecnico di Milano, PW from Pratt Whitney, TK-2 from Thiokol)[3-8]. Each one follows its own pattern of selection to fix reference instants.

Reference pressure is obtained from the recorded pressure-time history with an averaging operation. It is possible to consider a time-averaged pressure [Eqn (5)] or a rate-averaged pressure [Eqn (6)]. The second one appears more correct but needs an iterative loop to assess, as it can be seen in Eqn (6).

$$p_{nb} = \left(\frac{\int_B^E p^n\, dt}{t_E - t_B} \right)^{\frac{1}{n}} \qquad (5)$$

$$p_{nb} = \left(\frac{\int_B^E p^n\, dt}{t_E - t_B} \right)^{\frac{1}{n}} \qquad (6)$$

Application of most of the above data-reduction procedures is easy and fast to perform. The interpretation of the results is not complex because these procedures describe the propellant burning pressure dependence with only the two classical parameters (*a* and *n*). On the other hand, these procedures are subjected to several errors due to SSTM manufacturing (including motor hardware and propellant charge), experimental testing (including equipment and the actual test conduction), and limitations of the 'naïve' data-reduction procedures used to analyse the collected pressure-time profiles.

3. ANALYSIS OF PRESSURE-TIME PROFILES

Immediate application and easiness to interpret results are some aspects that industries are interested in. These are obtained with simplified models. These procedures need very few calculations and can be performed in few minutes, but these do tacitly imply some of the following restrictive hypotheses:

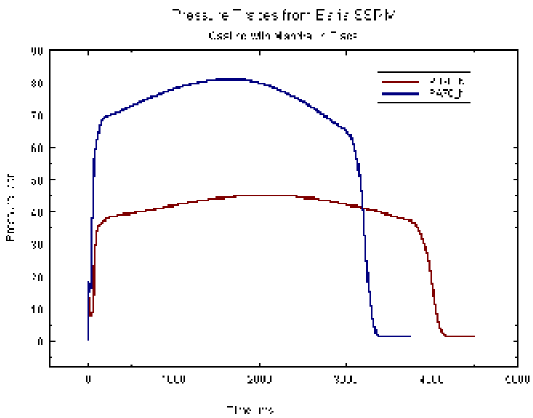

Figure 2. Baria pressure-time profiles

- The combustion behaviour is considered to be uniform with time, leading for each test to a pair of values for burn-rate and pressure. It is actually observed (Fig. 2) that pressure typically changes during the fire test. Subsequently, according to Eqn. 1, burn rate also changes.

- The combustion behaviour is also considered to be locally uniform in space, *ie*, independent on the web thickness in particular. This assumption amounts to neglect the small but perceivable differences of ballistic and physical properties that may locally arise in the propellant grain due to composition gradients, casting process, curing time, and other local effects.

Thus, standard data-reduction procedures describe only the average SSTM behaviour between the two conventionally chosen instants. Besides, since the burning time beginning and final instants are mainly searched in the neighborhood of the motor transient operations, the deduced burning time is sensibly affected by the shape of the pressure curve. For example, some procedures give better results with a sharp-end operation transient; therefore, the quality of the analysis is further deteriorated in case of presence of some slivers or of a motor configuration causing a smooth end of burning operations (absence of Friedman's Curl).

An example of variety of the results obtained by applying different procedures to the pressure profiles of a single test series (consisting of 9 groups of fire tests at 3 different pressure level, for a total of 27 fire tests) can be appreciated in Table 1. Even referenced to the same motor test, burn-rate measurement is different because each procedure performs its own time choices. In this case, the difference between the fastest and the lowest measurement is about 1.5 per cent at the reference pressure of 45 bar. Since the burn rate of the full-scale motor is unknown, the quality of the data-reduction procedure is often measured in terms of lower standard deviation.

4. EXPERIMENTAL VARIABILITY

In the previous studies[3-8], the experimental variability of several test series has been evaluated. Since each Ariane-5 solid booster segment requires 9 or 10 batches of nominally identical propellant, a total number of 27 or 30 SSTM were used for each segment (3 different pressure levels are tested for each propellant batch).

Table 1. Baria series S1-027 (9 groups of fire tests)

	$n \pm \sigma_n$	CVn (%)	$a \pm \sigma_a$	Cva (%)	$r_b \pm \sigma_{rb}$	CVr_b (%)
BC	0.393 ± ?0.005	1.168	1.661 ± ?0.012	0.713	7.415 ±? 0.033	0.444
BPD-1	0.394 ± ?0.005	1.214	1.657 ± ?0.012	0.749	7.425 ± ?0.034	0.452
BPD-2	0.392 ±? 0.005	1.179	1.664 ± ?0.012	0.727	7.400 ±? 0.033	0.445
SNPE	0.394 ± ?0.005	1.159	1.649 ± ?0.013	0.768	7.389 ±? 0.034	0.463
PM	0.387 ± ?0.004	1.116	1.690 ±? 0.012	0.713	7.374 ±? 0.034	0.456
PM-n	0.388 ±? 0.004	1.136	1.685 ± ?0.012	0.706	7.380 ± ?0.034	0.455
PW(ir = 0.995)	0.388 ±? 0.004	1.068	1.689 ± 0.011	0.617	7.397 ±? 0.032	0.432

Measured burn rate and ballistic properties change among test series with nominally identical propellants. Each burn rate has been self-normalised to circumvent the measurement dependence from the data-reduction procedure. It is shown that the scatter level introduced by the experimental procedure is larger than the one introduced by data-reduction algorithm. Reduction methods seem to be essentially equivalent once these are normalised.

In some cases, (eg studies reported by DeLuca,[7] *et al.*,)MB and TOT results can be distinguished due to the different approaches. Normalised results of Baria 027 series, obtained by implementing different reduction procedures, are seen in Fig. 3 to differ by less than 0.25 per cent within the same batch. If the whole series is considered, the burn rate can differ up to 2 per cent. A similar trend is observed in all other test series, while the scatter level can be higher.

At least for the reduction procedures tested in this work and the available experimental pressure-time profiles, it does not seem advisable to choose the best procedure based on the lowest standard deviation criterion because experimentation rather than data reduction is the main source of uncertainty.

5. SIMPLE MODEL FOR SSTM BALLISTIC ANALYSIS

The Baria SSTM configuration is designed to obtain a pressure essentially constant during the fire test to measure a steady burn rate. Under these circumstances, the empirical law of Eqn. 1 fits adequately the propellant ballistic properties and data-reduction methods operate under conditions close to their basic hypotheses.

But the real behaviour of Baria SSTM is far from producing a constant pressure (Fig. 2). Thus, data-reduction procedures give results which are somehow an average of the overall combustion process.

A simple model based on the quasi-steady mass balance of Eqn. 3 has been proposed by DeLuca[6] *et al*. This model follows the instantaneous pressure profile during the quasi-steady phase of the combustion process; transient effects are not taken into account. Mass storage in the combustion chamber is neglected, while it is considered after the burning end to simulate the chamber evacuation through the sonic nozzle. A parameter $K(w)$ depending on the web thickness has been introduced in the burn rate law to fit the instantaneous experimental pressure recording. Since the final target is a more sensitive data reduction procedure to be employed in an industrial environment, the model is admittedly very simple and does not intend to fully reproduce the whole combustion process. In this way, the proposed model has only few parameters to read out and a complete analysis can be performed in few minutes. Burning surface is assumed to remain plain and regular, but it changes its size during combustion. Since the Baria grain configuration allows combustion to take

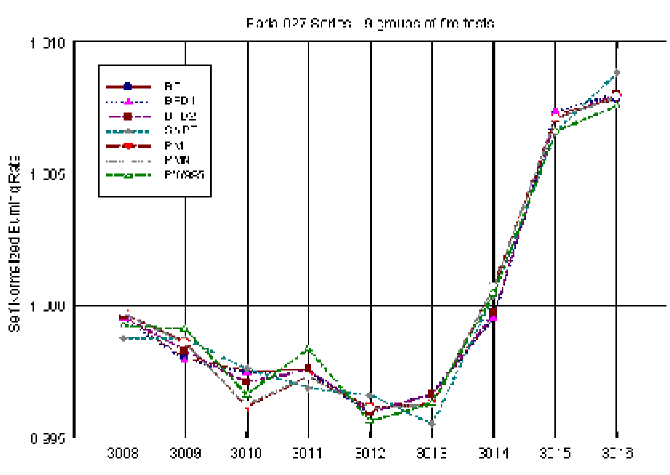

Figure 3. Self-normalised burn rates of standard data-reduction procedures

place both in the radial and axial directions, its regression is in principle defined by two different burn rates as shown in Fig. 4. Both the radial and axial burn rates can be calculated based on a simple modification of the Vieille law as

$$r_b = K\,ap^n \qquad (7)$$

The $K(w)$ function depends on the model used and its choice is based on experience. In general it is a very simple function, like a second-order algebraic function, and it affects only the radial burn rate. Of course, based on the results, this function can be modified towards more complicated models but this strategy would be in principle suspicious.

5.1 Model Application

The proposed model has been applied to Baria SSTM's produced with the mandrel put in place before casting process (the so-called 70N series in this work). The easiest correction function that yields computed pressure profiles comparable to the experimental ones is a symmetric parabola whose integral is equal to the unity.

$$\begin{cases} w(t) = \int_0^t r_b \, dt' \\ K(w) = aw^2 + bw + c \\ if \quad w = 0 \quad K = HF \\ if \quad w = w_{end} \quad K = HF \\ \int_0^{w_{end}} K \, dw' = 1 \end{cases} \qquad (8)$$

Under these conditions, the curve $K(w)$ is completely defined fixing the value HF (often called the Hump Factor in the literature). With the tested kind of propellant grains, best results are for HF in the range 0.95 and 0.85. In Fig. 5 a comparison between real and computed pressure profiles is shown for the fire tests marked as PA70_N and PB70_N

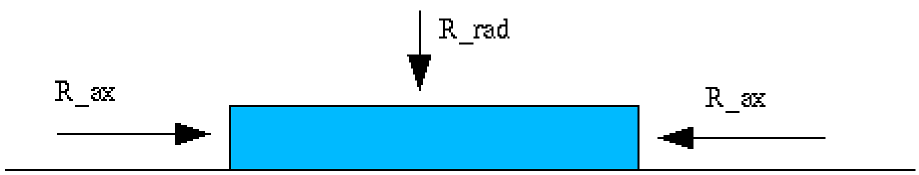

Figure 4. Sketch of axial and radial burn-rate modeling

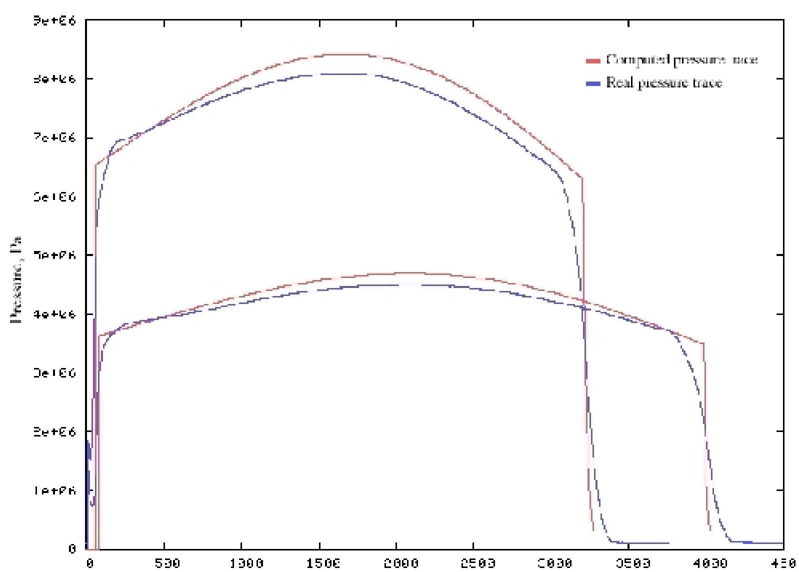

Figure 5. Comparison between experimental and computed pressure-time profiles–HF = 0.90

(respectively high pressure and low pressure tests with mandrel-in-place propellant casting). The ballistic parameters are given in Table 2.

Table 2. Ballistic characterisation with model application (series 70_N)

a	1.9297 mm / (bar^n)
n	0.3686
HF	0.90

If a standard data-reduction procedure is used (like the commonly adopted FiatAvio BPD1), the ballistic parameters are a = 1.510 mm/(bar)^n and n = 0.3704. It should be noted that BPD1, as other standard-reduction procedures, may suffer some difficulties like sharp motor extinction does not occur, as in the pressure-time profiles of Fig. 2. A complete discussion on the model application and the way it operates can be found in the research work of DeLuca[6].

5.2 Manufacturing Effect on SSTM Performances

Two kinds of Baria motors are compared in Fig. 6. The only difference is in the propellant casting procedure. One motor has been produced casting the propellant with the mandrel put in place before the operation (PA70_N). The other one is produced with the insertion of the mandrel after the propellant casting is done (PA87 - S1 026 series). The PA70_N plot is regular with no Friedman's curl at the end. PA87 plot is irregular with a non-constant behaviour; a well-defined Friedman's curl takes place at the end as well as at a point of relative minimum pressure in the middle of the combustion. Since the propellant composition is (nominally) the same and the motors have (nominally) the same configuration, the difference must have been introduced by the manufacturing process.

The PA70_N pressure-time profile is well approximated by a simple parabolic function of $K(w)$ in Eqn (7). Attempts to identify a simple function for the PA87 pressure profile has been unsuccessful. A function can be found but is looks artificial. This means that the simple model previously described does not adequately match what really happens.

Both pressure recordings are far from an ideal Baria fire test. According to the proposed model, the PA70_N grain motor burns with a radial burn rate that possibly varies along the web thickness. PA87 pressure-time profile features a complex behaviour and the propellant seems to burn with abrupt changes of burn rate.

This specific manufacturing effect is already known, as experimental and numerical studies have been reported[1,2,9-11]. The different casting procedures and the mandrel placing in Baria grains influence the rheological properties of uncured propellants. Shear stresses are different and this probably caused

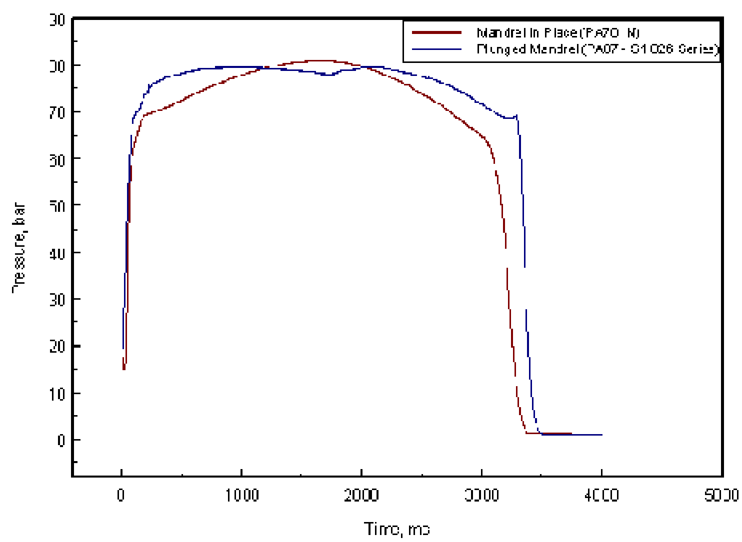

Figure 6. Pressure-time profiles from two Baria SSTM with different casting procedures

a different orientation of the solid particles (oxidizer, aluminum) inside the viscous binder. Besides, the effect is non-uniform inside the single propellant grain because shear stresses change with the position. By some researchers[1,2,9-11] the evaluation of these effects has been done for other SSTM's by measuring the variation of ballistic properties and the mechanical properties along the axial and radial directions.

Table 3. Baria production for propellant grain sampling

Referenced as	Series number	Inv.
Baria 1	8400	39
Baria 2	8399	11
Baria 3	---	17
Baria 4	4800	18

5.3 Sampling of Baria Motor

With the cooperation of FiatAvio, a series of 4 Baria propellant grains have been produced to be sampled; (Table 3). Due to the casting process configuration[12], a cylindrical symmetry can be assumed. The propellant radial and axial burn rate have been measured and also its density in different longitudinal positions. In the following, results obtained with Baria 3 are reported. Sampling of other motors is in progress.

5.3.1 Radial Burn Rate

A longitudinal propellant slice was cut from the grain and five main blocks were obtained in different positions (Fig. 7). Each block was 30 mm high and 20 mm long. The block depth is not important. The distance was the same between blocks. Before taking the blocks 1 and 5, a 5 mm propellant thickness was discarded to avoid curing boundary effects.

From each block a minimum of 9 radial samples were obtained (with a 4 mm X 4 mm surface and 30 mm height) to make 3 burning tests at each nominal Baria working pressure (30 bar, 45 bar, 70 bar). This amounts to at least 45 tests. Some tests were conducted done also at ambient pressure. Sample cutting and inhibition were performed at the same time for all the blocks. After at least 5 h of ambient drying, samples were put overnight in an oven at 29 °C with desiccating salts. At a time, only one sample was taken out of the oven and put in a thermally insulated box. Then, it was immediately moved to the combustion chamber. The setup and firing procedures take less than 5 min.

Combustion of samples was performed in a chimney burner under inert nitrogen atmosphere. The pressure was kept under control by a pressure gauge and a set of automatically driven exhaust valves. The burn-rate measurement was performed

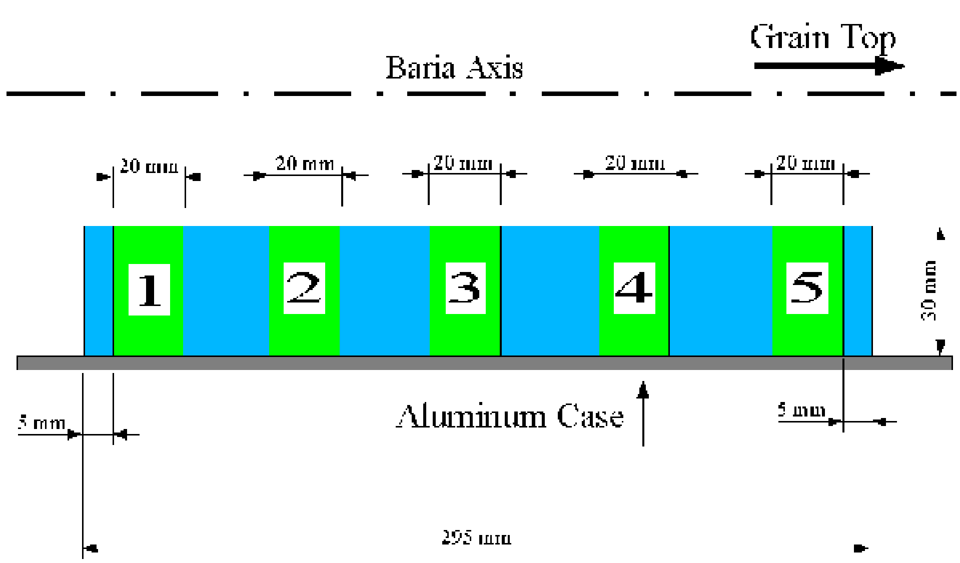

Figure 7. Sampling for radial burn-rate measurement

by an optical technique using a digital high-speed video camera recording the sample combustion. All of the samples were burnt along the internal-external direction.

Film analysis was done with a point-to-point measurement. The first 3 mm of samples combustion were discarded to avoid the starting transient effects. In few cases, measurements were considered valid only after 5 mm or 7 mm, because the burning surface distorted by ignition would cover some distance to return flat. Also, the last 3 mm of samples could not be considered because the experimental setup did not allow seeing the whole sample length. For a given location of the burning surface along the sample, each measurement point yielded the average burn rate over a distance of 2 mm backward and 2 mm forward wrt this location. A maximum of 11 measurements could be obtained for each test and these provided a discrete burn rate profile along the tested direction. Each burn rate profile was finally self-normalised by its mean burn rate.

5.3.2 Longitudinal Burn Rate

A longitudinal propellant slice was cut from the motor propellant grain and five main blocks were obtained in different positions (Fig. 8). Each block was 30 mm in longitudinal direction and 8 mm wide along the radius. The block depth is not important. The distance was the same between the blocks. Before taking the blocks 1 and 5, a 5 mm propellant thickness was discarded. The block consists of the core of the propellant grain. Since less propellant samples could be obtained with this sampling, only 2 fire tests were conducted at 30 bar, 45 bar, and 70 bar. This involves a minimum of 30 tests.

The sample treatment, burning procedure, measurement technique were the same as in the radial burn rate measurement (previous subsection). In this case, the samples were burnt along the top-bottom direction.

5.3.3 Density Measurement

Ten different blocks were taken from a longitudinal slide cut from the propellant grain. The sampled parts were never contiguous (Fig. 9). Blocks were treated at the same moment and with the same procedures. After cutting, these were put in an oven for an overnight with dehydrating salts at a fixed temperature (29 °C). Measurements were performed with an electronic densitometer with a precision of 0.001 kg/m^3.

6. BURN RATE RESULTS

Due to the high number of burn-rate measurements needed for all the motor configurations (more than 700 just for one motor), complete sampling of only Baria 3 is near completion. Work is in progress to examine the other motors as well.

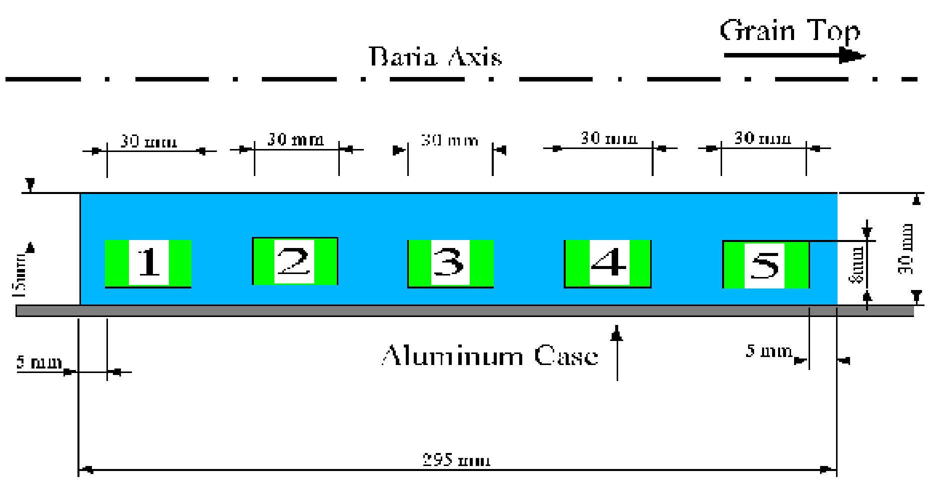

Figure. 8 Sampling for longitudinal burn-rate measurement

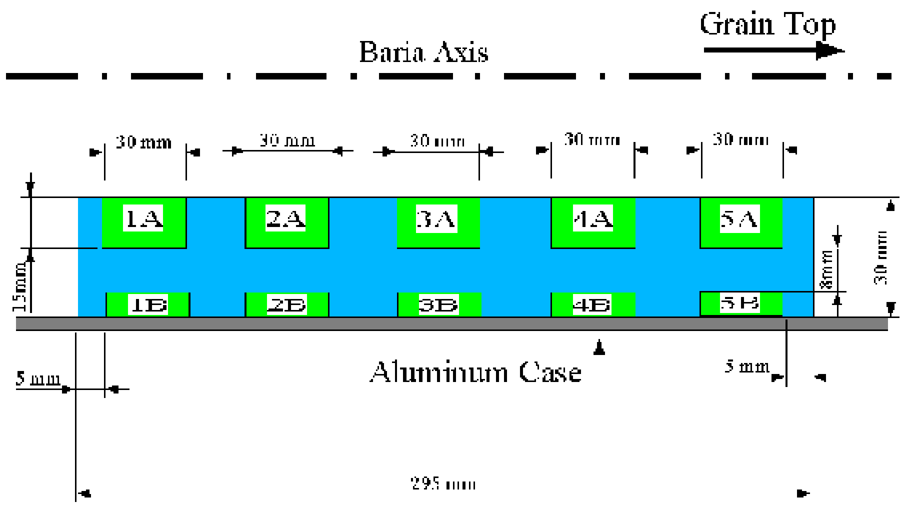

Figure 9. Sampling for density measurement

6.1 Average Radial Burn Rate

Single burn rate profiles were used to obtain the average burn rate of each sample under the tested operating conditions. The average burn rate of each block was then fitted with Eqn (1).

The results in Table 4 and in Fig. 10 show that the propellant feature similar average ballistic properties in different positions. The highest pressure exponent *n* can be found in blocks 1 and 5. The minimum is found in the middle Block 3. The ballistic parameter *a* follows an opposite trend; it has a maximum in block 3 and a minimum in blocks 1 and 5. If the graphic representation in Fig. 9 is considered, blocks 1 and 2 show two overlapping fitting curves always located above other blocks. Block 4 shows a fitting curve shifting towards lower values wrt blocks 1 and 2.

6.2 Radial Burn Rate Profiles

Normalised burn rate profiles show a high scattering. The variation of burn rate along the radius is expected to be very small (less than 5% in some cases reported in literature[10-11]) .

A common trend can be seen in Figs 11 to 13. In all the three cases, a central maximum peak is followed by a decrease of burn rate. The average behaviour suggests that the first-half of combustion is faster than the second-half. The highest burn rate location was placed at about 13-15 mm from

Table 4. Average radial burn rate

Block No.	a	n
1	1.216 ± 0.086	0.4703 ± 0.0182
2	1.313 ± 0.046	0.4502 ± 0.0092
3	1.493 ± 0.100	0.4135 ± 0.0176
4	1.298 ± 0.112	0.4464 ± 0.0229
5	1.143 ± 0.104	0.4846 ± 0.0245

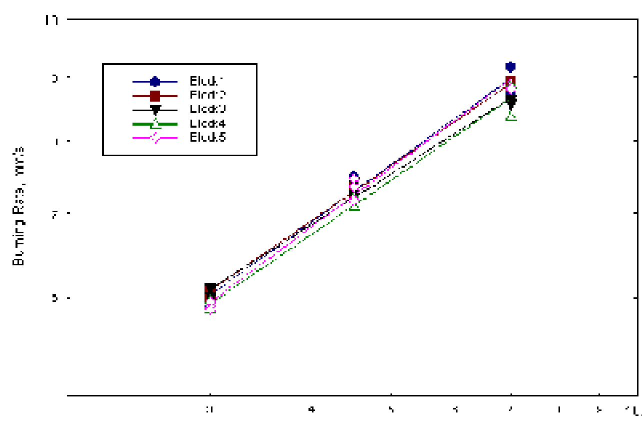

Figure 10. Average burn rates in Baria 3

the initial burning surface, while the lowest burn rate was placed at the end of the profile.

No evident difference could be detected between blocks in terms of normalised burn rate profiles. Some measurements were also done to evaluate

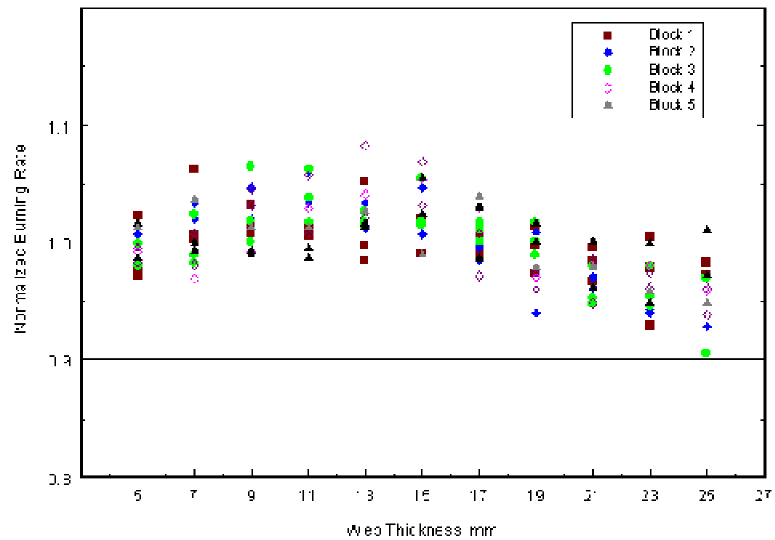

Figure 11. Normalised burn-rate profiles (Baria 3–30 bar)

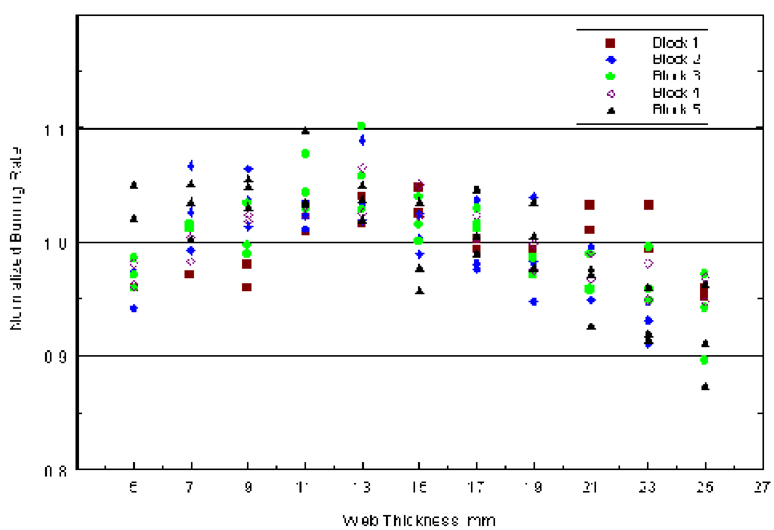

Figure 12. Normalised burn-rate profiles (Baria 3–45 bar)

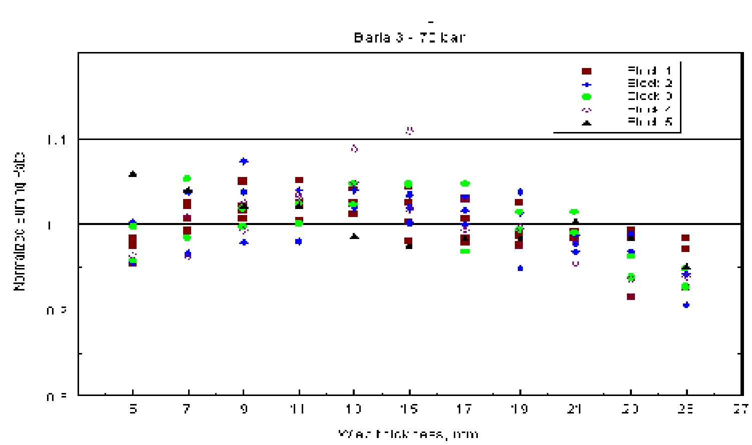

Figure 13. Normalised burn-rate profiles (Baria 3–70 bar)

the profile effect at 1 bar, in a similar but distinct experimental rig. Only few blocks could be tested. In this case (Fig. 14), the pattern observed at higher pressure seems to be missing and scattering of the experimental points was lower.

6.3 Longitudinal Burn-rate Profiles

Only longitudinal burn rate profiles obtained at 30 bar have been reported in Fig. 15. Further measurements are in progress.

The distance mentioned in Fig. 15 is the burnt distance of the sample, burning along a Baria top-bottom direction. In this case, no obvious trend could be detected. All measurement points were located around the line of unity. The scattering of measurement points around their average values was similar to that found in radial measurements.

6.4 Density Measurement

Block density measurement was performed to determine if the propellant was homogeneous. The position of the blocks can be derived from Fig. 9.

Average propellant density was 1.755 kg/m^3. All measurements were within a range of ± 0.35

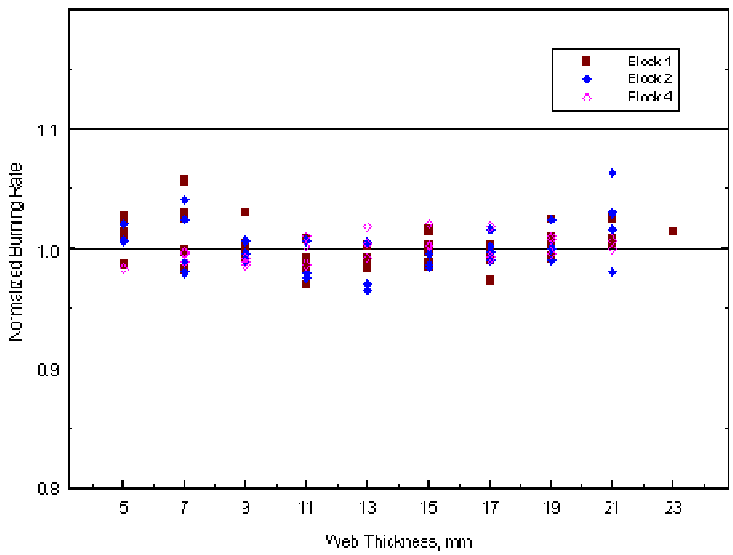

Figure 14. Normalised burn-rate profiles (Baria 3–1 bar)

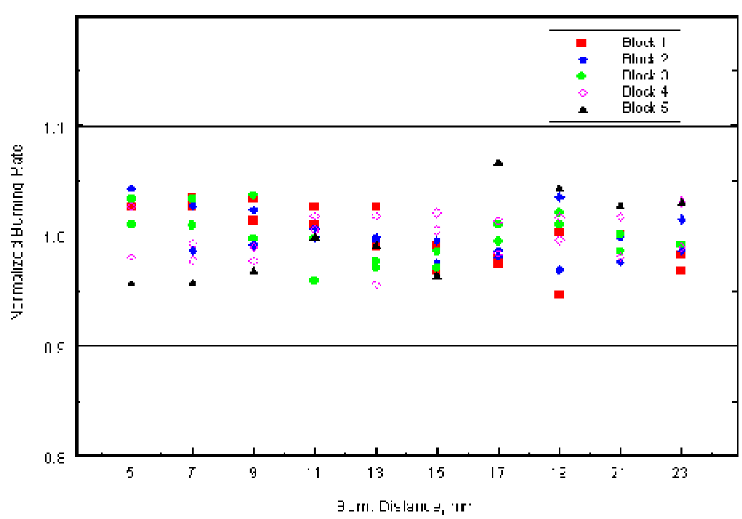

Figure 15. Longitudinal burn-rate profiles (Baria 3–30 bar)

per cent. There was no difference between the internal and the external position.

7. CONCLUSIONS

Industries make wide use of data-reduction procedures to obtain ballistic characterisation of propellant. These procedures employ experimental pressure-time profiles obtained from a SSTM and measure the average burn rate of fire tests. These procedures, very simple and fast to implement, may be defective when more than the average motor behaviour is sought for.

A simple ballistic model had previously been presented[6]. This model fits well pressure-time profiles from motors produced with the mandrel-in-place casting technique. But pressure profiles appear altered if the casting process is modified. Under these circumstances, the proposed model is not able to adequately fit the experimental trend. At any burn rate, the observed pressure-time plots are different from Baria ideal behaviour (with uniform and regular regression rates). This leads to the suspecsion that the propellant burn rate changes during the combustion process.

Thus, four Baria grains were produced to be cut and locally sampled. Up to now, only the analysis of one of these motors (Baria 3) has been concluded. The normalised radial burn rate at 30 bar, 45 bar and 70 bar (Figs 11 to 13) show an unsettled trend. In particular, the first-half of combustion is faster than the average rate while the second-half is slower. The magnitude of this variation is less than ± 5 per cent. No evident effect was observed in samples burning at ambient pressure. The normalised longitudinal burn rate shows a uniform behaviour (Fig. 15). Also average radial burn rates are close but not identical (Fig. 10 and Table 4). Differences exist from block to block with a maximum of the parameter *a* in block 3 and a maximum of pressure exponent *n* in blocks 1 and 5.

Density measurement (Table 5) demonstrates that propellant appears as homogeneous in all of the Baria grains. Hence, variations from the average radial burning behaviour cannot be attributed to local differences of the propellant density. The

Table 5. Baria 3 density measurement

Block	ρ_{int} (marked as *A*)	ρ_{ext} (marked as *B*)
1	1.757	1.756
2	1.749	1.755
3	1.755	1.753
4	1.757	1.755
5	1.758	1.757

change in local propellant burn rate is introduced by the different ways putting the mandrel inside the Baria's centrally perforated grain, probably due to different particles orientation during the casting and forming processes in the uncured propellant.

8. FUTURE WORKS

The complete analysis of one motor grain is a long procedure since it requires at least 75 burning tests and more than 800 measurements to be analysed. Up to now, only the total mapping of Baria 3 samples is near completion. The next step includes the complete mapping of Baria 1, 2, and 4 to obtain a point-to-point comparison between propellant grains from different manufacturing techniques. The obtained burn rate profiles can also be used to achieve a precise modelling of Baria motor to be used in more advanced data-reduction procedures.

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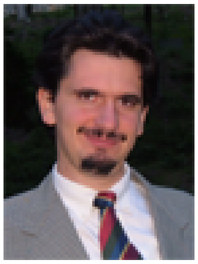

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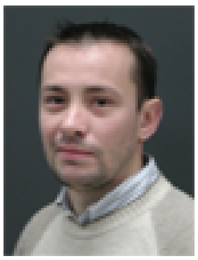

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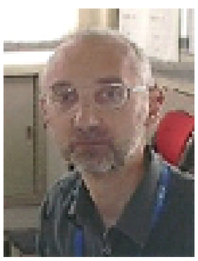

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