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Parametric Studies on Star Port Propellant Grain For Ballistic Evaluation

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ABSTRACT

Star port propellant grains have been extensively studied for their operating as well as geometrical parameters. It is observed that reduced tail-off and better neutrality cannot be achieved simultaneously in a configuration. Parametric study is conducted to know the effect of various parameters of star-shaped propellant grains for ballistic evaluation motor. For reduced tail-off, higher characteristic velocity, lower outer diameter of the star, and lower value of angular fraction is preferred. Star angle, burning rate, and throat diameter have negligible effects on the tail-off factor. For better neutrality, higher value of angular fraction, higher star outer diameter, and star angle near to neutrality, is needed. An alternate configuration is suggested using this parametric study to ascertain least tail-off and enhanced neutrality.

Keywords: Solid propellant grain, ballistic evaluation, star port propellant grains, tail-off factor, burning rate, ballistic evaluation motor, propellant configuration, tail-off reduction, BEM.

1. INTRODUCTION

Solid propellant grains in star port central recess have been extensively used in the propulsion units of rockets, missiles, and launch vehicles. Since propellant processing cycle is long, it is natural to establish the propellant properties on a small scale before undertaking work of any large-scale production. For such small batches, physical (density), chemical (combustion gases properties), mechanical (tensile strength, percentage elongation, modulus) and ballistic (specific impulse, burning rate, characteristic velocity) properties of the products are determined and matched with pre-specified values. Ballistic evaluation motor (BEM) is very popular for such assessments, especially for the evaluation of ballistic properties. These give an insight into the burning rate of propellant at various operating temperatures and pressure ranges.

This paper presents details about the existing BEM propellant configurations, parametric studies on star port propellant grains and their role in designing propellant configuration for the BEM.

2. PROPELLANT CONFIGURATIONS FOR BALLISTIC EVALUATION

A popular preliminary shows that BEM contains a tubular propellant grain with no inhibition. It bums on all the sides and gives a slightly regressive pressure-time profile. The propellant quantity involved is around 2.5 kg and has dimensions of OD 115 mm, ID 60 mm, length 200 mm (Fig. 1). A typical burn area versus web profile is given in Fig. 2. These grains are evaluated in standard motors with adjusted throat to cover different pressure ranges. For typical propellant properties (burning rate of

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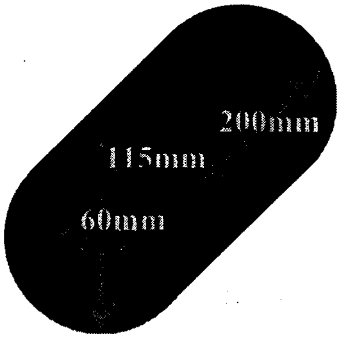


Figure 1. A 2 kg ballistic elastic motor propellant grain

10 mm/s at 70 kg/cm^2, characteristic velocity of 1520 m/s, and density of 1.75 g/cc) and motor operating condition (throat diameter of 25 mm), pressure-time profile of the grain are shown in Fig. 3. In France, a propellant grain code-named CAMPANULE is being used for such activities.

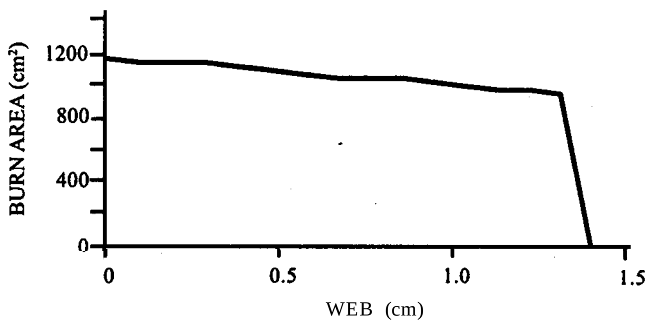


Figure 2. Burn area variation with web

This has lo-point star port with 90 mm OD and 300 mm length. This weighs around 2.5 kg. In other countries, cylindrical grains are preferred.

Another class of propellant configuration, which has been extensively used for BEM is called 40 kg

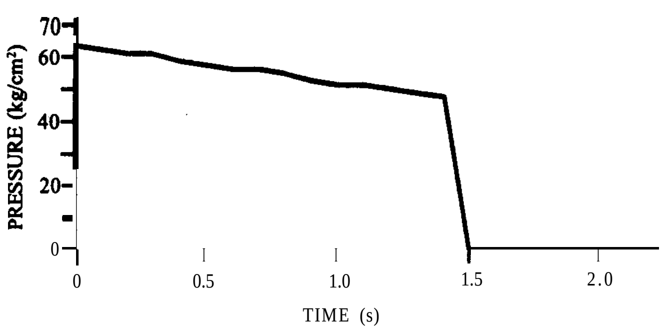


Figure 3. Pressure-time profile

BEM grain or AGNI motors. These grains are generally configured as star-shaped port at the centre. Various parameters of the star-shaped port configuration are shown in Fig. 4.

In France, it is customary to use star port grain with 10 petals as a control solid propellant grain for the evaluation of ballistic properties of propellant batches. It weighs around 45 kg with dimensions of 203 mm diameter and lm length. It shows good neutrality defined as percentage variation in the surface area of propellant during burning. For 40 kg BEM, a 6 petal star-shaped propellant grain configuration has been standardised to assess the propellant performance. Salient features of the BEM are given in Table 1. A typical burn area to web profile and pressure-time diagram are given in Figs 5 and 6.

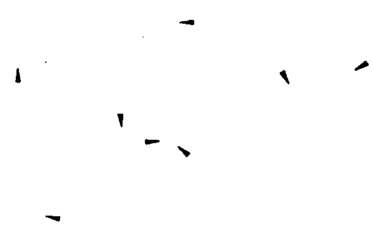


Figure 4. Governing star parameters

Although this grain has good neutrality, but some fine tuning is required to get reduced tail-off. Sometimes, term configuration efficiency is used to assess the ballistic quality for a grain design[2]. This is defined as a ratio of the actual total delivered impulse at action time to the ideal impulse produced if all the original propellant is burned to deliver a constant maximum pressure, equivalent to the maximum pressure actually experienced, and expended through a nozzle with an optimal expansion ratio. So, it becomes a measure of losses that accrue as a result of deviation from neutrality, maximum pressure performance with sliverless exhaust. In the United States,

Table 1. Standard BEM details (grain identification)

Input parameters	Data
Outer diameter of the grain (mrn)	198
Port configuration	**Star**
Number of star points	6
Angular fraction of star	0.80
Star half-angle (deg)	33.53
Star outer diameter (mm)	115
Fillet radius (mm)	6
Tip radius (mm)	2
Density of the grain (g/cc)	1.75
Characteristic velocity (m/s)	1520
Burning rate at std pressure	5
Standard pressure **(kg/cm^2)**	30
Burning rate index	0.30
Length of propellant (mm)	970
Throat diameter (mm)	52
Weight of propellant (kg)	40.82997
Calculated wt of propellant (kg)	40.80864

ballistic test evaluation system (BATES) type of grains are very popular, which give constant burn area versus web-burnt profile with no

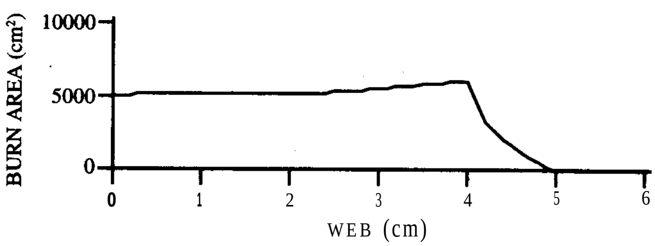


Figure 5. Burn area-web profile

combustion tail-off. For specific situations like for characterisation of energetic binder compositions, very good tail-off is desired so that unburnt

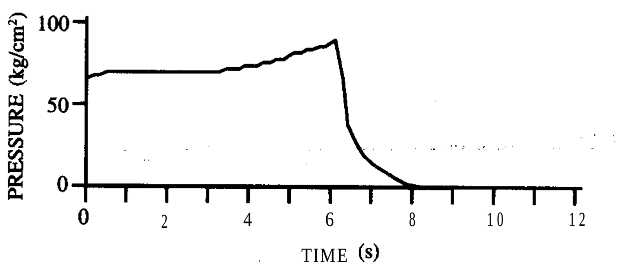


Figure 6. Pressure-time profile

residual propellant can burn with other initial surfaces, but for the BEM, least tail-off is desirable. This paper deliberates various approaches to tail-off reduction methods and suggests an alternate grain configuration for 40 kg BEM.

3. PARAMETRIC STUDIES

3.1 Burn Area

Propellants with star-shaped port have been extensively used in several rocket systems. For evaluation of burn area variation with consumption of web, several algorithms have been proposed. Ricciardi[3] has proposed an algorithm for nine alternative intermediate configurations possible during burning of star port propellant grains. He has also deliberated on mathematical formulations. In a relatively latest article, Shekhar[4] has evolved a new zoning concept for the prediction of burning area for a taper star port propellant grain. Williams[5], et al. have given a mathematical formulation for a star port propellant grain till sliver formation and have also mentioned a constant star angle for neutral burning profile from multi-point star port propellant grain. The value of a star angle for neutrality is reproduced in Table 2.

The existing 40 kg BEM grain configuration with a central star-shaped recess/port has been studied in detail for characterising the effect of various propellant properties (density, C-star, burning rate), configuration parameters (number of star points, angular fraction, star diameter, star angle, fillet radius) and motor parameters (throat diameter). Since during burning, propellant grain recedes in layers, inner diameter of star

Table 2. Star angles for neutrality

Number of star points	Star half-angle
4	28°12′.96
5	31°07′.71
6	33°31′.70
7	35° 33’40
8	37°18′.40
9	38°50′.38
10	40°12′.00

is consumed later than its outer diameter. When outer diameter of radially outward burning propellant grain reaches outer diameter of the propellant, propellant grain gets divided into several unburnt masses called slivers. These slivers are mainly responsible for tail-off.

For quantitative analysis, two major factors neutrality and tail-off have been considered. Neutrality is measured in terms of ratio of pressure variation to average pressure before sliver formation. It is reported as neutrality factor. Tail-off factor can be defined as tail-off duration to total burn time of the propellant grain.

3.2 Density of the Propellant

Density of the propellant composition is assumed to change from 1.40 g/cc to 1.90 g/cc and pressure-time profile for each case is plotted on the same scale as shown in Fig. 7. It is clear that at lower density, pressure realised for the same configuration is lower. In this case, both neutral as well as peak pressure are lowered with minor increase in the burning duration. But neither the neutrality factor is affected nor the tail-off factor has any variation. It is observed that tail-off duration reduces with rise in density but corresponding rise in total burning time neutralises the effect, resulting in no variation in tail-off factor. Higher density ensures higher propellant weight also. Although density of propellant formulations do not change significantly, and on the other hand, changing density of realised formulation with similar ballistic, mechanical, and other qualitative requirements is difficult to implement. In general, propellant density of 1.75 g/cc is observed in most of the practical formulations.

3.3 Characteristic Velocity

Characteristic velocity (C*), which is treated as performance parameter of propellant formulation, is changed for the same configuration from 1200 m/s to 1700 m/s. Pressure-time profile is plotted in Fig. 8 . Pressure level of the profile rises with increase in characteristic velocity, leading to negligible variation in neutrality factor. Before tail-off starts, profile for all the values of characteristic velocity

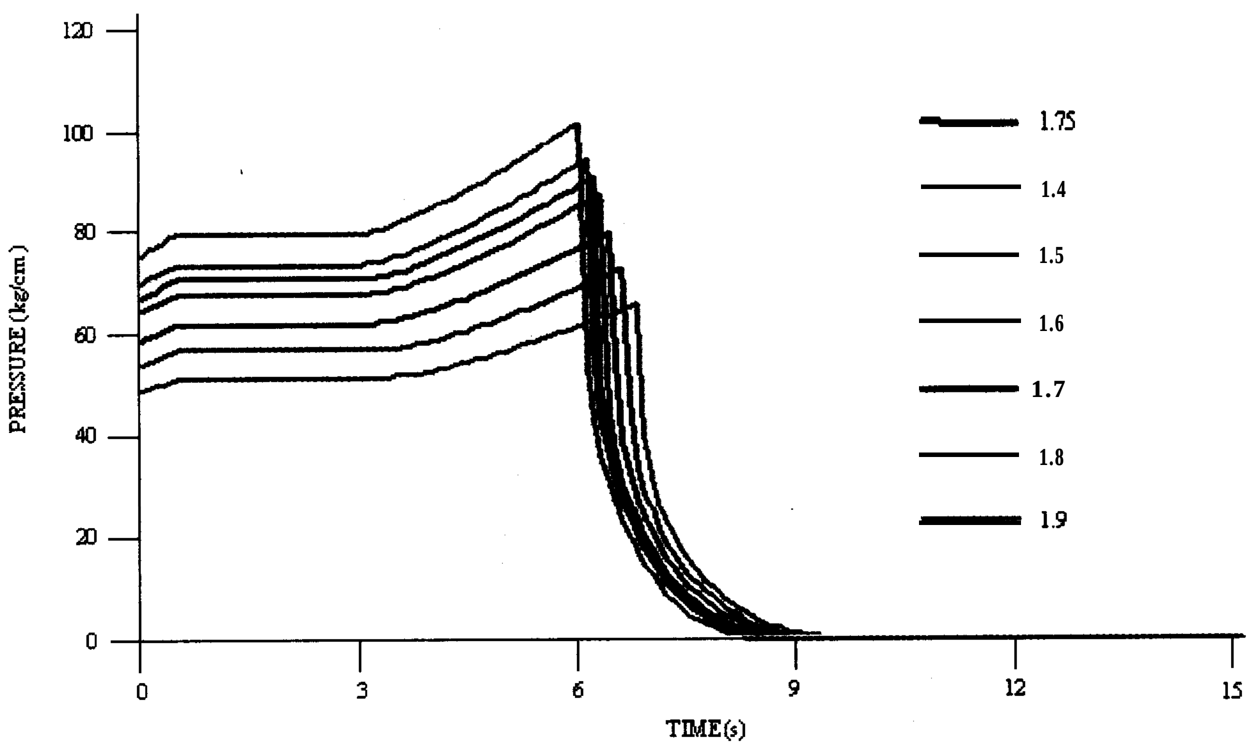


Figure 7. Parametric curve for density: Effect of variation of density of propellant

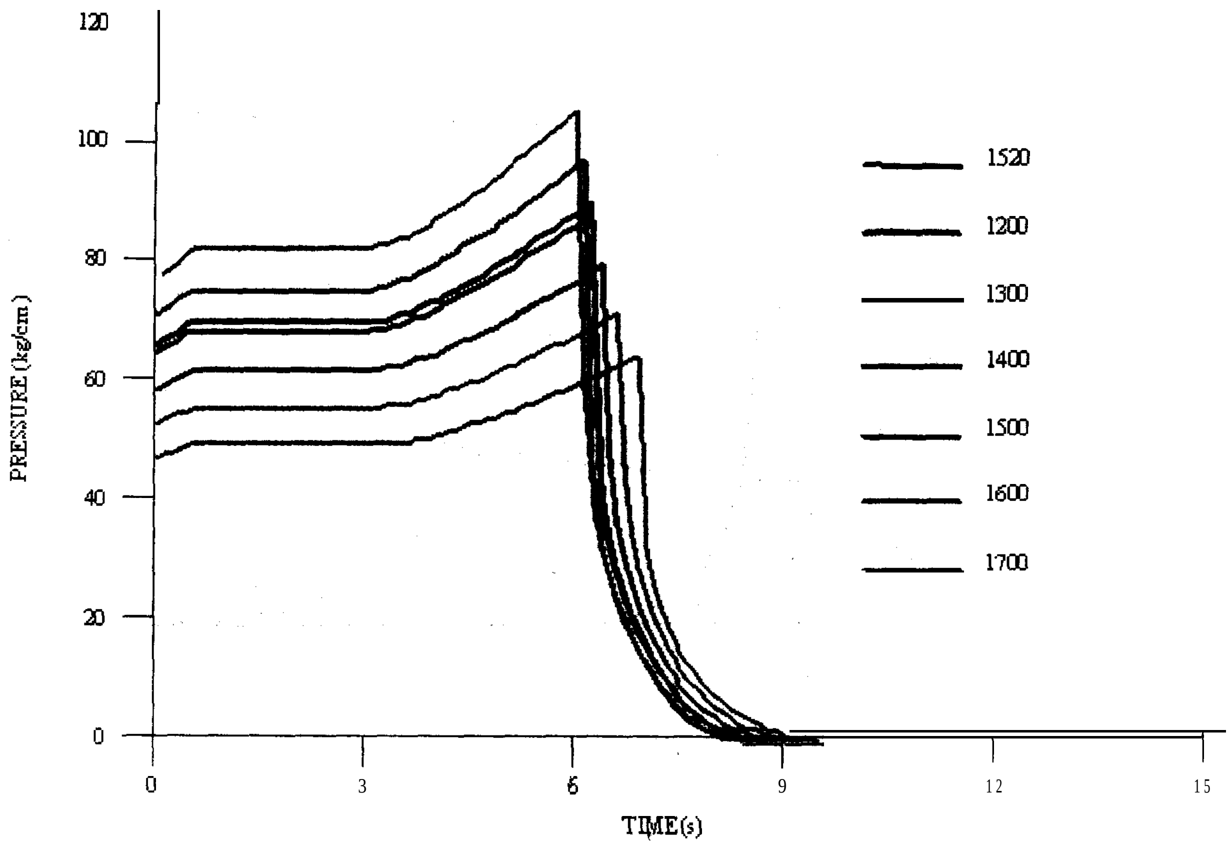


Figure 8. Parametric curve for characteristic velocity: Effect of characteristic velocity

are parallel to each other as obvious in Fig. 8. As far as tail-off duration is concerned, rise in characteristic velocity reduces tail-off duration as well as total burning time. The ultimate effect is the reduction of tail-off factor with increase in characteristic velocity. So, both tail-off duration and tail-off factor reduce with rise in characteristic velocity. However, characteristic velocity for a propellant composition cannot be varied much, but at higher characteristic velocity values, same configuration gives the same neutrality factor with reduced tail-off factor.

3.4 Burn Rate Variation

Burn rate of a propellant is a major factor in propellant development. The pressure-time profiles for burn rate varying from 4 mm/s to 8 mm/s at 30 kg/cm^2 have been plotted in Fig. 9. As burn rate rises, pressure level also rises at the cost of reduction in burning duration. However, neutrality factor remains almost, constant due to same shift in peak and minimum pressure. It is also observed that tail-off duration reduces significantly with rise in burn rate, but at the same time, total burn duration also reduces and tail-off factor remains almost constant.

3.5 Throat Diameter

The throat diameter is another factor, which is mainly a motor-performance variable. The value of the throat diameter is changed from 30 mm to 50 mm and the pressure-time profile is plotted for each case in Fig., 10. It is natural to expect higher pressure with reduced throat area but effect of throat area on the neutrality factor is negligible. The tail-off duration increases with increase in throat diameter, but simultaneous rise in total burn time offsets the effect to give tail-off factor also independent of throat diameter.

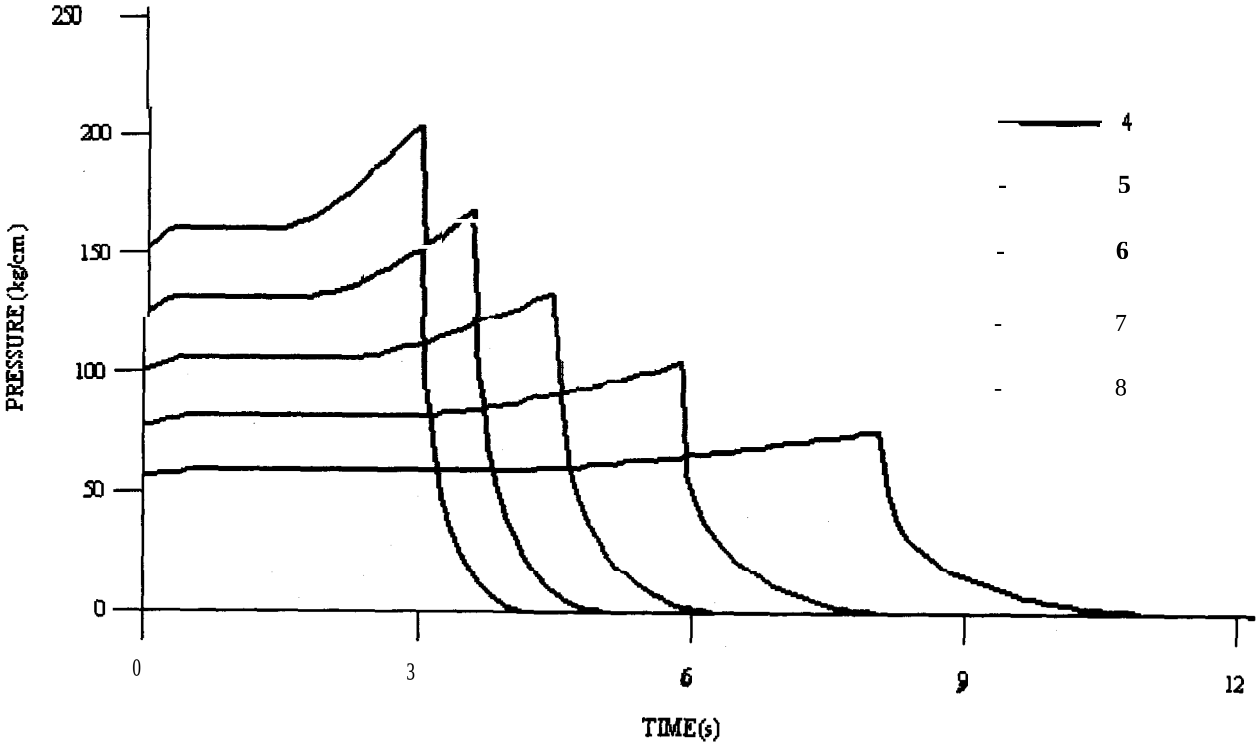


Figure 9. Parametric curve for burn rate: Effect of variation in burn rate

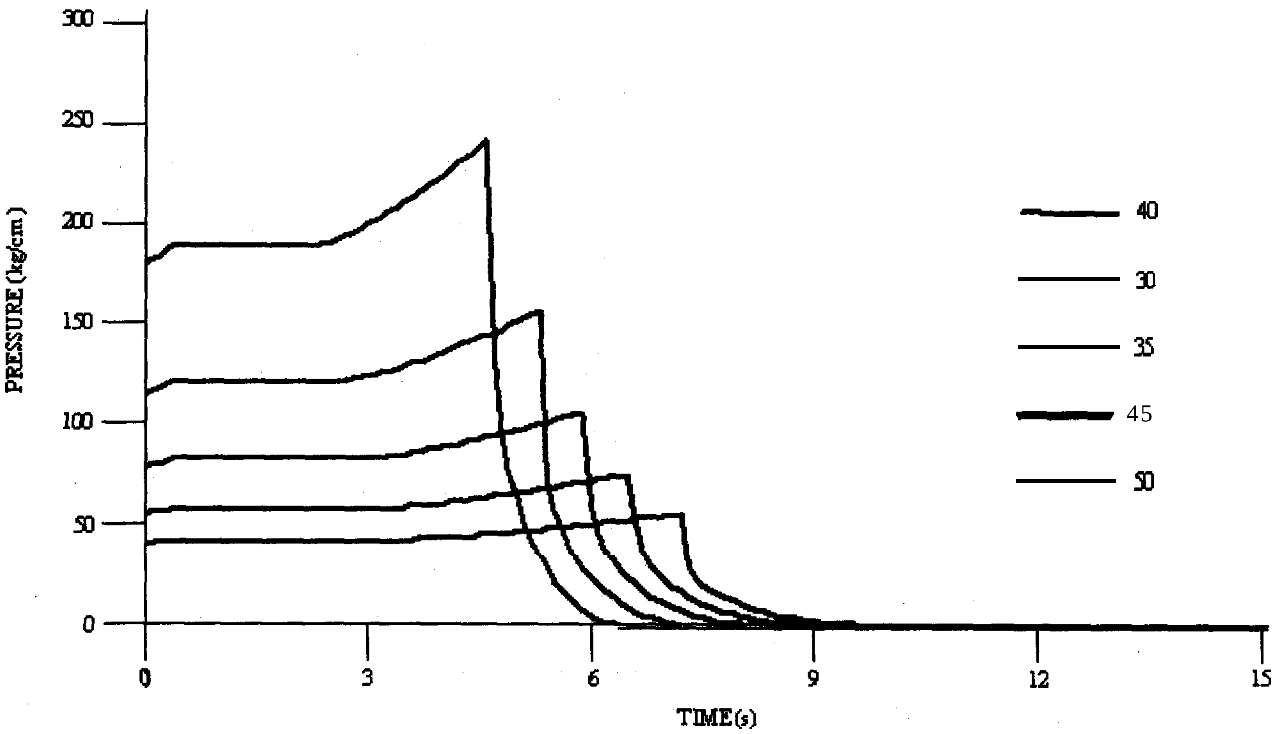


Figure 10. Parametric curve for throat diameter: Effect of variation in throat diameter

4. QUANTITATIVE ANALYSIS

4.1 Neutrality Factor

The above-mentioned effects are compositional and motor-related parameters and the values of neutrality factor are found independent of these parameters. Lower tail-off duration needs higher density of propellant, lower characteristic velocity value needs higher burning rate of propellant and lower throat diameter.

4.2 Tail-off Factor

On the contrary, tail-off factor is affected only by characteristic velocity and a higher value of characteristic velocity is recommended for achieving lower value of this parameter.

Next, the factors which define the propellant configuration be considered. These factors affect pressure-time profile significantly and instead of parallel shift in the values, nature of pressure-time profile also varies. For star-shaped grain configuration, these parameters are angular fraction, star outer diameter, star angle, and the number of star points/petals.

5. FACTORS DEFINING PROPELLANT CONFIGURATION

5.1 Angular Fraction

The value of angular fraction is changed from 0.5 to 1.0 for the 6-petal star-shaped port of the propellant grain. This results in reduced thickness of the star port, and consequently, propellant weight increases. Pressure-time profile is plotted in Fig. 11. At high angular fraction, peak as well as neutral pressure have high values, but rise in neutral pressure is more pronounced. This results in reduced neutrality factor at higher angular fraction values. On the other hand, tail-off duration at higher angular fraction also rises along with total time of burning. Overall effect is increased tail-off factor at higher angular fraction values. Angular fraction is to be chosen carefully after compromising both the factors, and at the same time, increase in weight of propellant to be considered for an efficient design.

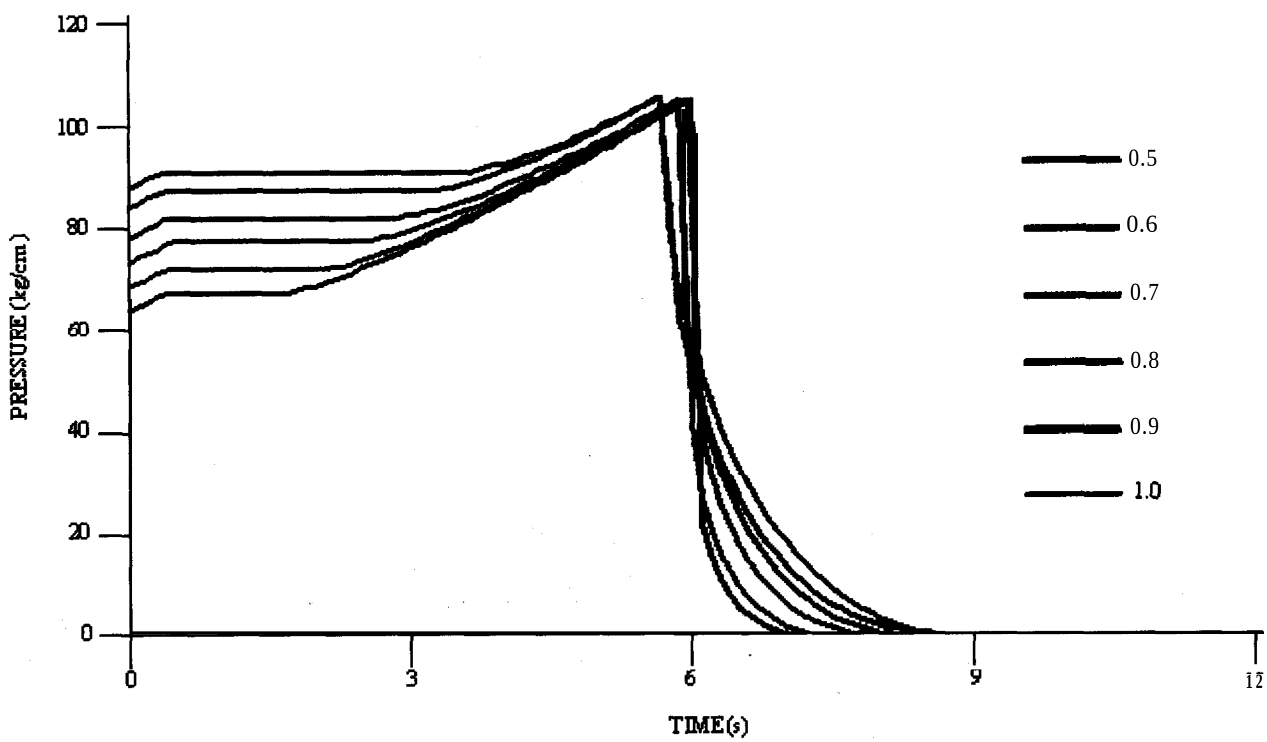


Figure 11. Parametric curve for angular fraction: Effect of variation in angular fraction

5.2 Star Outer Diameter

Star outer diameter can be changed as part of propellant design. This results in reduced propellant weight in the same chamber volume and the same motor cross-section. At higher values of star outer diameter (lower propellant volumetric loading), pressure-time profile is almost neutral, but at the same time, tail-off duration increases tremendously (Fig. 12). Neutrality factor reduces with increase in star outer diameter and the realised peak pressure increases marginally. Tail-off duration increases with increase in star outer diameter and total burning time reduces, resulting in marked increase in tail-off factor. So, requirements of star outer diameter are contradictory for better neutrality and lower tail-off factors.

5.3 Star Angle

Star angle, which is considered to be a major factor affecting neutrality, is changed on either side from neutrality value ($33^\circ 31'.70$ for a 6-petal star port). At lower than neutral angles, the pressure-time profile is M shaped, whereas for higher than neutral angle values of the star angle, the pressure-time profile monotonically rises to peak pressure (Fig. 13). Although peak pressure realised is the same in all the cases, minimum pressure is much lower for higher star angle. So at higher star angle, neutrality factor is adversely affected. At tail-off, all the curves almost merge and value of tail-off duration and total burning time is almost the same. Consequently, tail-off factor is not affected by this parameter at all.

5.4 Star Points

As far as number of star points are concerned, change in geometry needs entirely new configuration and based on the parametric studies, configuration can be selected. For good neutrality, higher angular fraction, higher star outer diameter, and star angle near to neutrality angle, must be maintained. Reduced tail-off duration is observed for lower angular fraction and lower star outer diameter and same is the case for obtaining reduced tail-off factor.

6. ALTERNATE CONFIGURATION

With considerations of lower neutrality factor and lower tail-off factor, parameters of propellant

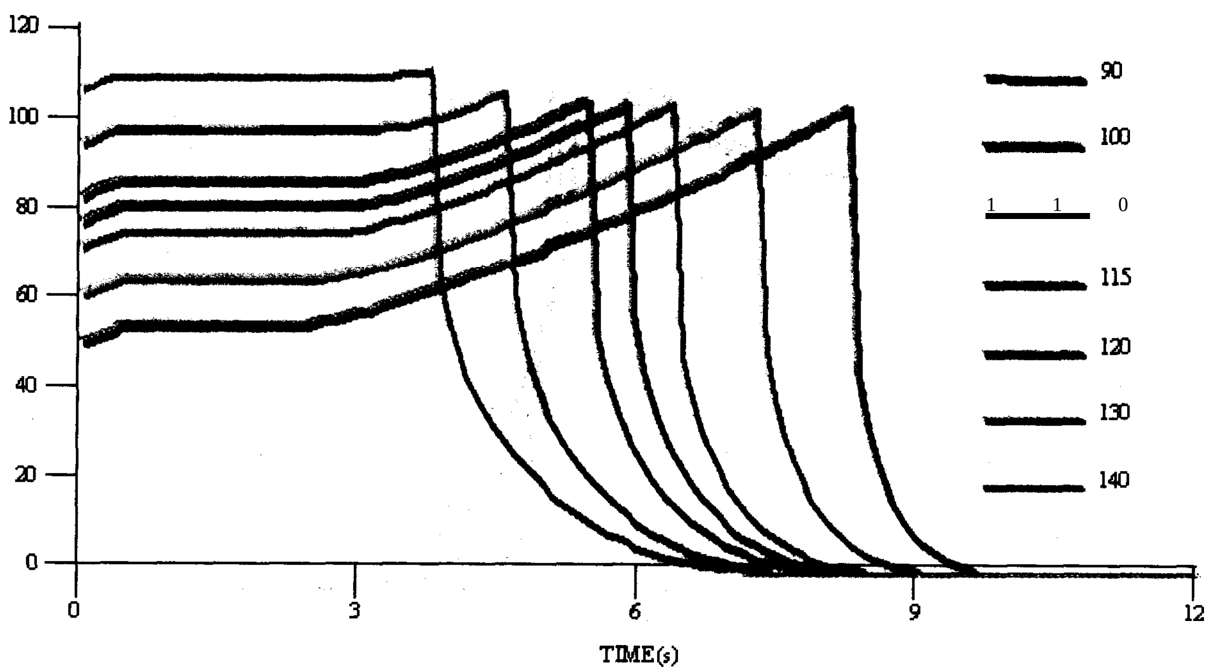


Figure 12. Parametric curve for angular fraction: Effect of variation in star point outer diameter

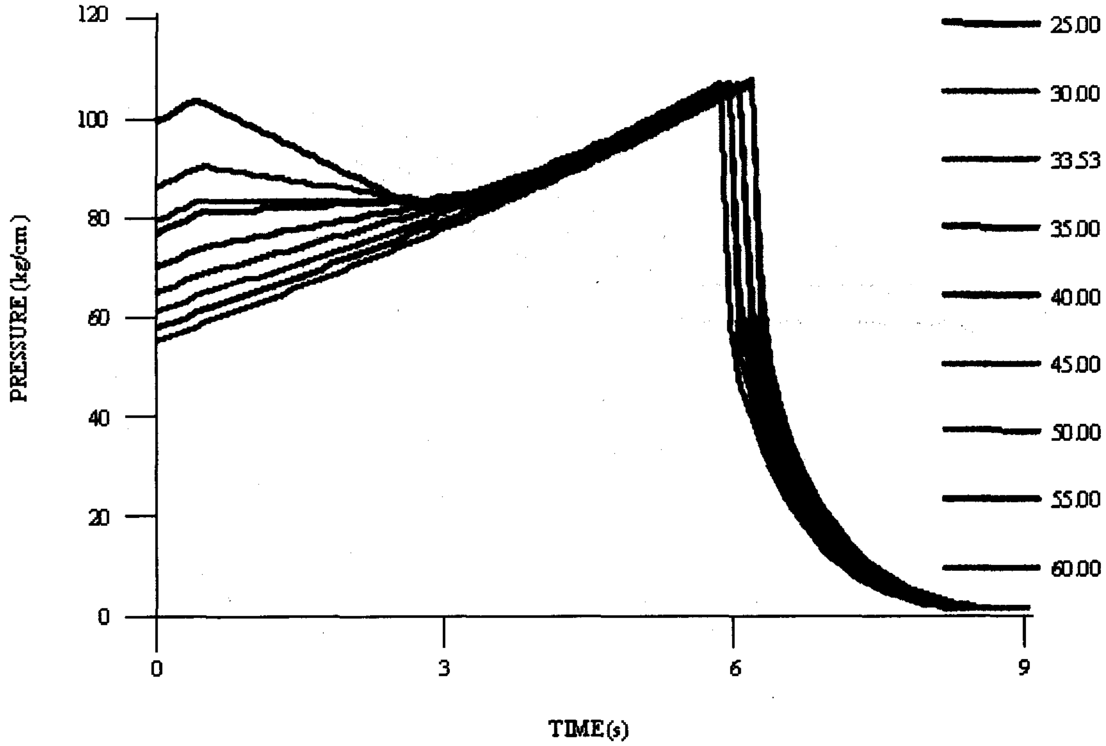


Figure 13. Parametric curve for star half-angle: Effect of variation of star half-angle

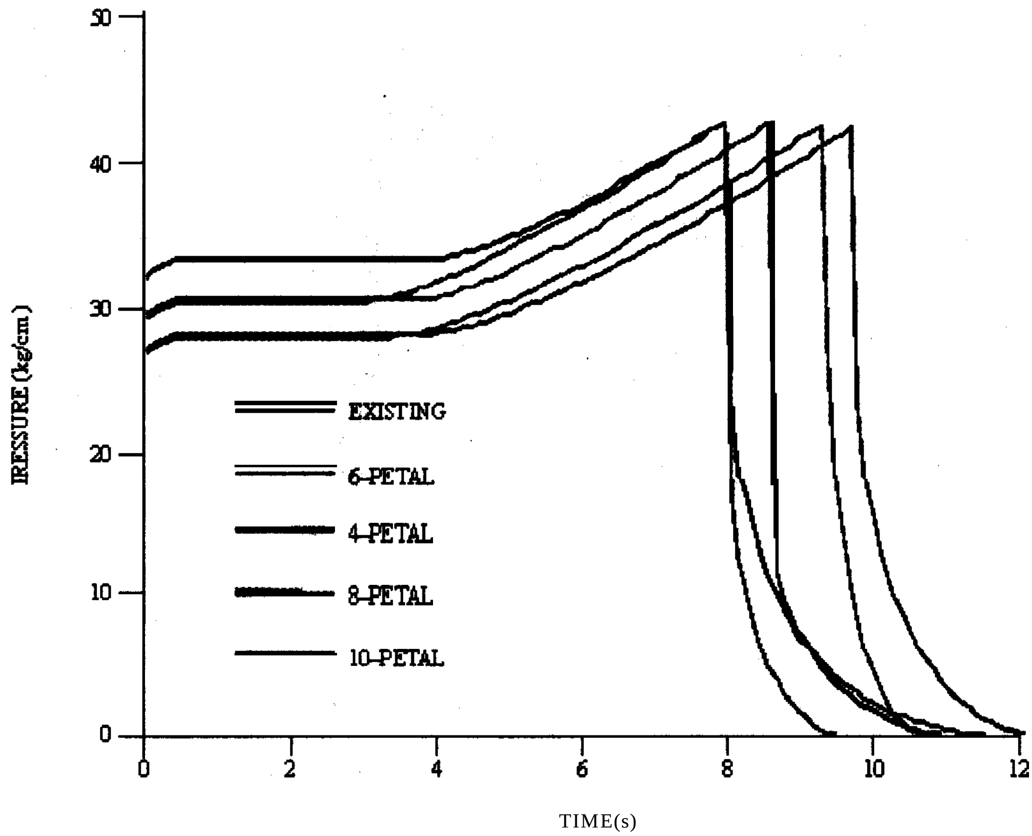
grains are selected in a 6-petal star port configuration. The existing design configurations can be altered for getting better neutrality. These changes in configurations have been made in the direction depicted by the parametric studies. Reduction in star outer diameter from 115 mm to 100 mm and reducing fillet radius from 6 mm to 4 mm can improve the pressure-time profile for its neutrality. This results in increased burning duration and low initial pressure values. Peak pressure remains the same but neutrality is compromised.

A 4-petal star profile is also assumed with star angle similar to the neutrality angle. For an angular fraction of 0.5 and star outer diameter of 110 mm, this configuration provides better tail-off properties.

Configuration for 8-petal star and IO-petal star have been optimised also with constraints of maintaining star half-angle for neutrality and propellant weight in the range approx. 40 kg. Pressure-time profiles are generated for different port configurations and optimised profiles are shown in Fig. 14. The salient parameters for different designs are shown in Table 3.

Table 3. Comparison of different proposed configurations

Parameter	Existing	Design 1	Design 2	Design 3	Design 4
Number of star points	6	6	4	8	10
Angular fraction	0.80	0.80	0.50	0.70	0.95
Star half-angle (deg)	33.53	33.53	28.21	37.30	40.20
Star OD (mm)	115.00	100.00	110.00	116.00	104.00
Fillet radius (mm)	6.00	4.00	4.00	4.00	3.00
Weight of propellant (kg)	40.82	43.68	40.03	37.21	41.86



Fire 14. Comparison of pressure-time profile for different designs

From the pressure-time profile, it is clear that reduced tail-off is observed for 8-petal star port configuration without affecting other parameters adversely (Fig 15). Hence, this configuration is a preferred choice for the BEM evaluation of propellant ballistics.

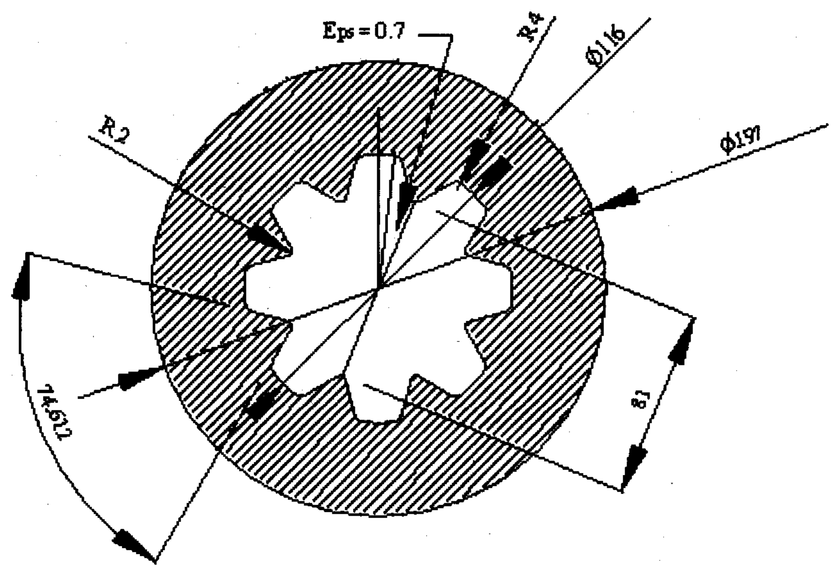


Figure 15. Proposed 40 kg ballistic evaluation motor gain cross-section

7. CONCLUSION

Based on the parametric studies, it is observed that several alternate designs are possible for improving tail-off duration and neutrality. However, compared to the existing design, S-petal star port propellant grain can be recommended for use in the BEM evaluations in place of the existing BEM configuration of 6-petal star port propellant grain.

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