Recent Advances in Solid Fuels for Rockets of Multi Barrel Rocket Launchers

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***Abstract*— Global search is on for a solid fuel for the area weapon Multi Barrel Rocket Launcher (MBRL). Solid fuel is the first choice due to ease of design, manufacturing, handling, packaging, transportability and deployability. It also has the capability of prolonged storage without noticeable degradation of its quality. It is also quite safe and does not pose safety hazards. Also with solid propellant end use by the troops is comparatively simple as only trigger operation is needed. Tactically it suits the requirement of very fast response time and generates high thrust for small duration. Solid fuel, better known as solid propellant is classified as single base and double base propellant. Single base propellant contains nitrocellulose (NC) where as double base contains homogeneous mixture of nitrocellulose and nitroglycerine (NG) with small amount of additives. There is a third category of solid propellant known as composite propellant. Double base propellant used to be preferred in tactical missiles and rockets. However, with the advent of the third category, it is now most preferred. In this category additives are added to meet the requirement of manufacturing, operational requirements and to improve physical properties. It contains heterogeneous mixture of solid fuel and oxidizer held together in a matrix like binder. Polybutadiene is the most effective binder which improves the physical properties. In this mixture when solid ammonium perchlorate (AP) and aluminum (Al) are added the density of the mixture is increased resulting in improvement of specific impulse. Presently composite propellant is cast from a mixture of AP crystals, Al powder and liquid HTBP (Hydroxyl terminated Polybutadiene). It is called CMDB (Composite Modified Double Base) propellant. Pressure time curve for burning of CMDB propellant obtained during static trial in Ballistic Evaluation Motor establishes that propellant grain with star shape internal and cylindrical outer cross section maintains constant pressure over the entire burning time. This is because such cross section provides constant (neutral) burning and leaves negligible sliver at the end. This paper brings out recent advances in solid fuel and analyses suitability of CMDB propellant to fulfill the requirement for use in MBRL. From the analysis of Pressure-Time plot of the subject propellant it is found to be most suitable as solid rocket propellant for MBRL.**

Keywords- Multi Barrel Rocket Launcher, Single & double base propellant, Composite modified double base propellant, Nitrocellulose, Nitroglycerine, Pressure – Time plot.

I. Introduction

Truck mounted multi barrel rocket launcher (MBRL) is an area weapons which is capable of launching free flight rockets (FFR) at the target from a distance of 30 – 40 km. A FFR as the name implies, has all its guidance given to it by the launcher, which is trained on to the target like a conventional artillery gun. So MBRL provides a means for delivering lethal fire power in short time, at long range, and from comparatively light equipment. It also has the capability to deliver nuclear war head [1]. Despite their logistical penalties and the ease with which they can be detected due to generation of heavy smoke at the launch end, MBRLs are favoured by Western armies in place of heavy guns [2]. Propellant is required as fuel to propel the rocket. FFR motors use solid propellants as it possess well defined, reproducible, and near constant rate of burning, non hygroscopicity, ability to be worked into grain of widely varying sizes, shapes and burning times. It has adequate mechanical and physical properties to allow it to be cycled through extremes of temperature without cracking and have sufficient strength to prevent sagging at higher temperatures, or imbrittlement at low temperatures [3]. It is also quite safe and does not pose safety hazards. Also with solid propellant, various associated mechanisms are simple and thus use by the troops in field condition is comparatively easy. After manufacture by ordnance factories a rocket is required to be stored in depots/units for many years and solid rocket is suitable as it provides high shelf life. The major problems here is mid course thrust control as burning rate of propellant cannot be altered unlike its liquid counterpart; the other problem being low specific impulse [4]. However, in futuristic missile system three approaches are being considered. These are use pulsed and pintle motors and gel propellant. Gel propellants have not yet been accepted for tactical missile applications due to concerns of toxicity [5]. However, for rocket launcher application, burning rate is not required to be altered as the change of thrust is dispensed with due to its maximum range less than 50 km and time of flight few minutes. Solid propulsion offers cost effective, large thrust capabilities, but operating times limited to 2 min. Liquid propulsion offers high specific impulse and restart capabilities [6]. The specific impulses of solid propulsion systems are 20% and 80% lower than that of liquid and cryopropulsion systems, respectively. However, liquid and cryo systems, having to employ relatively larger number of flow control components, are more complex and expensive than the solid propulsion system [7]. So the former if suitable for MBRLs where as the later is for long range missiles. A solid propellant charge, called grain, contains all the chemical elements for complete burning. Once ignited, it usually burns smoothly at a predetermined rate on all the exposed surfaces of the grain [8]. Based on the thrust requirement the grain is designed as progressive, regressive or neutral burning. For rocket launcher application the requirement is of constant thrust which is met by neutral burning surface. The desired surface is given during manufacture which is either by casting or extrusion.

This paper brings out recent advances in solid fuel and analyses suitability of CMDB propellant to fulfill the requirement for use in MBRL. It also brings out the further scope of work to design and develop an advanced solid propellant for similar application.

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II. ADVANCES IN SOLID FUELS

In the class of solid fuels composite propellant is preferred [9] over homogeneous propellants (Nitrocellulose (NC) and Nitroglycerine (NG) based propellants). It presents the main advantage of low vulnerability and high specific impulse. Moreover, properties of composite propellant may be tailor made by changing the compositions and compound rate. It is composed of one binder (typically, Polybutadiene or glycidyle azide polymer), one oxidizer (typically NH_4ClO_4) and one fuel (Al, Zr or Mg). The metallic particles remain after combustion may cause damage to the nozzle if flight duration is considerable. However, in case of rockets of MBRL, to reach the target at a maximum distance of 40 km the time of flight is only few min. Small duration of burning and expelling of burning gases quickly does not provide adequate time to cause damage to the nozzle. Another disadvantage of composite propellant is its low specific heat value. This problem is resolved by mixing NC and NG (both have high specific heat) making it Composite Modified Double Base (CMDB) propellant.

Composite rocket propellants have acquired greater significance [10] because of advantage of wide range of mechanical properties and superior strain capability compared to conventional propellants in addition to higher delivered I_{sp}. RDX and HMX are also explored as component of both the classes of propellants for realizing smokeless exhaust [11]. Addition of combination of AP and nitramine improves the I_{sp} marginally. Attempts towards realization of the superior performance level are directed towards replacement of hydroxy-terminated polybutadine (HTPB) binder by energetic polymer systems comprising of GAP and BAMO copolymers as polymer matrix in combination with TMETN/TEGDN/ BTTN/BDNPF/A as plasticizers[12-13].

Although materials like CL-20, FOX-7 was synthesized as an explosive of interest. It has also been evaluated as a component of propellants. Floreszek [14-15] has reported the effect of replacement of AP by FOX-7 in slurry cast composition. They determined burning rate of the propellant in sub scale rocket motor and observed marginal decrease in it on replacement of AP by FOX-7. It is predicted that a combination of HNF / ADN with energetic binders like GAP, BAMO, NIMMO can offer I_{sp} of the order of 300 s. However, such claim need to validated [16,17] in a practically useful propellant.

Aluminized propellants are [18] are frequently used in solid rocket motors to increase specific impulse. Unlike the other ingredients, aluminum particles can burn in a significant portion of the chamber and produce a condensed phase that is carried out into the flowfield. Thereby, aluminum particles can affect appreciably combustion instabilities by acting as driving or, on the contrary, as damping mechanisms.

Solid rocket composite propellant with AP oxidizer emits plumes containing HCl. The acid reduction is done by adding neutralizer during manufacturing stage. The extent of acid reduction [19] by the magnesium neutralized propellants is in the range of 1-10 %, while sodium nitrate scavenged propellants (HTPB/$NaNO_3$/AP/Al) have the potential of reducing it by about 1 - 3 %.

III. GRAIN GEOMETRY

Design of a solid propellant grain is governed by ballistic, processing, and structural integrity requirements. Pressure-time, thrust-time, acceleration, velocity, and trajectory are decided by propellant configuration, and are largely a geometric consideration [20]. Pressure developed by the burning of propellant depends upon along with other parameters geometry of the grain. It includes shape and size of the cross section, web and surface area dimensions. Mass burnt is proportional to exposed surface area which in turn responsible to the pressure developed by its burning. Relation between web and mass burnt is established by form function relation; relation between web and surface area is established by surface area relation.

Let a propellant grain (Figure 1) is set to burn and after time t, and the given data we consider, fraction of mass burnt Z and fraction of remaining web f. Initially Z = 0 and f = 1, therefore

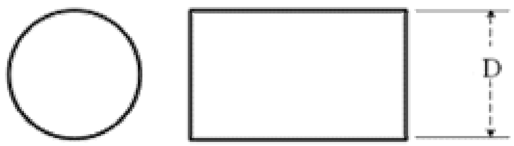

Figure 1. Cylindrical Grain

$Z = (1 - f)(1 + \theta_1 f + \theta_2 f^2 + \dots \quad \dots \quad \dots)$

As t increases, f decreases and the equation becomes

$$Z = (1 - f)(1 + \theta f) \text{ for } \theta_1 = \theta \qquad (1)$$

θ is called form factor and depends upon shape and size of the grain. Equation (1) is the form function relation.

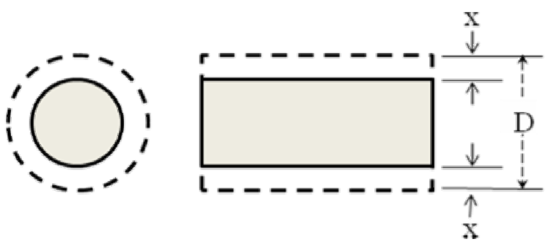

Figure 2. Burnt Grain at Time t

Considering the cylindrical grain (Figure 1) of web D initially, which becomes D – 2x at time t due to burning (Figure 2). It has initial volume and surface area as V_0 and S_0 respectively.

By definition,

$f = (D - 2x)/D$; which gives $2x = D(1 - f)$ and

$$dx = -\tfrac{1}{2} D\, df \qquad (2)$$

$Z = \frac{\int_0^x \rho S dx}{\rho V_0}$, which gives $dZ = \frac{S dx}{V_0}$; and putting the values of dx from equation (1) we get,

$$\frac{dZ}{df} = -\frac{DS}{2V_0}$$

For initial condition, $\left(\frac{dZ}{df}\right)_{initial} = -\frac{DS_0}{2V_0}$, so the surface area ratio becomes

$$\frac{S}{S_0} = \frac{\frac{dZ}{df}}{\left[\frac{dZ}{df}\right]_{initial}} \qquad (3)$$

From equation (1) we get, $\frac{dZ}{df} = -(1 - \theta + 2\theta f)$ and

$\left(\frac{dZ}{df}\right)_{initial} = -(1 + \theta)$,

Thus, $\frac{S}{S_0} = \frac{1-\theta+2\theta f}{1+\theta}$; which becomes [21],

$$\frac{S}{S_0} = \left(1 - \frac{4\theta Z}{(1+\theta)^2}\right)^{1/2} \qquad (4)$$

If θ is negative, $S/S_0 > 1$, so it is progressive burning because the surface area increases as the burning progresses. This is suitable for booster rocket in space application. If $\theta = 0$, $S/S_0 = 1$, and the surface area remains constant as the burning progresses, known as neutral burning. So the burning rate remains constant and thus suitable for MBRL as well as sustainer rocket in space application.

If θ is positive, $S/S_0 < 1$, so the surface area decreases as the burning progresses. It is called regressive propellant and suitable for artillery gun ammunition.

To extract the maximum chemical energy of a propellant in terms of heat, its complete combustion needs to be ensured. By suitably modifying the grain design 99% decomposition of propellant into gas can be achieved. One of the method is to design neutral burning surface having internal cross section of the grain such that negligible sliver is left after burning of the propellant. This can be achieves by designing propellant with cylindrical outer surface and star shape cross section running along the length of the grain. Sliver in this case is 4 – 10% of the total propellant and increases as the main burning surface area variation is made more neutral.

Shelf life [22] of solid propellant is predicted by measuring the variation of Poisson's ratio during storage and it is also treated as one of the measurable controlling degradation parameters for solid propellants. An HTBP composite propellant behaves as compressible material in most of the regions [23] and near-failure region or at higher strains; Poisson's ratio is near 0.25. Miloš Predrag [24] suggested a specific methodology for optimization of star shape propellant grains in the sense of minimizing stress and strain without compromising the required internal ballistic performances. The design of solid propellant grain that provides neutral burning is important to optimize rocket motor performance.

The star configuration has been widely used to achieve this goal.

IV. BURNING RATE

Solid propellant decomposes only on the surface [25] and the decomposition is normal to the burning surface. Composite propellants exhibits a burning rate (r) which normally only depends on the combustion pressure (p). This is expressed by Vieille's law. This is an empirical relation [26] and expressed as $r = a\,p^n$, where the exponent n is called the pressure index and depends upon the chemical composition of the propellant. For composite propellant it varies between 0.4 – 0.5. If $n = 1$, $r \infty p$; so r becomes very pressure sensitive and thus not desirable in rocket propellant. If $n = 0$, r becomes independent of pressure and it is convenient in design of solid rocket propellant. Experimentally it is established that [27] for a multi-perforated solid propellant n is 0.32 for pressure range from 50 kg/cm^2 to 250 kg/cm^2. The constant 'a' is the burning rate coefficient and depends upon initial temperature of propellant. At ambient temperature its value is close to 0.15.

V. MATHEMATICAL MODELING

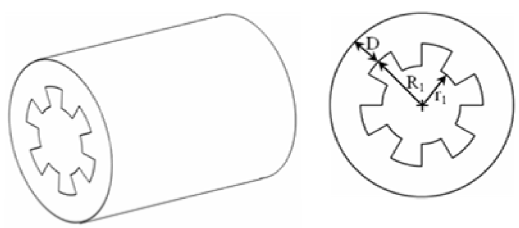

Figure 3. Star Shape Grain

The following are chosen or solved simultaneously. The results are exact dimensions for grain, nozzle and case geometries [28];

- The grain burns at a predictable rate, given its surface area and chamber pressure.
- The chamber pressure is determined by the nozzle orifice diameter and grain burn rate.
- Allowable chamber pressure is a function of casing design.
- The length of burn time is determined by the grain 'web thickness'.

The burning process of star shaped grain (Figure 3) having web D, internal and external radii of star as r_1 and R_1 respectively is considered to be obeying Piobert's law of burning. The law conforms burning of propellant layer by layer (Figure 4). It is like decaying of soap cake due to use. Hera, layer of depth x has been shown burnt in time t. However, in this grain a small amount of sliver is observed (Figure 5). But it is less than 0.6% of the total surface area. Hence the same has been neglected in mathematical modeling.

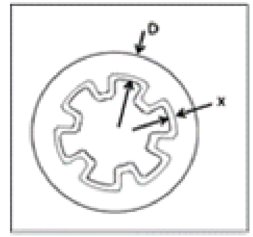

Figure 4. Layer by Layer Burning

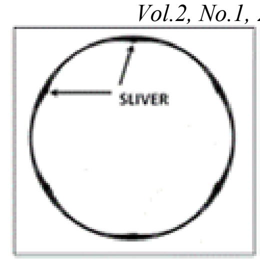

Figure 5. Sliver

As the burning progresses the grain geometry changes drastically. Hence mathematical modeling is considered in following phases [29] :

Phase I It is the starting point (Figure 6) when surface of adjoining 'Petals' merge to each other.

Phase II It is the end of Phase I where surface 1 disappears altogether (Figure 7).

Phase III Here the surfaces (radius of the petals) get fully consumed (Figure 8) leaving very small amount of sliver.

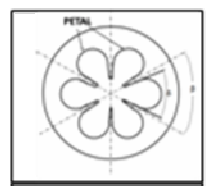

Figure 6. Phase I

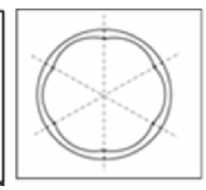

Figure 7. Phase II

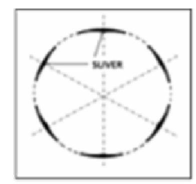

Figure 8. Phase III

A. Modeling for Determination of Changeover Points

1) Modeling of Changeover Points in Phase I

In this phase the change over point from Phase I to Phase II is determined. The geometry of Phase I is shown in Figure 9 which is intersection of common surface with outer radius of the petals. Hence it is intersection of straight line with a circle.

Let us consider the following parameters.

x = Web burnt

δ = Included angle of the slot

β = Included angle of one star = $2\pi / n$

n = No of petals

$\gamma = \frac{1}{2}(\beta - \delta)$

c = Intercept of line L1 on vertical axis = $x/\sin\gamma$

Equation of circle, $X^2 + Y^2 = (r_1 + x)^2$

Intersection of circle with line at Y = - Y,

therefore, $2Y^2 = (r_1 + x)^2$ and $Y = \quad (r_1 + x)^2$

Equation of straight line, $Y = m X + c$

For $Y = - x$, $- x = m x + c$

$c = - (1 + m)\, x$ or $x = - c / (1 + m)$

So, $X_1 = - c / (1 + m)$

Again, $X^2 + Y^2 = (r_1 + x)^2$

Intersection of circle with line Y = - X, therefore

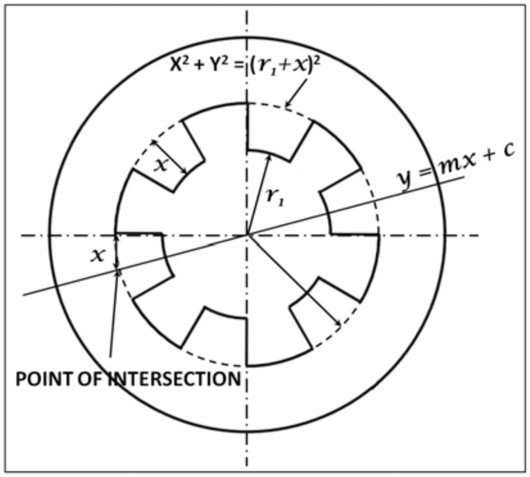

Figure 9. Intersection of line and cicle

$2X^2 = (r_1 + x)^2$, which becomes $X = (r_1 + x)^2$

So, $X_2 = (r_1 + x)^2$

If $X_2 > X_1$, It is change over point for Phase I.

2) Modeling of Changeover Points in Phase II

In this phase, we need to find out the point where two adjoining star petals i.e. circles C1 and C2 become tangent to each other (Figure 10). This is done by following steps :

- Establish P1 which is intersection of C1 with line L1
- If P1 lies on C2, then it is the point of tangency with C2

Then, $c = x / \sin\gamma$, $X_1 = - c / (1 + m)$ and $Y_1 = - X_1$

Difference = $(X_1 – X_{cen})^2 + (Y_1 – Y_{cen})^2$

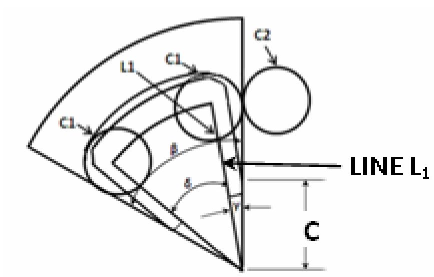

Figure 10. Geometry of Change Over Point Phase II

3) Modeling of Changeover Points in Phase III

This phase ends when R1 + x > Rmax

B. Modeling for Determination of Changeover Points

1) Modeling of Burning Surface Area Phase I

Total burning surface area (Figure 11) can be determined by calculating the total arc length. Here, total burning surface area is equals to total arc length multiplied by length of the grain.

The total arc length = Arc1 + Arc2 + Arc3 + Arc4

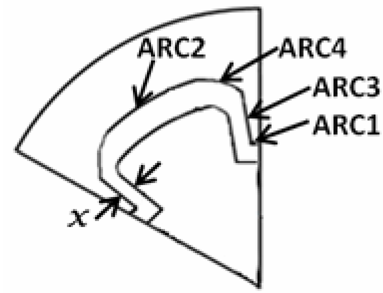

Figure 11. Geometry of Burning Surface Area Phase I

Each arc is determined as under :

Arc 1 = $(r_1 + x)(\beta – \delta) – 2x$

Arc 2 = $(R_1 + x)\delta$

Arc 3 = $2[(R_1 + x) – (r_1 + x)]$

Arc 4 = $2(½ \pi x) = \pi x$

2) Modeling of Burning Surface Area Phase II

Total arc length in Phase II as shown in Figure 12 can be calculated as under :

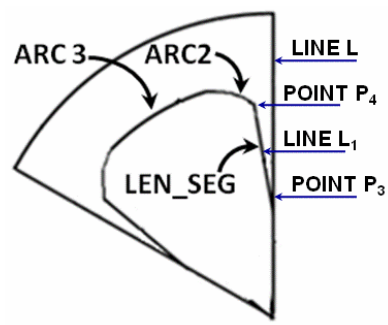

Figure 12. Geometry of Burning Surface Area Phase II

Total Arc length = 2(length of segment) + 2(Arc 2) + Arc 3

Length of segment = $(P_{3x} – P_{4x})^2 + (P_{3y} – P_{4y})^2$, where P_3 and P_4 are unknown.

For P_3, intersection point of L1 and L are known. Also $c = x / \sin\gamma$, $x = – c / (1 + m)$, $m = – \tan [½(\beta + \delta)]$ and $Y = – x$

So, P_{3x} and P_{3y} are thus have known value now.

For P_4 the following relations are used :

$X_4 = X_{cen} + (x \cos\gamma)$ and $Y_4 = Y_{cen} + (x \sin\gamma)$

X_{cen} and Y_{cen} are known factor,

also x is instantaneous web burnt.

So, P_{4x} and P_{4y} are thus have known value now.

Length of segment can be found out as :

Arc 2 = $2(½ \pi x) = \pi x$ and Arc 3 = $(R_1 + x)(\beta – \delta)$

3) Modeling of Burning Surface Area Phase III

Total arc length in Phase III as shown in Figure 13 can be calculated , Total Arc length = Arc 1 + 2(Arc 2)

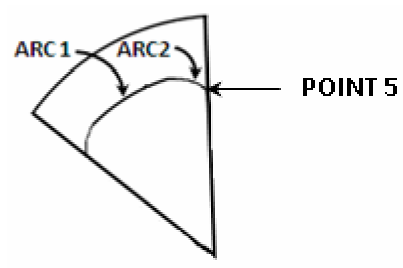

Figure 13. Geometry of Burning Surface Area Phase III

Here, Arc 1 = $(R_1 + x)(\pi\, 25/180)$ and
Arc 2 = $x\, \alpha\, (\pi\, \phi/180)$
Where $\cos \alpha = a^2 + c^2 - b^2/2ac$
(a and b being the coordinates of point 5) and
$\cos \phi = (2X^2 - P_1 P_2^2)/2X^2$

VI. PRESSURE-TIME PREDICTION

A CMDB propellant with HTBP binder has been considered for prediction of pressure with respect to time for its suitability to propel the rockets of MBRL above 200 mm calibre. Compositions and properties of the propellant are as under :

(a) Composition

(i)	AP	66 ± 1%
(ii)	Al	19 ± 1%
(iii)	Fe_2O_3	2 ± 1%
(iv)	HTPB	13 ± 1%

(b) Physical Properties

(i)	Tensile Strength	> 10 kg/cm^2
(ii)	% Elongation	>10
(iii)	Density	> 1.76 gm/cc

(c) Thermal Properties

(i)	Calorific Value	1500 kcal/gm
(ii)	Burning Rate at 27^0 C	10 ± 0.3 mm/sec

VII. PRESSURE-TIME PREDICTION

The aim is to select a shape for CMDB propellant which would maintain constant pressure over the entire burning time. This is achieved with the propellant having star shaped cross section as provides constant (neutral) burning. Another favorable factor of selecting the grain of star cross section is that it leaves negligible sliver at the end of burning and complete propellant energy is evolved. Moreover no leftover propellant means no erosion of nozzle due to clean exhaust. Given below (Figure 14) the plot of pressure time curve for burning of CMDB propellant obtained during static trial in BEM. The burning of the propellant has been considered to be layer by layer and thus follows Piobert's Law.

It can be seen that the pressure is constant initially due to pure neutral burning, after that it dips a bit and some instability is noticed during transient phase. It is then linearly increased due to progressive burning up to 4 sec during equilibrium phase. Beyond 4 sec is the tail off phase where the pressure drops sharply and the drop of pressure is due to the burning of sliver as left over propellant. So it provides close to constant pressure up to initial 88% of burning time. During this period constant thrust is produced by the rocket motor.

The burning surface area is not the only controlling factor to affect the pressure-time relation. Nozzle erosion or deposition, faulty ignition, erosive and unstable burning, defects in the grain like voids and cracks; damage due to improper handling etc. also affects the pressure time relation. Total impulse of the propellant can be calculated from the total area under the curve multiplied by the scale factor.

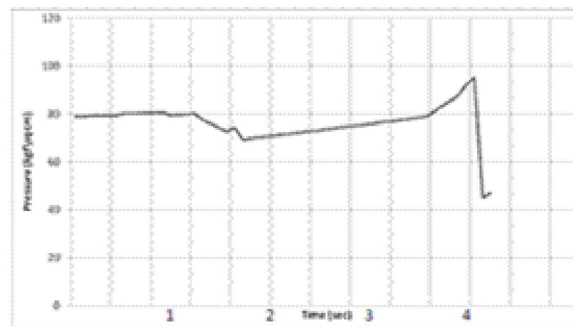

Figure 14. Predicted Pressure – Time Plot for Burning of CMDB Star Shape Propellant

VI. CONCLUSION

So important is the choice of fuel for getting maximum I_{sp} that this dominated work on rocket for very long time [30]. It is seen that solid propellant provides the ease to design, manufacture, handling, packaging, transportability and deployability. It also has capability prolonged storage without noticeable degradation of its physical and chemical properties. It is also quite safe and does not pose safety hazards. It can also able to withstand adverse weather condition and variable climatic condition. Also triggering mechanism associated with solid propellant is comparatively simple and thus easy to use by the troops in battle field scenario.

Pressure time relation of star shaped solid propellant establishes the development of almost constant thrust up to initial 88% of the burning time. Tactically this suits the requirement of very fast response time by generating high thrust for small duration. All the inherent capabilities of solid propellant discussed in the paper fulfill military requirements and make it a preferred propellant for rockets used in MBRL.

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