INTERNAL BALLISTICS OF A H/L GUN

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1. Introduction

Corner (1948, 1950) worked out a simple theory of the Internal Ballistics of the high-low pressure gun for a tubular propellant ($\theta = 0$). His theory was recently extended to a propellant with its form-function in the standard form

$$z = (1-f)(1+\theta f)$$

by Aggarwal (1955). In both these papers, the expression for the maximum pressure in the first chamber has not been explicitly obtained. For a tubular propellant (Corner, 1950) the maximum pressure occurs at all-burnt, but for propellant of any general shape, this is not necessarily true. As a matter of fact, it is shown here that for cord charge the maximum pressure in the first chamber must necessarily occur before all-burnt, and that for moderate densities of loading, this will occur when about three-fourths of the ballistic size of the propellant has been burnt through. In such a case it is important to know how near the maximum pressure is to the pressure at the all-burnt position.

Aggarwal (1955) has also discussed the Internal Ballistics for the second chamber of the H/L gun and has obtained the fundamental differential equation for this chamber. The further discussion is based on the solution of this differential equation and he has given a series solution of this equation on the same lines on which Corner gave the series solution for his equation for the particular case $\theta = 0$. But unlike Corner's variable, the dependent variable X and the constant ν occurring in the fundamental differential equation of Aggarwal are not dimensionless. As a matter of fact both have the dimensions of a volume (L^3). The convergence of the series solution obtained by him for X cannot, therefore, be discussed. Also the statement that $\nu < 0{\cdot}3$ for a H/L gun, while valid for Corner's dimensionless constant ν, is meaningless for a constant of which the value depends on the units used. Further, since our fundamental differential equation contains only dimensionless variables, we are able to discuss the convergence of the series solution more effectively.

2. Maximum Pressure in the First Chamber

In Corner's notation, the fundamental equations are:

$$P\left[K - \frac{C(1-z)}{\delta} - CNb\right] = CN\lambda \quad \ldots \quad (1)$$

$$p[K_0 + Ax - C(z-N)b] = C(z-N)\lambda \quad \ldots \quad (2)$$

$$W_1 v\frac{dv}{dx} = W_1\frac{dv}{dt} = Ap \quad \ldots \quad (3)$$

$$D\frac{df}{dt} = -\beta p \quad \ldots \quad (4)$$

$$\frac{dN}{dt} = \frac{dz}{dt} - \frac{\psi SP}{C\sqrt{\lambda}} \quad \ldots \quad (5)$$

$$z = \phi(f) \quad \ldots \quad (6)$$

Only our equation (6) differs from those of Corner and Aggarwal. Instead of (6) Corner uses

$$z = 1-f \quad \ldots \quad (7a)$$

and Aggarwal uses

$$z = (1-f)(1+\theta f) \quad \ldots \quad (7b)$$

From (4), (5) and (6)

$$\frac{dN}{dt} = \frac{dz}{dt} + \Psi\frac{df}{dt} \quad \ldots \quad (8)$$

where

$$\Psi = \frac{\psi S}{C\sqrt{\lambda}}\frac{D}{\beta} \quad \ldots \quad (9)$$

is the dimensionless leakage parameter.

Integrating (8), we get

$$N = z-\Psi(1-f), \quad \ldots \quad (10)$$

since initially $t = 0, f = 1, z = 0, N = 0$.

Now from (1) and (6)

$$P = \frac{C\lambda N}{K-\frac{C}{\delta}+\frac{C}{\delta}\phi(f)-CNb} \quad \ldots \quad (11)$$

Differentiating and using (8), we get

$$\left[K-\frac{C}{\delta}+\frac{Cz}{\delta}-CNb\right]^2\frac{1}{C\lambda}\frac{dP}{dt} = \left[K-\frac{C}{\delta}+\frac{C}{\delta}\phi(f)\right]\left[\phi'(f)\frac{df}{dt}+\Psi\frac{df}{dt}\right]$$

$$-\phi'(f)\frac{df}{dt}\frac{C}{\delta}[\phi(f)-\Psi(1-f)] \quad \ldots \quad (12)$$

Using (10) and simplifying we get

$$\left[K-\frac{C}{\delta}+\frac{C}{\delta}\phi(f)-bC[\phi(f)-\Psi(1-f)]\right]^2\frac{1}{\lambda C}\frac{dP}{dt} = \phi'(f)\left[K-\frac{C}{\delta}+\frac{C}{\delta}\Psi(1-f)\right]$$

$$+\Psi\left[K-\frac{C}{\delta}+\frac{C}{\delta}\phi(f)\right] \quad \ldots \quad (13)$$

Initially when $f = 1, z = 0, N = 0$, (13) gives

$$\left[K-\frac{C}{\delta}\right]^2\frac{1}{\lambda C}\left[\frac{dP}{dt}\right]_{f=1} = \left[K-\frac{C}{\delta}\right][\phi'(1)+\Psi] \quad \ldots \quad (14)$$

Finally when $f = 0, z = 1, N = 1-\Psi$

$$[K-bC(1-\Psi)]^2\frac{1}{\lambda C}\left(\frac{dp}{df}\right)_{f=0} = \phi'(o)\left[K-\frac{C}{\delta}+\frac{C\Psi}{\delta}\right]+K\Psi \quad \ldots \quad (15)$$

Since z is a decreasing function of f, $\phi'(f)$ is always negative. As initially the pressure increases, $\frac{dP}{df}$ is negative.

The maximum pressure would occur at all-burnt if $\frac{dP}{df}$ is negative or zero at all-burnt, i.e. if

$$\phi'(o)\left[K-\frac{C}{\delta}+\frac{C\Psi}{\delta}\right]+K\Psi \leqq o, \qquad \ldots \quad (16a)$$

and would occur before all-burnt if

$$\phi'(o)\left[K-\frac{C}{\delta}+\frac{C\Psi}{\delta}\right]+K\Psi > o \qquad \ldots \quad (16b)$$

For the propellant of which the form-function is given by

$$z=\phi(f)=(1-f)(1+\theta f), \qquad \ldots \quad (17)$$

(14) and (15) give respectively

$$\left[K-\frac{C}{\delta}\right]^2\frac{1}{\lambda C}\left(\frac{dp}{df}\right)_{f=1}=\left[K-\frac{C}{\delta}\right][-1-\theta+\Psi] \qquad \ldots \quad (18)$$

and

$$[K-bC(1-\Psi)]^2\frac{1}{\lambda C}\left(\frac{dp}{df}\right)_{f=0}=(-1+\theta)\left(K-\frac{C}{\delta}+\frac{C\Psi}{\delta}\right)+K\Psi \qquad \ldots \quad (19)$$

As $K>\frac{C}{\delta}$ and Ψ is of the order of ·5, $\frac{dP}{df}$ is initially negative, as we expect. As for (16a) and (16b) above, we find that maximum pressure will occur at all-burnt if

$$\theta \leqslant \frac{\left(K-\frac{C}{\delta}\right)(1-\Psi)}{K-\frac{C}{\delta}+\frac{C}{\delta}\Psi} \qquad \ldots \quad (20)$$

and will occur before all-burnt if

$$\theta > \frac{\left(K-\frac{C}{\delta}\right)(1-\Psi)}{K-\frac{C}{\delta}+\frac{C}{\delta}\Psi} \qquad \ldots \quad (21)$$

i.e. if

$$\theta > 1-\frac{\frac{C}{\delta}}{K-\frac{C}{\delta}+\frac{C}{\delta}\Psi} \qquad \ldots \quad (21a)$$

When θ is negative or zero, (20) is definitely satisfied. *Thus for progressive-burning and constant-burning surfaces, the maximum pressure in the first chamber occurs at all-burnt.*

For $\theta=1$, (21a) is definitely satisfied and *thus for cord charges, the maximum pressure in the first chamber must occur before all-burnt.*

This result, it may be noted, is consistent with the corresponding result for the orthodox gun, for there the condition for the maximum pressure to occur before all-burnt is

$$\gamma M > \frac{1-\theta}{f_0}, \qquad (22)$$

and this is certainly satisfied for $\theta = 1$.

When (21) is satisfied, the maximum pressure occurs when $\frac{dP}{df}$ vanishes, i.e. from (13) and (17), when

$$\chi(f) = \frac{\theta C\Psi}{\delta} f^2 - 2\theta f\left[K-\frac{C}{\delta}+\frac{C}{\delta}\Psi\right] + \theta\left[K-\frac{C}{\delta}+\frac{C}{\delta}\Psi\right]-\left[K-\frac{C}{\delta}\right][1-\Psi] = 0 \qquad (23)$$

The signs of $\chi(f)$ are given by

f	$-\infty$	0	$\cdot 1$	∞
$\chi(f)$	$+\infty$	$+$	$-$	$+\infty$

The root between 0 and 1 determines f_m, the value of f at which pressure is maximum. Then from (1)

$$P_{\text{max.}} = \frac{C\lambda[(1-f_m)(1+\theta f_m)-\Psi(1-f_m)]}{K-\frac{C}{\delta}-C\left(b-\frac{1}{\delta}\right)(1-f_m)(1+\theta f_m)+Cb\Psi(1-f_m)} \qquad (24)$$

When (20) is satisfied, the maximum pressure is the pressure at all-burnt, so that

$$P_{\text{max.}} = \frac{C\lambda[1-\Psi]}{K-Cb[1-\Psi]} \qquad (25)$$

For the particular case of a cord charge, (23) becomes

$$\frac{C\Psi}{\delta} f^2 - 2f\left[K-\frac{C}{\delta}+\frac{C}{\delta}\Psi\right]+K\Psi = 0$$

or if

$$\rho = \frac{\frac{C}{\delta}}{K-\frac{C}{\delta}}, \qquad (26)$$

$$\rho\Psi f^2 - 2f(1+\rho\Psi)+(1+\rho)\Psi = 0 \qquad (27)$$

Now Ψ, for most practical cases, is of the order of $\cdot 5$.

Putting $\Psi = \cdot 5$ in (26)

$$\rho f^2 - 2f(\rho+2)+(1+\rho) = 0$$

so that

$$f = \frac{(\rho+2)\pm\sqrt{3\rho+4}}{\rho} \qquad (28)$$

Now if the density of loading is not high, ρ is comparatively a small number and since $0 < f < 1$, we have to take the negative sign in (28), so that

$$f_m = \frac{1}{4} + \frac{9}{64}\rho - \frac{27}{512}\rho^2 + \ldots\ldots$$

For ρ small, f_m is of order $\frac{1}{4}$, for moderate densities of loading. *Thus for a cord charge, the maximum pressure occurs when about three-fourths of the ballistic size has been burnt through.*

It is obvious from (23) that as

$$\theta \rightarrow \frac{K - \frac{C}{\delta} + \frac{C}{\delta}\Psi}{\left(K - \frac{C}{\delta}\right)(1-\Psi)},$$

$$f_m \rightarrow 0 \qquad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (29)$$

Again when (21) is satisfied, the ratio of maximum pressure to pressure at all-burnt is given by

$$\frac{P_{\max}}{P_B} = \frac{z_m - \Psi(1-f_m)}{1-\Psi} \cdot \frac{K - bC[1-\Psi]}{K - \frac{C}{\delta} + \frac{C}{\delta} z_m - bC[z_m - \Psi(1-f_m)]} \quad \ldots \quad \ldots \quad (30)$$

For $\theta = 1$, $\Psi = \frac{1}{2}$, $K = 800$ cubic inches, $C = 10$ lbs., $b = 25$ cubic inches/lb.

$\frac{1}{\delta} = 17{\cdot}5$ cub. inches/lb.

(30) gives approximately

$$\frac{P_{\max}}{P_B} = \frac{9}{8}.$$

Thus in this case, the maximum pressure is about 12% greater than the pressure at all-burnt.

3. Fundamental Differential Equation for the Second Chamber

From (1), (4), (6) and (8)

$$-\frac{D}{\beta}\frac{df}{dt} = \frac{C\lambda[\phi(f) - \Psi(1-f)]}{K - \frac{C}{\delta} - C\left(b - \frac{1}{\delta}\right)\phi(f) + Cb\Psi(1-f)} \quad \ldots \quad \ldots \quad (31)$$

Let us take

$$\phi(f) = A + B(1-f) - E(1-f)^2 \quad \ldots \quad \ldots \quad \ldots \quad (32)$$

This form-function reduces to Corner's case when

$$A = 0, \quad B = 1, \quad E = 0 \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (33)$$

and to Aggarwal's case when

$$A = 0, \quad B = (1+\theta), \quad E = \theta \quad \ldots \quad \ldots \quad \ldots \quad (34)$$

Also let

$$Z = 1 - f \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (35a)$$

so that

$$\phi(f) = A + BZ - EZ^2, \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (35b)$$

then (31) gives

$$\frac{\left[K-\frac{C}{\delta}-C\left(b-\frac{1}{\delta}\right)A\right]+\left[\frac{C\Psi}{\delta}-C\left(b-\frac{1}{\delta}\right)(B-\Psi)\right]Z+C\left(b-\frac{1}{\delta}\right)EZ^2}{A+[B-\Psi]Z-EZ^2}\,dZ \quad (36)$$

$$=\frac{\beta}{D}C\lambda\,dt$$

or

$$\frac{dZ}{dt}=\mu\frac{P+Z-QZ^2}{1+GZ-HZ^2} \quad \ldots \quad (37)$$

where

$$\mu=\frac{\beta C\lambda}{D}\,\frac{B-\Psi}{K-\frac{C}{\delta}-C\left(b-\frac{1}{\delta}\right)A} \quad \ldots \quad (38a)$$

$$P=\frac{A}{B-\Psi} \quad \ldots \quad (38b)$$

$$Q=\frac{E}{B-\Psi} \quad \ldots \quad (38c)$$

$$G=\frac{\frac{C\Psi}{\delta}-C\left(b-\frac{1}{\delta}\right)(B-\Psi)}{K-\frac{C}{\delta}-C\left(b-\frac{1}{\delta}\right)A} \quad \ldots \quad (38d)$$

$$H=\frac{C\left(b-\frac{1}{\delta}\right)E}{K-\frac{C}{\delta}-C\left(b-\frac{1}{\delta}\right)A} \quad \ldots \quad (38e)$$

From (36)

$$\left[-C\left(b-\frac{1}{\delta}\right)+\frac{c}{a-Z}+\frac{d}{b+Z}\right]dZ=\frac{\beta C\lambda}{D}\,dt \quad \ldots \quad (39)$$

where

$$Eab=A \quad \ldots \quad (40a)$$

$$E(a-b)=B-\Psi \quad \ldots \quad (40b)$$

$$E(cb+ad)=K-\frac{C}{\delta} \quad \ldots \quad (40c)$$

$$-E(c-d)=\frac{C\Psi}{\delta} \quad \ldots \quad (40d)$$

Integrating (39), we get

$$-C\left(b-\frac{1}{\delta}\right)Z-c\log\frac{a-Z}{a}+d\log\frac{b+Z}{b}=\frac{BC\lambda}{D}t. \quad \ldots \quad (41)$$

(41) gives an explicit relation between f and t valid throughout the period of burning.

From (2), (3) and (10)

$$W_1 \frac{d^2x}{dt^2} = \frac{AC\lambda\Psi Z}{K_0+Ax-bC\Psi Z} \quad \ldots \quad (42)$$

We have now two alternative methods available:

(i) From (41), we can tabulate t as a function of Z. This table can be interpreted as giving Z as a tabulated function of t. From (42), we can then integrate for x and v as functions of t, subject to initial conditions $t = 0$, $v = 0$, $x = 0$ .. (43)

(ii) From (37) and (42), we can eliminate t to get a differential equation between x and Z. Thus from (42)

$$W_1 \frac{dZ}{dt}\frac{d}{dZ}\left[\frac{dx}{dZ}\frac{dZ}{dt}\right] = \frac{AC\lambda\Psi Z}{K_0+Ax-bC\Psi Z}$$

or

$$W_1\mu^2\left[\frac{P+Z-QZ^2}{1+GZ+HZ^2}\right]\frac{d}{dZ}\left[\frac{P+Z-QZ^2}{1+GZ+HZ^2}\right] = \frac{AC\lambda\Psi Z}{K_0+Ax-Cb\Psi Z} \quad \ldots \quad (43)$$

Now let

$$X = (K_0+Ax)\,\frac{\mu}{A}\left(\frac{W_1}{C\lambda\Psi}\right)^{\frac{1}{2}} \quad \ldots \quad (44)$$

then we get

$$\frac{d}{dZ}\left[\frac{P+Z-QZ^2}{1+GZ+HZ^2}\frac{dX}{dZ}\right] = \frac{Z}{X-\nu Z}\,\frac{1+GZ+HZ^2}{P+Z-QZ^2}, \quad \ldots \quad (45)$$

where

$$\nu = \frac{b\mu}{A}\left(\frac{W_1 C\Psi}{\lambda}\right)^{\frac{1}{2}} \quad \ldots \quad (46)$$

It is easily verified that X, Z, P, Q, G, H, ν are all dimensionless. The initial conditions for the integration of (45) are

$$\frac{ZdX}{dZ} = 0,\ X = X_0 = K_0\frac{\mu}{A}\left(\frac{W_1}{C\lambda\Psi}\right)^{\frac{1}{2}},\ Z = 0. \quad \ldots \quad (47)$$

For a tubular charge, using (33), (35) and (38)

$$\left.\begin{aligned} \mu &= \frac{\beta C\lambda}{D}\,\frac{1-\Psi}{K-\frac{C}{\delta}},\ P = 0,\ Q = 0 \\ G &= \frac{\frac{C\Psi}{\delta} - C\left(b-\frac{1}{\delta}\right)(1-\Psi)}{K-\frac{C}{\delta}},\ H = 0,\ z = Z \end{aligned}\right\} \quad \ldots \quad (48)$$

and (45) becomes

$$\frac{d}{dz}\left(\frac{z}{1+Gz}\frac{dX}{dz}\right) = \frac{1+Gz}{X-\nu z} \quad \ldots \quad (49)$$

This is the same as Corner's equation and it is easily verified that μ, ν are the same constants as his and G denotes the constant denoted by him by B.

For a charge with form-function $z = (1-f)(1+\theta f)$,

$$P = 0,\ Q = \frac{\theta}{1+\theta-\Psi} \qquad \ldots \quad \ldots \quad \ldots \quad (50a)$$

$$G = \frac{\left(\frac{C}{\delta} - Cb\right)(1+\theta)+Cb\Psi}{K-\frac{C}{\delta}},\quad H = \frac{C\theta\left(b-\frac{1}{\delta}\right)}{K-\frac{C}{\delta}} \qquad \ldots \quad \ldots \quad (50b)$$

and (45) becomes

$$\frac{d}{dZ}\left[\frac{Z-QZ^2}{1+GZ+HZ^2}\frac{dX}{dZ}\right] = \frac{1+GZ+HZ^2}{(X-\nu Z)(1-QZ)} \qquad \ldots \quad \ldots \quad (51)$$

This is similar to, but not exactly the same, as the equation (21) of Aggarwal. His dependent variable is defined as

$$\bar{X} = \frac{\beta}{AD}(K_0+Ax)\left(\frac{CW_1\lambda}{\Psi}\right)^{\frac{1}{2}} \qquad \ldots \quad \ldots \quad \ldots \quad (52)$$

so that

$$\frac{\bar{X}}{X} = \frac{\beta C\lambda}{D\mu} = \frac{K-\frac{C}{\delta}}{1+\theta-\Psi} \qquad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (53)$$

Similarly he defines $\bar{\nu}$ by

$$\bar{\nu} = \frac{Cb\beta}{AD}(W_1C\lambda\Psi)^{\frac{1}{2}}, \qquad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (54)$$

so that

$$\frac{\bar{\nu}}{\nu} = \frac{C\beta\lambda}{D\mu}\frac{K-\frac{C}{\delta}}{1+\theta-\Psi} \qquad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (55)$$

Aggarwal defines

$$\alpha_1 = K-\frac{C}{\delta},\quad \alpha_2 = \theta+1-\Psi,$$

$$\alpha_3 = C\left(\frac{1}{\delta}-b\right)(1+\theta)+Cb\Psi,\quad \alpha_4 = C\left(\frac{1}{\delta}-b\right), \qquad \ldots \quad \ldots \quad (56)$$

so that

$$\frac{\bar{X}}{X} = \frac{\bar{\nu}}{\nu} = \frac{\alpha_1}{\alpha_2} \qquad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (57)$$

Also

$$Q = \frac{\theta}{\alpha_2},\ G = \frac{\alpha_3}{\alpha_1},\ H = -\theta\frac{\alpha_4}{\alpha_1} \qquad \ldots \quad \ldots \quad \ldots \quad (58)$$

His solution (25) in dimensionless variables reduces to

$$X = X_0 + Z\frac{1}{X_0} + Z^2\left[\frac{3G}{4X_0} + \frac{1}{4}\frac{\nu}{X_0^2} - \frac{1}{4}\frac{1}{X_0^3} + \frac{3}{2}\frac{Q}{X_0}\right]$$

$$+ Z^3\left[\frac{1}{6X_0}\left[\frac{14}{3}QG + \frac{11}{3}Q^2 + \frac{8}{3}H + G^2\right]\right.$$

$$+ \frac{1}{6X_0^2}\left[\frac{5}{3}\nu Q + \frac{5}{3}\nu G\right]$$

$$+\frac{1}{18X_0^3}\left[2\nu^2-\frac{13}{2}Q-\frac{13}{2}G\right]$$

$$-\frac{1}{4}\frac{\nu}{X_0^4}+\frac{5}{36}\frac{1}{X_0^5}\Bigg] \quad + \ldots . + \ldots . \qquad \ldots \quad \ldots \quad (59)$$

Now as pointed out by Corner, for moderate densities of loading, his ν (we call it here $\bar{\nu}$) is less than ·3 for H/L guns.

But
$$\frac{\nu}{\bar{\nu}}=\frac{1+\theta-\Psi}{1-\Psi},$$

which for a cord charge would give approximately

$$\frac{\nu}{\bar{\nu}}=3$$

Thus our
$$\nu<\cdot 9 \qquad (60)$$

Now

$$\frac{G}{B}=\frac{\left(\frac{C}{\delta}-Cb\right)(1+\theta)+Cb\Psi}{\frac{C}{\delta}-Cb+Cb\Psi}$$

$$=1-\frac{C\theta\left(b-\frac{1}{\delta}\right)}{\frac{C}{\delta}-Cb+Cb\Psi}$$

For $\theta=1$, it gives

$$\frac{G}{B}=2-\frac{b}{\frac{2}{\delta}-b}.$$

or
$$\frac{G}{B}\approx-\cdot 5 \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (61)$$

As B generally varies from $-0{\cdot}5$ to $+0{\cdot}5$, G is expected to vary from $-{\cdot}25$ to $+25$.

∴ G is sufficiently small.

Again
$$Q=\frac{\theta}{1+\theta-\Psi} \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (62)$$

For a tubular propellant $Q=0$ and for cord, it is approximately $\frac{2}{3}$. Thus Q varies from 0 to $\frac{2}{3}$.

$$H=-\frac{\theta C\left(\frac{1}{\delta}-b\right)}{K-\frac{C}{\delta}}=\frac{\theta C\left(b-\frac{1}{\delta}\right)}{K-\frac{C}{\delta}} \quad \ldots \quad \ldots \quad \ldots \quad (63)$$

Since $C\left(b-\frac{1}{\delta}\right)$ is small as compared with $K-\frac{C}{\delta}$, H would be small.

Thus we find that ν, G, Q, H are all small, though ν is here much larger than its value for a tubular propellant. Thus the convergence of the series (59) will be slow except for large X_0.

For X_0 greater than 5 or 6, series (59) can be used with confidence. For smaller values of X_0, numerical integration in powers of G, ν, Q, H as done by Corner for a tubular propellant is desirable.

The other series obtained by Aggarwal for p, v, p_B, v_B can be easily adapted to our dimensionless variables and their convergence can be similarly discussed.

The series solution for the more general equation (45) can also be obtained easily.

Summary

In the present paper, we have obtained explicit expressions for maximum pressure in the first chamber of a H/L gun and in particular we have proved that for a cord charge, the maximum pressure must occur before all-burnt. We have also put the fundamental differential equation for the second chamber in dimensionless variables and discussed its convergence.

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