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8) ABSTRACT

In this report we perform a study of the burn velocity of tracer compositions. Both the burn velocity during flight and in static conditions is studied. In addition we present results for varying densities of the tracer composition and varying calibres of the tracer cups.

We find that the static burn velocity is different for different tracer compositions. Also we find a linear decrease of the static burn velocity with the calibre of the tracer cup. The static burn velocity is marginally increasing with the density of the tracer composition.

The burn velocity during flight (dynamic burn velocity) is larger than the static burn velocity. We find a linear increase of the dynamic burn velocity with the angular velocity of the circumferential position of the tracer cup. We finally construct a model where the burn velocity is proportional with the density of the composition and is linearly increasing with the angular velocity of the circumferential position of the tracer cup.

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1 INTRODUCTION

In general, during flight a supersonic turbulent boundary layer separates at the base corner of a projectile. A free shear layer region is formed behind the corner. The flow expands at the base corner and is followed by the recompression shock downstream of the base which realigns the flow. Thus the flow redevelops in the trailing wake.

One way of enhancing kinetic energy of a projectile at a given range is to reduce the drag on the projectile during flight. This can be achieved by increasing the pressure at the base of the projectile. By out-flux of gases at the rear during flight, the pressure can be increased. The common approach is to use a so called base bleed charge. In the absence of a base bleed, a low pressure region is formed immediately downstream of the base, which is characterized by a low velocity recirculation region. Interaction between this recirculation flow and the inviscid external flow occurs through free shear mixing. In this mixing region turbulent flow is important. Injection of gas into the base region displaces the recirculation region in the wake. The result is an increase of base pressure and a reduction in base drag.

But also tracers create gas at the rear of the projectile. The purpose of this report is to study the burn velocity of tracers as input to base bleed calculations for reducing drag on projectiles. By doing this we have collected experimental data at Nammo Raufoss both from static and dynamic measurements of burning velocities. Based on the data we put forward a purely empirical model that puts the data in the same framework. Finally, we suggest an explanation for why the dynamic burn velocity is so much larger than the static burn velocity. See references [1]-[11] for further studies.

2 THE STATIC RESULTS

Figure 2.1 show the static burn velocity as a function of the diameter of the tracer cup for different tracer compositions. A linear regression curve is also fitted to the solutions. Observe that the static burning velocity is decreasing with the diameter of the tracer cup. The igniter burning velocity is decreasing faster with the diameter than the tracer burn velocity. We do not know why the burning velocity is decreasing with the diameter of the tracer cup. The heat loss into the walls of the tracer cup relative to the heat production at the surface, should decrease with the diameter of the tracer cup.

Notice that the igniter compositions (RS 58, RS 59 (dark igniter)) burn faster than the tracers. Observe also that the igniter burns faster than the dark igniter. The IR-Dim igniter has a very fast burning rate. The results suggest that RS36 and RS 302/202 have approximately the same burning velocity as a function of the diameter of the tracer cup. RS 302 is approximately the same composition as RS 36, while RS 202 is somewhat different. The burning velocity data suggest that the difference is not significant. Observe that the dark igniter of the 30 mm burns faster than the tracer. Finally, notice that the pressure (more precisely the axial stress) used to press the tracer into the tracer cup is somewhat varying.

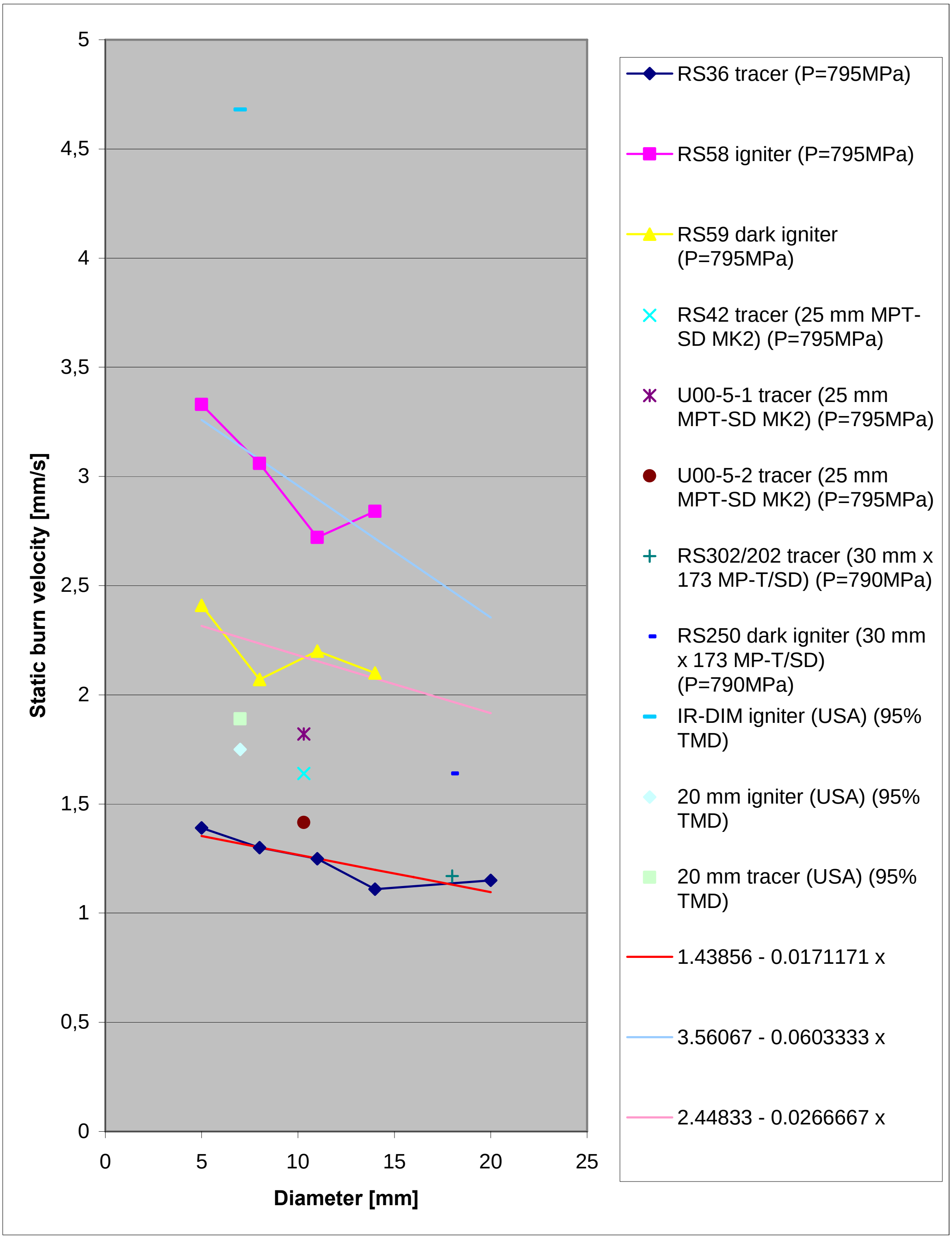

Figure 2.1 : The static burn velocity in millimetre per second as a function of the diameter of the tracer cup.

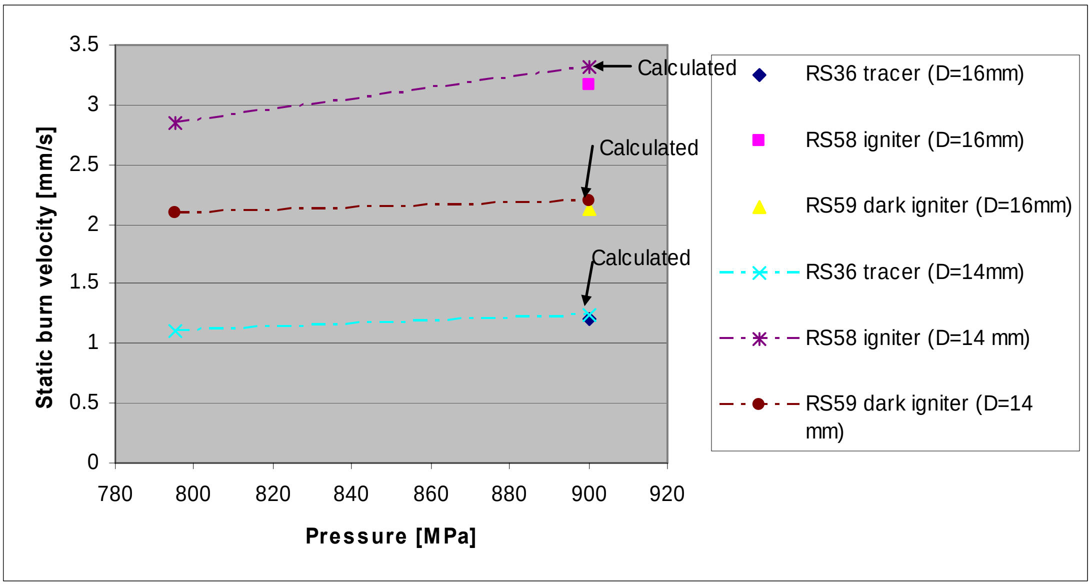

Figure 2.2: The static burn velocity in millimetre per second as a function of the pressure in mega Pascal used during pressing into a tracer cup.

Figure 2.2 shows the static burning velocity as a function of the pressure used when pressing the tracer into the tracer cup. We see a small increase due to increasing pressure (or density). There is a slight difference in the diameter of the tracer cup in the plot. Thus the steepness should have been somewhat larger when using a tracer cup with the same diameter. To account for this we have inserted points (calculated) found from the linear regression curves shown in Figure 2.1 and the corresponding linear regression curves.

We believe that the reason for the increased burn velocity with the pressing pressure is that the heat flux from the reaction gases on the burning surface increases with increasing density of the tracer due to a larger energy content per unit volume of the solid material.

3 THE DYNAMIC RESULTS

The burning velocity of the tracers was measured by observing the light intensity of the tracers during flight. Figure 3.1 shows the dynamic burning velocity as a function of the angular velocity. We have not obtained any data for igniters. The dynamic burn velocity for the 30 mm RS 302/202 is not directly measured but calculated as such: The total burning time is reported to be 5.5 - 5.8 second. The tracer height (or length) is 19 mm. The tracer consists of both a tracer and an igniter. Based on the static results we conceive the tracer RS 302 and the igniter RS 202 as effectively an RS 302 tracer. In addition the mass of the dark igniter (RS 250) in the tracer is only 13 % of the total mass. The dynamic burn velocity of RS 303/202 is calculated by assuming the same velocity of RS 250 as for RS 302/202. This is obviously not quite correct (see the static burn velocity) , but we believe that the calculated dynamic burn velocity of RS 303/202 is not significantly flawed due to the small percentage mass of RS 250.

Further observe that the 30 mm results do not quite have the same steepness as for the 25 mm results. The result for the RS 302/202 is for a larger diameter and a smaller pressure during pressing into the tracer cup. Corrected for this, the initial point on the vertical axis should have been lifted somewhat to higher values, but still below the results for U00-5-2.

The dynamic result for the APEX is suggested. The tracer composition is of the type RS 302/208 with 25% RS 208= RS 58. The 30 mm tracer is of the type RS 302/202 with only 10% RS 202. The igniter RS 202 is reported to burn faster than the RS 208= RS 58. Since the mass fraction of RS 208 is larger than the amount of RS 202 for the 30 mm we believe that the burn velocity of the APEX is larger than the burn velocity of the 30 mm even when we assume the same spin, in pressing pressure and calibre of the tracer cup. Since we do not have access to any dynamic burn velocities for igniters the suggested value is more like a guess.

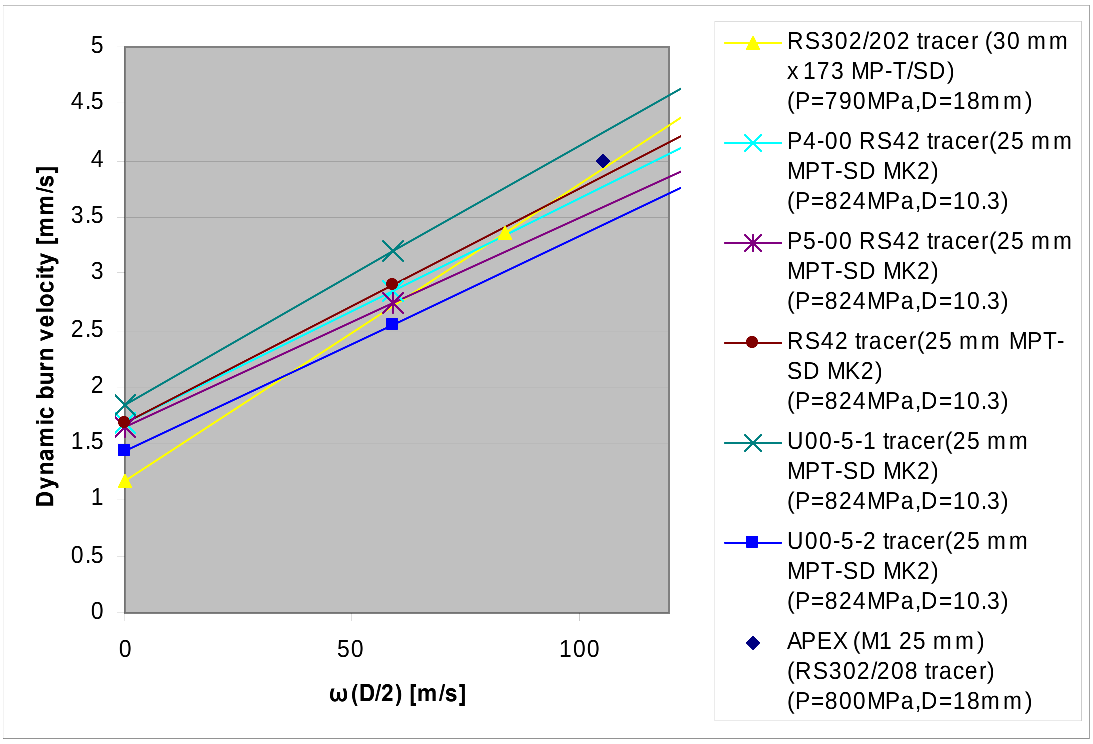

Figure 3.1: The dynamic burn velocity as a function of the angular velocity of the circumferential position of the tracer cup. D=diameter of tracer cup. The APEX result is estimated.

4 THE MODEL

The following model is suggested for the burning velocity of the tracers during static and dynamic conditions

$$\underbrace{\dot{r}}_{\substack{burn\ velocity\\ of\ tracer}} \overset{mod}{=} \underbrace{H_1(D)}_{\substack{diameter\\ dependency}}\ \underbrace{H_2(\rho_s)}_{\substack{density\\ dependency}}\ \underbrace{\left(\dot{r}_s^0 + b\,\dot{r}_\vartheta\right)}_{\substack{composition\\ dependency}},\ \underbrace{\dot{r}_\vartheta}_{\substack{angular\\ velocity}} \overset{def}{=} \underbrace{\omega}_{\substack{spin\ in\ radians\\ per\ second}}\ \underbrace{D/2}_{\substack{radius\ of\\ tracer\ cup}},$$

$$\begin{aligned}&\dot{r}_s = H_1(D)H_2(\rho_s)\dot{r}_s^0 : static\ burn\ velocity\\ &\dot{r}_s^0 : static\ velocity - only\ dependent\ of\ tracer\ composition\\ &\dot{r}_\vartheta : angular\ velocity\\ &b : constant - independent\ of\ tracer\ composition\\ &H_1(D) - linear, H_2(\rho_s) - linear\end{aligned} \tag{4.1}$$

The model says that the burn velocity is increasing linearly with the angular velocity of the outer radius of the tracer cup. For zero angular velocity (static burning) the dynamic velocity equals the static velocity. The static and the dynamic burning velocity are dependent of the density of the tracer composition and the diameter of the tracer cup. An alternative to the formula in equation (4.1) could be

$$\dot{r} = H_1(D)H_2(\rho_s)\dot{r}_s^0 + b\,\dot{r}_\vartheta \tag{4.2}$$

The experimental results do not clearly separate between the two formulas in equation (4.1) and (4.2).

5 WHY IS THE BURNING VELCITY INCREASING WITH THE CIRCUMFERENTIAL VELOCITY OF THE SPINING TRACER CUP?

Consider the following steady state energy balance during burning of a tracer

$$\underbrace{Q\rho_s\ a\ \dot{r}\Delta t}_{\substack{Energy\ for\ bringing\\ the\ surface\ to\\ the\ reaction\ temperature}} \overset{mod}{=} \underbrace{\dot{q}_i a\,\Delta t}_{\substack{Influx\ of\ energy\ through\\ the\ surface}} - \underbrace{\chi\frac{k(T_R - T)a}{l}}_{\substack{Energy\ loss\ from\ the\\ surface\ into\ the\ solid\ tracer}}\ \Delta t, \tag{5.1}$$

k is the conductivity, T_R is the ignition temperature, T is the temperature of the solid far into the solid, a is the area of the surface, Q is the energy per unit volume needed to heat the solid up to the ignition temperature, ρ_s is the density of the solid and $\dot{q}_i$ is the heat flux into the solid surface from the hot gases. Equation (5.1) thus says that the energy used for increasing the surface temperature up to the reaction (ignition temperature) during in an infinitesimal zone during a infinitesimal time interval, equals the energy fluxed into the surface minus the energy loss due to heat loss into the solid. This heat loss is proportional with the temperature difference and inversely proportional with a typical length scale of this difference.

Equation (5.1) gives

$$\dot{r} = \frac{\dot{q}_i}{Q\rho_s} - \chi \frac{k\left(T_R - T\right)}{lQ\rho_s} \tag{5.2}$$

But the equation of heat conduction says that for a stationary situation, $\dot{r} = k / \left(\rho_s c_v l\right)$, where c_v is the heat capacity. Inserting equation (5.2) into equation (5.1) and using that $\dot{r} = k / \left(\rho_s c_v l\right)$, gives the burning velocity as

$$\dot{r} = \frac{\dot{q}}{\left(Q\rho_S + \chi c_v \rho_S \left(T_R - T\right)\right)}, l = \frac{k}{\dot{r}\rho_S c_V}, Q\rho_S = Q_M \rho_S + c_v \rho_S \left(T_R - T\right), \tag{5.3}$$

where Q_M is the heat of melting. Equation (5.3) gives that the burning velocity is proportional to the incoming heat flux. Observe the dependency of the heat capacity and the reaction temperature which both tend to reduce the velocity of the burning surface for increasing values. Note that the velocity is independent of the conductivity of the solid reactants. The reason is simply that although the length of the heated layer increases for increasing conductivity, the velocity of the surface stays constant.

We can insert numerical values, to read

$$k = 1W / \left(mK\right), \rho_S = 2260 kg / m^3, T = 300K, c_V = 1000 J / (K\, kg), T_R = 600K \tag{5.4}$$

Then it follows that the thickness of the heat affected zone and the heat flux becomes

$$\begin{aligned} &l = k / \left(\dot{r}\rho_S c_V\right) = \begin{cases} 1/(0.001\ 2260\, 1000) = 0.4mm,\ when\ \dot{r} = 1mm/s\ (static) \\ 0.1mm,\ when\ \dot{r} = 4mm/s\ (dynamic) \end{cases} \\ &\dot{q} = \dot{r}\left(Q_M + c_v \rho_S \left(T_R - T\right) + \chi c_v \rho_S \left(T_R - T\right)\right) \\ &= \begin{cases} 1x10^6 W/m^2 + 0.001 m/s\, Q_M,\ when\ \dot{r} = 1mm/s\ (static) \\ 4x10^6 W/m^2 + 0.004 m/s\, Q_M,\ when\ \dot{r} = 4mm/s\ (dynamic) \end{cases} \\ &\chi = 1 \end{aligned} \tag{5.5}$$

The heat flux $\dot{q}_{rad}$ into the solid surface due to radiation from the hot reaction gases is given by

$$\dot{q}_{rad} = \varepsilon\sigma\left({T_g}^4 - \lambda T^4\right) \approx \varepsilon\sigma {T_g}^4 = \varepsilon\ \sigma\ 5.6x10^{-8} 3000^4 = \varepsilon\, 4.5x10^6 W/m^2 \tag{5.6}$$

By comparing the calculated heat flux in equation (5.5) with the heat flux due to radiation in equation (5.6) it turns out that both the dynamic and the static heat flux can be achieved by radiation if $\varepsilon \approx 1$ for the dynamic situation. Thus we suggest that the convective heat transfer is not significant. We hypothesize that the increased burning velocity due to spin is due to a larger heat transfer into the surface. This could be due to a faster mixing of the gas phase reaction, or a larger heat transfer to the solid surface due to convective heat transfer. In general it is known that the static burning rate of tracers is dependent of the pressure. A larger pressure moves the gas reaction zone closer to the burning surface. This enhances radiation heat flux of the hot gas back to the solid surface. We suggest that the most reasonable explanation for the increased burning rate during spinning is that the gas phase reaction takes place closer to the burning surface. We believe that the reason for this is a more thoroughly developed turbulence close to the burning surface. This enhances a rapid mixing of the gas reactants which leads to a larger temperature closer to the solid surface. The circumferential velocity is around 100 m/s, while the tracer gas velocity relatively to the burning surface is around 100 m/s. Thus the Reynolds number is larger when the projectile is spinning.

6 CONCLUSION/DISCUSSION

In this report we have performed a study of the burn velocity of tracer compositions. The burning velocity is studied during flight and in static conditions. In addition we present results for varying densities of the tracer composition and varying calibres of the tracer cups.

We find that the static burn velocity is different for different tracer compositions. Also we find a linear decrease of the burn velocity with the calibre of the tracer cup. The static burn velocity is marginally increasing with the density of the tracer composition.

The burn velocity during flight (dynamic burn velocity) is larger than the static burn velocity. A linear increase of the dynamic burn velocity with the angular velocity of the circumferential position of the tracer cup is suggested.

We construct a model where the burn velocity is proportional with the density of the composition and is linear increasing with the angular velocity of the circumferential position of the tracer cup.

The increased burning velocity during spinning is assumed to be the result of a larger turbulence mixing in the reaction zone. This lead to a higher temperature of the reaction gases close to the burring surface. We do not believe that convective heat transfer is significant.

For further studies we strongly recommend experimental studies of dynamic burn velocities of igniters.

Acknowledgement

We thank Monica Strømgård and Anne Sønsteby at Nammo Raufoss for the raw material for the burning velocities of tracers.

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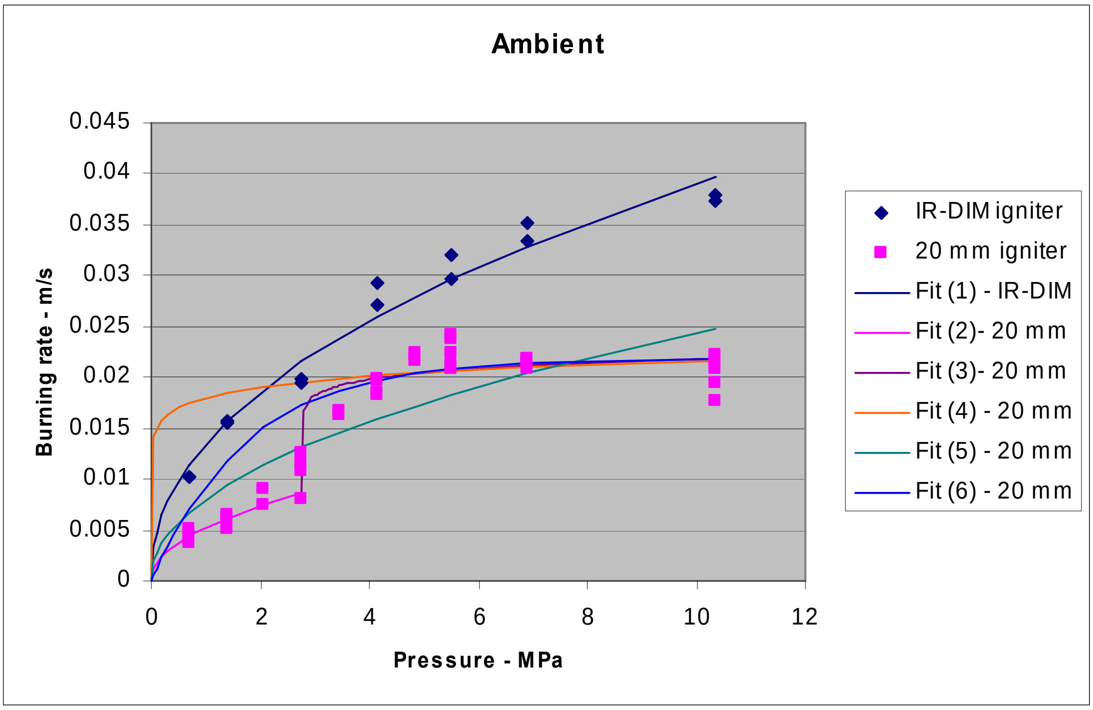
APPENDIX A, SOME BURNING VELOCITIES OF TRACERS AND BASE BLEEDS



1) 1)

Figure A1: The static burning velocity in meter per second as a function of pressure in MPa.
v: 1) $0.0135\ P^{0.46}$ 2) $0.00529\ P^{0.48}$ 3) $0.00809+0.0115(P-2.758)^{0.08}$
4) $0.0179\ P^{0.08}$ 5) $0.00806\ P^{0.48}$ 6) $0.0218(1-E^{-0.571\ P})$

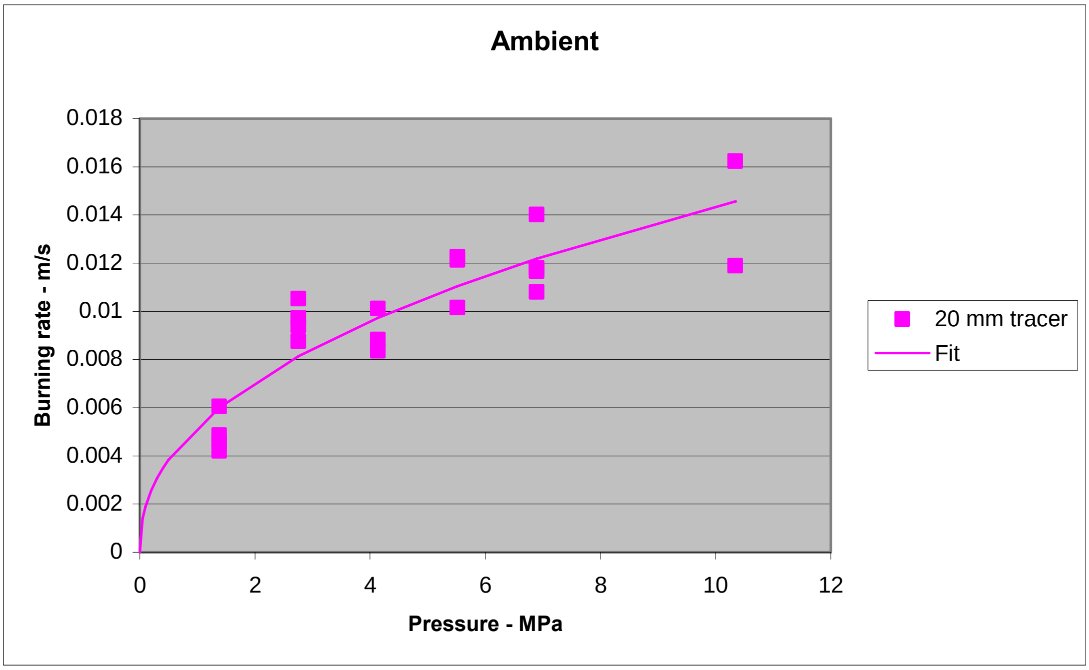


Figure A2: The burning velocity in meter per second as a function of pressure in MPa.
$v = 0.00520858\ P^{0.44}$

Other pyrotechnical charges used for base bleed: r= b p^(n) f(spin) Pressure in bar

charge	*B (mm/s)*	*n*	*Multiplication factor due to spin*
Gunners, 1992	*1.14*	*0.6*	
	1.01	*0.6*	
	1.25	*0.7*	
	1.09	*0.7*	
	1.35	*0.8*	
	1.21	*0.8*	
	1.49	*0.9*	
	1.33	*0.9*	
Gunners, 1995	*1.03*	*0.86*	
Wwang and Kim 1996	*1.1*	*0.7*	*1.187+ 0.0019768 s +1.2485 Exp(-7) s^2 (rps)*
Wu and Chai, 1995	*1.27*	*0.56*	*x 1 when a <= 15000 m^2/s* *x 0.023705 a^0.3894 when a>= 15000m1^2/s: radial direction*
Jaramaz and injac, 1988	*1.12*	*0.7*	