

INFLUENCE OF IGNITION RELATED PARAMETERS⁶²
AND CHARGE CONFIGURATION ON XKTC MODEL
PREDICTIONS

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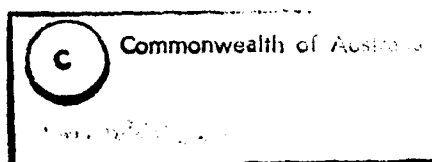
ANNA E. WILDEGGER-GAISSMAIER

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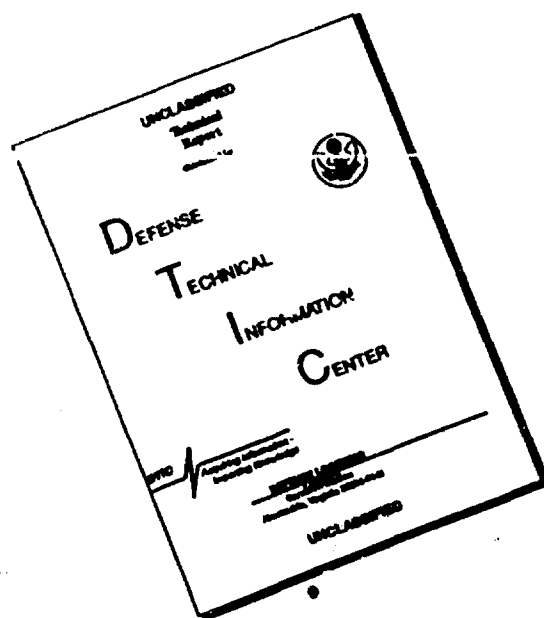
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Influence of Ignition Related Parameters and Charge Configuration on XKTC Model Predictions

Anna E. Wildegger-Gaissmaier

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Abstract

A parametric study has been conducted to assess the influence of ignition related parameters and charge configurations on model predictions using the one-dimensional two-phase flow interior ballistics code XKTC. The investigation showed that the code is sensitive to charge configuration parameters such as bed porosity and ullage, and their effect on compression wave speed. Minimisation of ullage and maximisation of bed porosity reduce the probability of damaging pressure waves. Substantial changes in interior ballistic performance could be observed for the different kinetics options available in XKTC and for changes in kinetic parameters. Although the code is useful for igniter design, a two dimensional model is recommended for more realistic predictions.

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Author

Anna E. Wildegger-Gaissmaier

Anna Wildegger-Gaissmaier graduated Dip.-Ing. (TU) (Mechanical Engineering) in 1980 at the Technische Universität München (Germany). She worked for several years as a process engineer. Following the award of a PhD from Adelaide University in 1989 in chemical engineering she spent one year working for CSIRO (Division of Wool Technology) before joining DSTO in 1990. Her main interests include combustion, ignition and fluid dynamics.

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Influence of Ignition Related Parameters and Charge Configuration on XKTC Model Predictions

1. Introduction

This investigation covers the influence of ignition related parameters and charge packaging on interior ballistic model predictions for 5"/54 LOVA propelling charges. The main reasons responsible for pressure wave development in large and medium calibre gun charges are uneven ignition due to an unsuitable igniter design, increased mass burning rates due to propellant grain fracture and problems associated with the packaging of the charge (e.g. void regions, compactible filler elements, low bed porosity).

The interaction between igniter and propellant exerts a profound influence on the performance of a gun charge. Ignition occurs through the convective and conductive energy transfer from the hot ignition gases and particles to the propellant grains and effective ignition of the charge is strongly dependent on temperature, local distribution and mass flow rate of these ignition products throughout the propellant bed. The propelling charge for the 5"/54 gun utilises a bayonet igniter and the ignition products are vented radially through flash holes in the tube. Although the geometry of the tube and the location of the vent holes are designed to provide even distribution of the hot gases/particles flowing through the propellant bed, experimental evidence [1] shows that this is not always achieved. Uneven ignition results in localised high pressures and enhancement of burning rate which can ultimately lead to the generation of destructive pressure waves. This situation is exacerbated when LOVA propellants are used because they are less readily ignitable than are nitrocellulose based propellants and this tends to amplify any igniter shortcomings. It is therefore necessary to address igniter design concurrently with the design of the LOVA charge and since this is initially carried out by a theoretical approach it is necessary to evaluate the capabilities of the models available.

Packaging of a propellant charge also plays an important role in pressure wave development. The standard 5"/54 BS-NACO charge is fitted with a polyethylene

compactible filler element and a spacer to take up the ullage and a cork case closure plug. These components hold the propellant grains in place during handling and storage but, during the interior ballistic cycle, pressure differentials are generated and cause the propellant bed to move towards the front of the case. The propellant compacts the filler element and spacer (possibly fracturing propellant grains) and creates ullage within the charge. This process can be responsible for the building up of pressure waves. Another important aspect in that context is the porosity of the propellant bed which effects the flow resistance of the ignition products through the bed and it also can result in the generation of pressure differentials. While the version of XKTC available to us is able to model compaction of filler elements and spacers and to take bed porosity into account, fracture of propellant grains is not explicitly considered.

Lumped parameter models and two-phase flow models are the two main categories of interior ballistic models currently available to the charge designer. Lumped parameter models are based on the overall energy balance and use an empirical burning rate equation to model the combustion process. These models do not take hydrodynamics into account and have no spatial resolution of interior ballistic quantities and do not consider flame spreading in a charge. They are therefore not useful for ignition modelling. Two-phase flow models, such as the one-dimensional XKTC [2] model used in this work, take into account the two-phase nature of the contents of the chamber. This allows the influence of flame spreading to be considered. Differences between experimental LOVA charge firings and model predictions [3] showed that a more sophisticated approach than using the basic burning rate law is necessary for modelling those propelling charges. A combustion sub-model is included in the XKTC code and this allows the influence of the chemical reactions occurring during combustion to be treated in more detail. XKTC was therefore chosen for evaluation for its use in igniter design and the work reported here is a series of parametric studies investigating the influence of igniter discharge functions and kinetic parameters on interior ballistic model predictions.

2. Igniter Discharge Function

Several experimental investigations [4-6] using gun simulators looked at the influence of primer body configurations on the ignition process. Chang and Roccio [5] obtained a more effective ignition in tank gun charges by reducing the duration and increasing the rate of flow. East [4] achieved shorter ignition delays and a more uniform axial pressure field by using a tubeless igniter design for 5"/54 charges. Various studies [7-10] were also conducted to investigate the suitability of different igniter materials to act as an ignition stimulus for LOVA propellants. Only a few theoretical studies have been done in this area. Heiser [11] reviewed the commonly used interior ballistic models for their suitability to predict the interaction between the igniter system and the solid propellant. He came to the conclusion that reasonable results could only be obtained using two-phase flow models and pointed out that one-dimensional models like XKTC are restricted to cases where the flame spreads nearly one-dimensionally as it occurs with base bad igniters. For multi-dimensional propagation of the flame, which is likely to happen with primer tubes, a

two- or three-dimensional model would be more appropriate. Almeyda [12] tried to reproduce experimental data for 76 mm gun charges using the XNOVAK code. Discrepancies between experimental firings and model predictions were found. Parameter changes in the speed of compression wave and drag enabled him to obtain a better agreement between model and experiment. He also concluded that the simulations were rather insensitive to igniter stimulus as represented by mass discharge function for conventional charges using bayonet igniters.

In this study on the influence of igniter related parameters on interior ballistic model predictions, an XM39 LOVA propellant was chosen for the simulation because it displayed a tendency to develop pressure waves using the standard igniter discharge function [13] and might therefore be assumed to be sensitive to changes in igniter discharge functions. The burning rate of the propellant, its thermochemical data and the propellant grain size used for the simulations are listed in Table 1.

Table 1: Propellant Data

THERMOPHYSICAL DATA*	
Impetus (kJ/kg)	1096
Molecular Weight	20.954
Ratio of Specific Heats	1.281
Covolume (m ³ /kg)	1.028
Flame Temperature (K)	2012
BURN RATE DATA*	
Burn Rate = $B \times P^n$	
Pressure (MPa)	≤ 41.38
n	1.1088
B (mm/s MPa ⁿ)	0.4094
Pressure (MPa)	≤ 137.9
n	0.5758
B (mm/s MPa ⁿ)	2.9774
Pressure (MPa)	≤ 551.7
n	1.1608
B (mm/s MPa ⁿ)	0.1668
GRAIN GEOMETRY	
Grain diameter (mm)	9.75
Grain length	9.75
Perforations	7
Perforation diameter	1.0

* Data obtained from Ref. [3].

Figures 1a-i show various igniter discharge functions which were used to assess igniter design for the following model calculations.

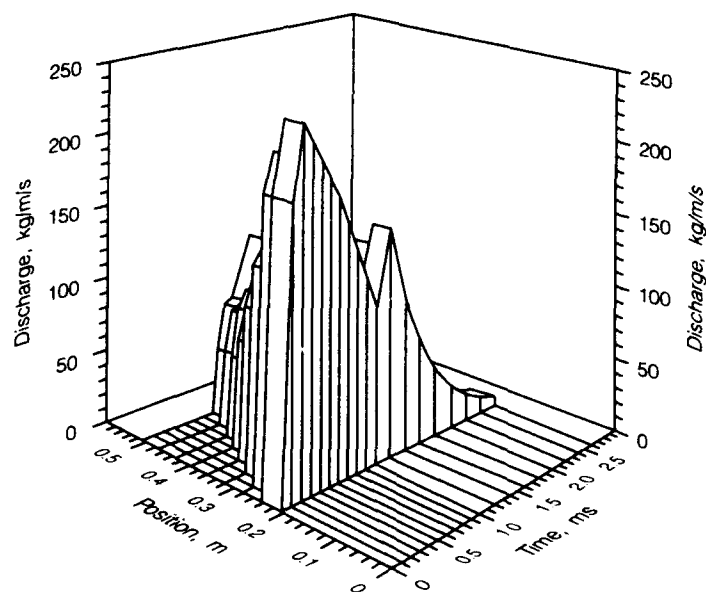


Figure 1a: Standard igniter discharge function.

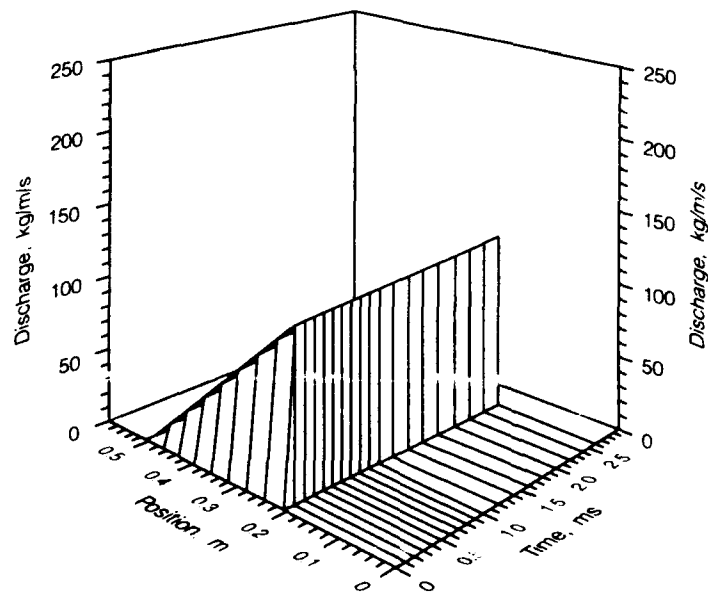


Figure 1b: Igniter discharge function 1.

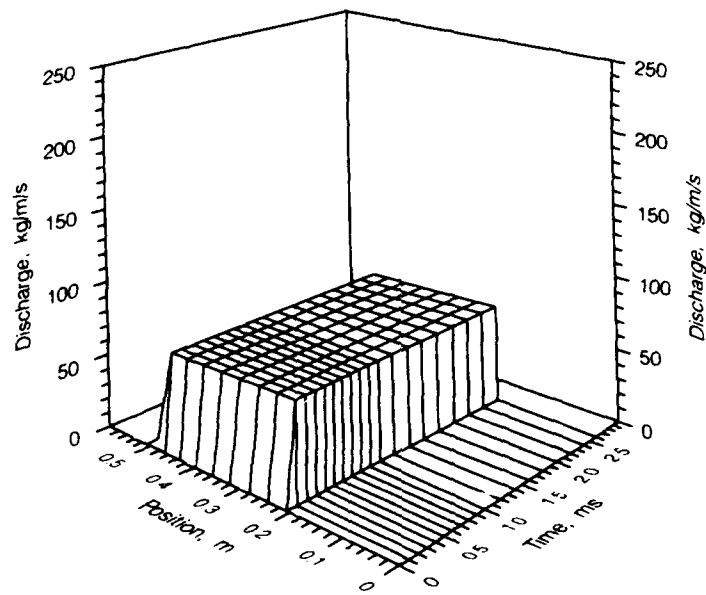


Figure 1c: Igniter discharge function 2.

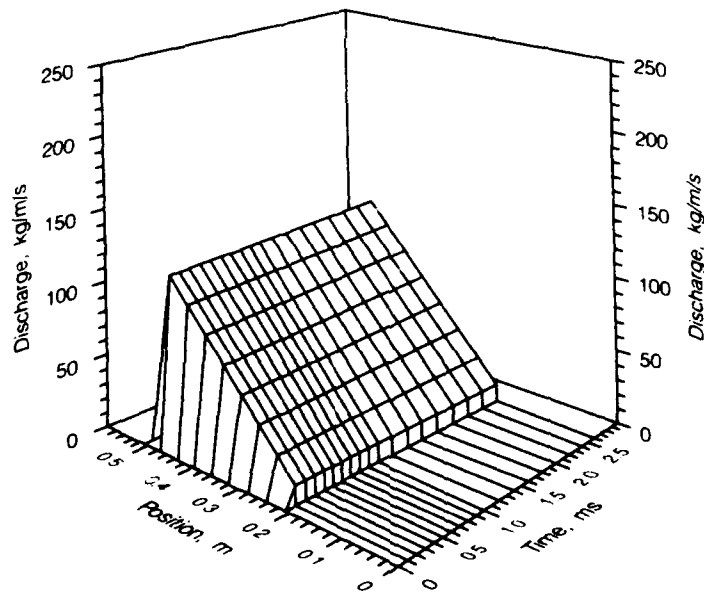


Figure 1d: Igniter discharge function 3.

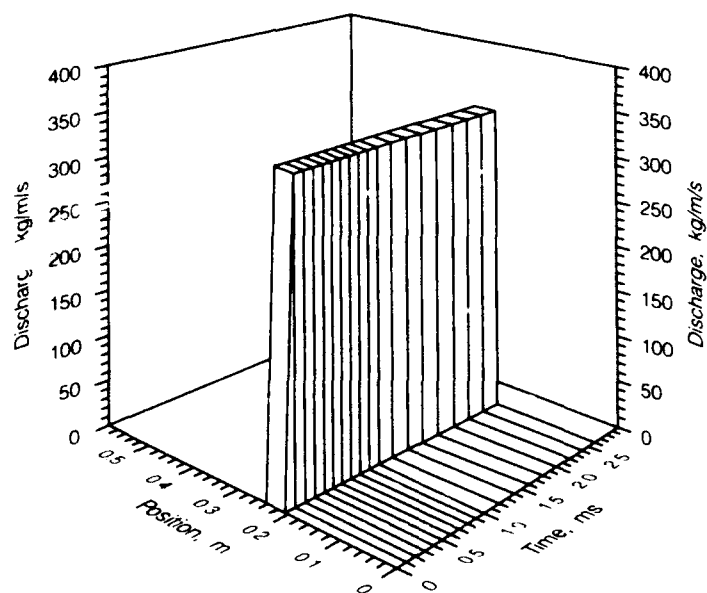


Figure 1e: Igniter discharge function 4.

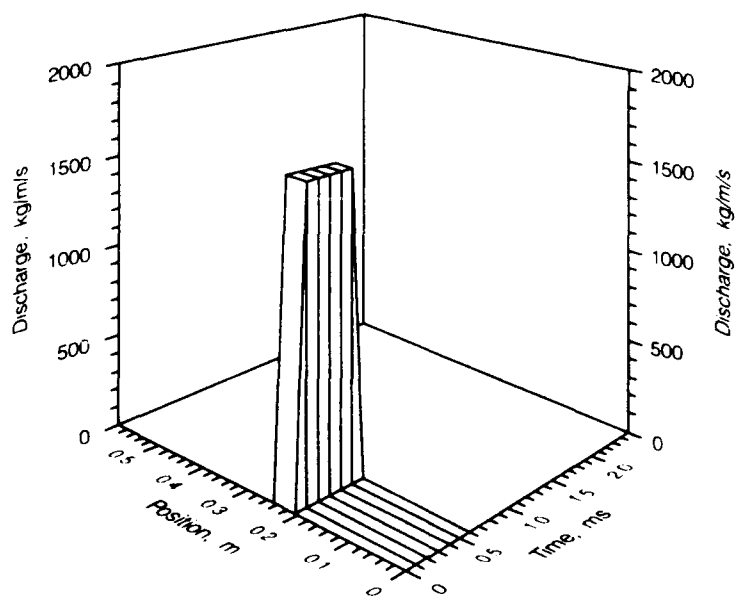


Figure 1f: Igniter discharge function 5.

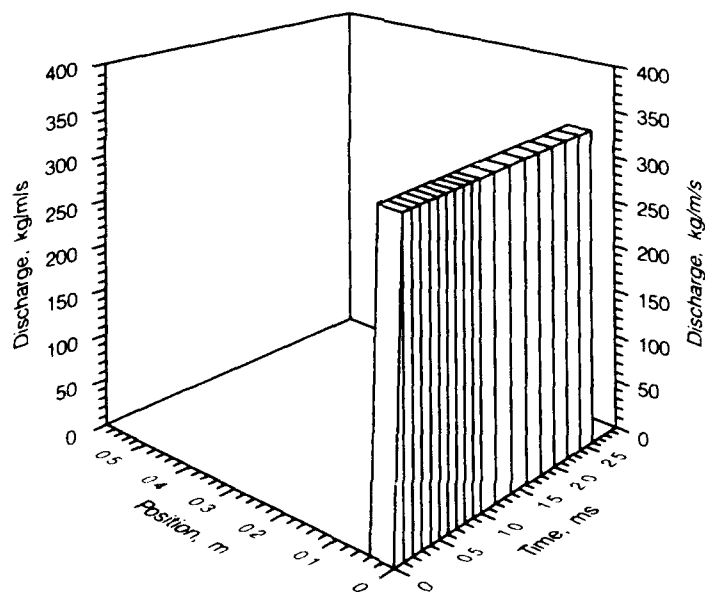


Figure 1g: Igniter discharge function 6.

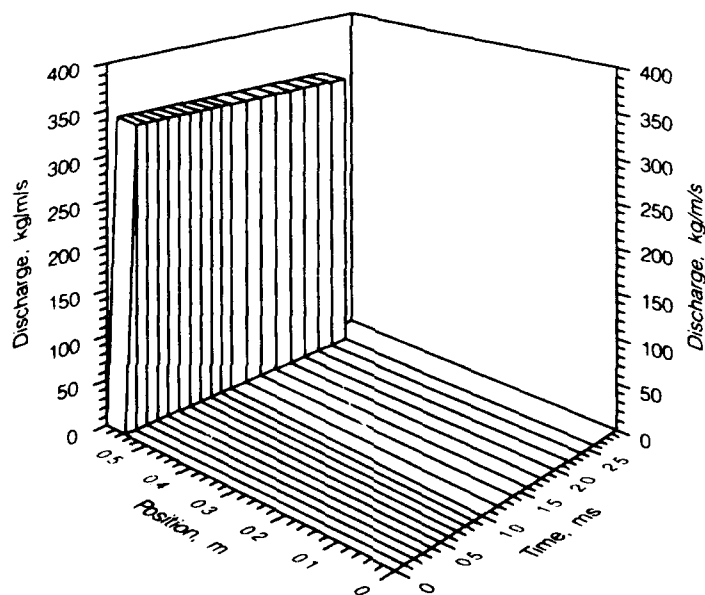


Figure 1h: Igniter discharge function 7.

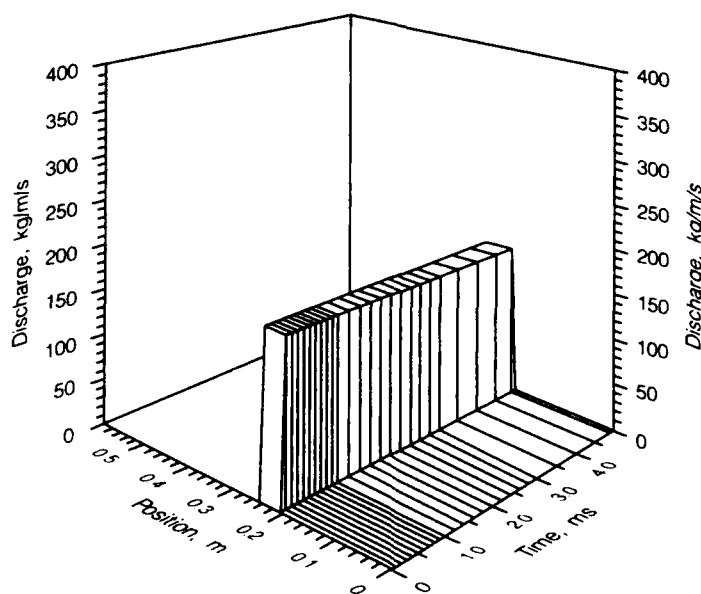


Figure 1i: Igniter discharge function 8.

Figures 2a and 2b show the calculated pressure time curves and the history of flame spreading for an XM39 charge utilising the standard igniter discharge function and standard packaging. The igniter discharge function for the standard Mk 45 Mod 1 igniter as displayed in Figure 1a shows an erratic discharge behaviour over position and time and this was assumed to lead to the predicted high differential pressures as shown in Figure 2a.

The influence of various igniter discharge functions, as shown in Figures 1a-i, were assessed for a standard charge configuration (compactible filler element and spacer which results in ullage) and the predicted effects on the interior ballistics are shown in Table 2. The bed porosity for these simulations was 0.34 and the compression wave speed was 5307 m/s.

For all simulations the same igniter mass (52 g) was assumed with only the flow rate and the discharge positions being varied. As can be seen from Table 2 the predicted maximum pressures differ from the standard case by approximately - 6% and + 13%, the muzzle velocities differ by - 3% and + 4% and the differences in the first pressure wave amplitudes are 22%.

Figures 3a and 3b show examples of the pressure-time and differential pressure-time profiles and flame spreading respectively for substantially different igniter functions. One would expect that the differences in discharge functions and flame spreading predictions would be reflected in the predicted interior ballistic performance but in fact the effects are only minor.

Figures 3c and 3d show the pressure-time and differential pressure-time curves and flame spreading for igniter functions 4, 5 and 8. The discharges occurred at the same

position in the charge, however the rates involved were different for each case. As expected the highest discharge rate (igniter 5) results in the shortest ignition delay, in the fastest flame front and in the development of the highest differential pressure. In the case of igniter 8 the longer time involved in the discharge allows a more uniform distribution of the ignition stimulus and results in a longer ignition delay with less severe pressure wave development.

Figure 3e shows the influence of discharge position on the interior ballistic performance. The highest pressure waves were encountered for igniter 6 which was discharged at the breech. The highest maximum pressure and the lowest differential pressure occurred when the discharge position was at the front end. Figure 3f shows the flame spreading history for these cases. The longest time necessary to ignite the whole charge occurs with the ignition source at the projectile base which also corresponds with the longest predicted ignition delay. For this case the lowest pressure waves are predicted, this might be due to the longer time available to equalise pressure differences in the charge.

The results discussed above indicate that positioning the vent holes towards the front of the charge or decreasing the rate of the discharge minimises pressure wave development. Generally the differences in predicted interior ballistics are quite small but this is not borne out experimentally in the case of 76 mm charges [12] in which large variations in interior ballistics for different igniter designs were evident. One might expect similar behaviour in a 5"/54 charge.

As already pointed out in the introduction, igniter design might not be the sole reason for pressure wave development. To eliminate the influence of the discharge function, model predictions have been obtained for the case where the whole charge is uniformly ignited at time 0 ms. The results of these calculations are compared with the standard igniter case and shown in Figure 4. As can be seen the only difference is in the slightly shorter ignition delay time for the instantaneous ignited charge. It can be concluded that the igniter discharge function for the standard charge configuration plays only a minor role in the evolution of pressure waves.

Table 2: Interior ballistic performance for different igniter discharge functions

Igniter Function	$P_{\max}$ (MPa)	$V_{\max}$ (m/s)	$\Delta P_{\min}$ (MPa)	$\Delta P_{\max}$ (MPa)
Standard	297.5	835.8	- 68.7	+ 51.3
1	297.7	835.4	- 65.7	+ 49.9
2	302.6	840.2	- 65.9	+ 50.8
3	306.5	844.1	- 64.0	+ 51.9
4	295.0	833.2	- 73.3	+ 44.7
5	288.5	823.2	- 83.0	+ 50.0
6	280.2	811.2	- 95.3	+ 50.8
7	336.2	870.6	- 48.4	+ 44.8
8	295.2	834.6	- 64.2	+ 35.9

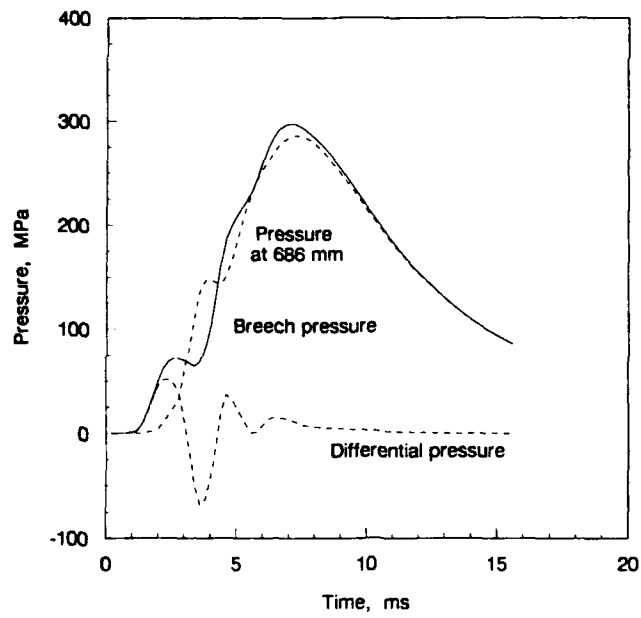


Figure 2a: Pressure-time profiles for standard igniter.

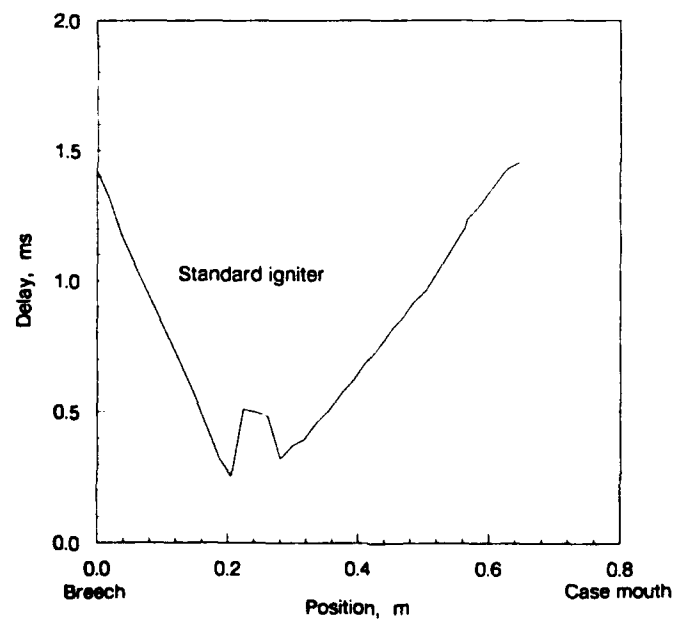


Figure 2b: History of flame spreading.

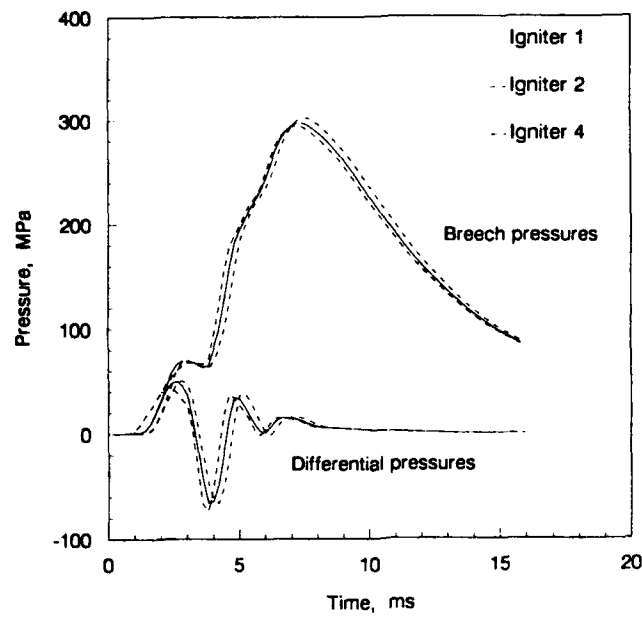


Figure 3a: Breech - and differential pressure-time curves.

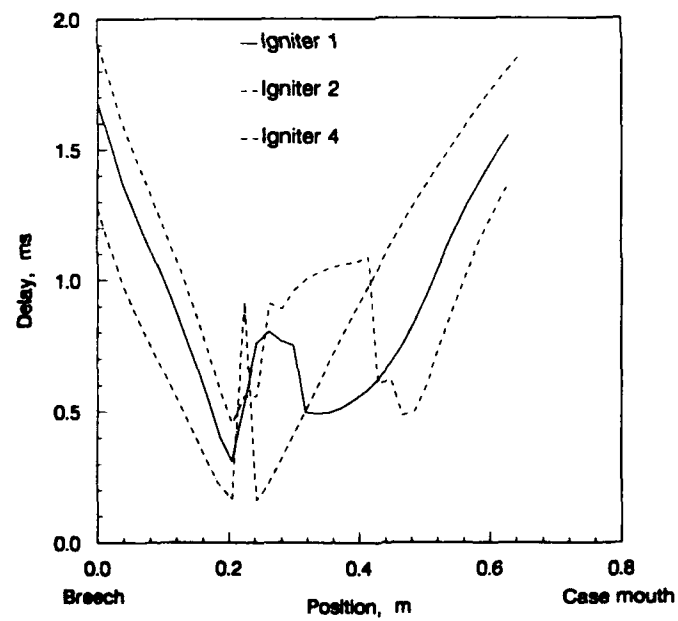


Figure 3b: History of flame spreading.

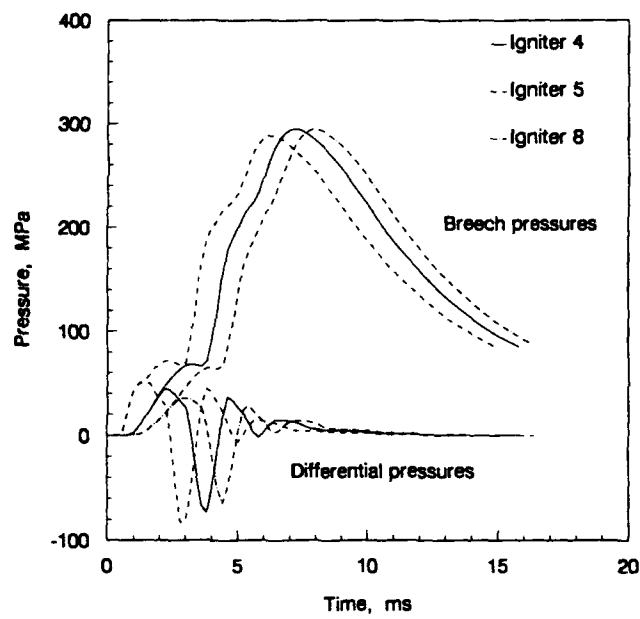


Figure 3c: Breech - and differential pressure-time curves.

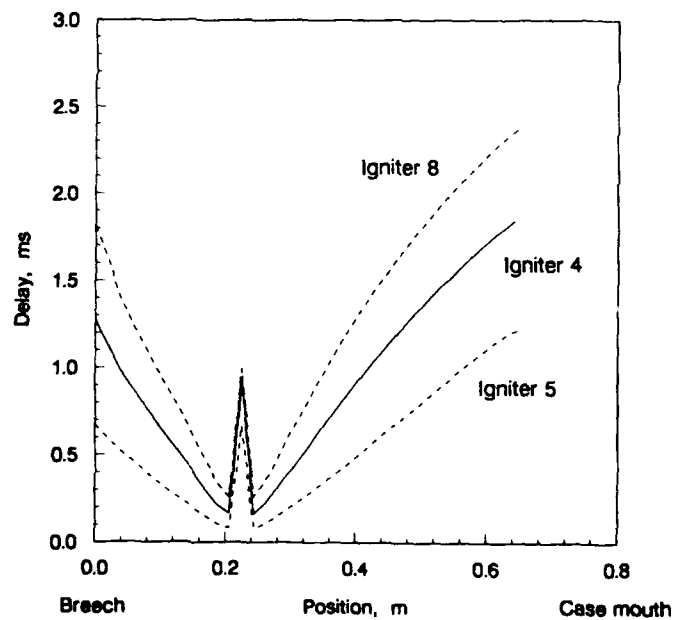


Figure 3d: History of flame spreading.

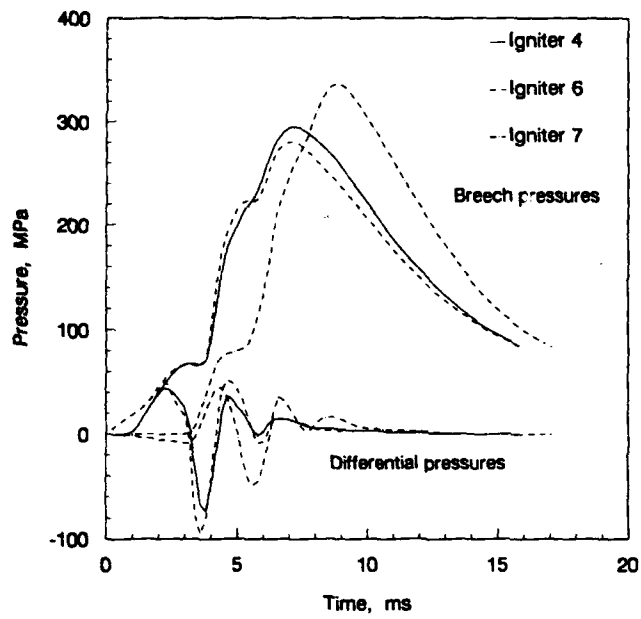


Figure 3e: Breech - and differential pressure-time curves.

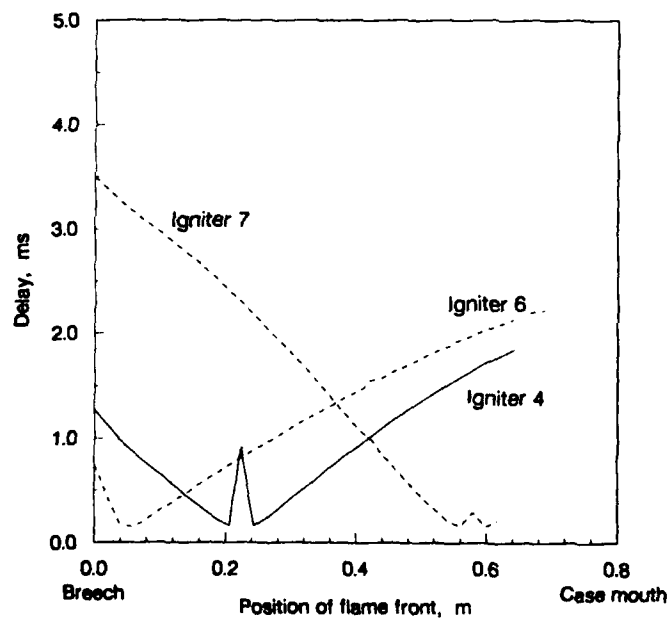


Figure 3f: History of flame spreading.

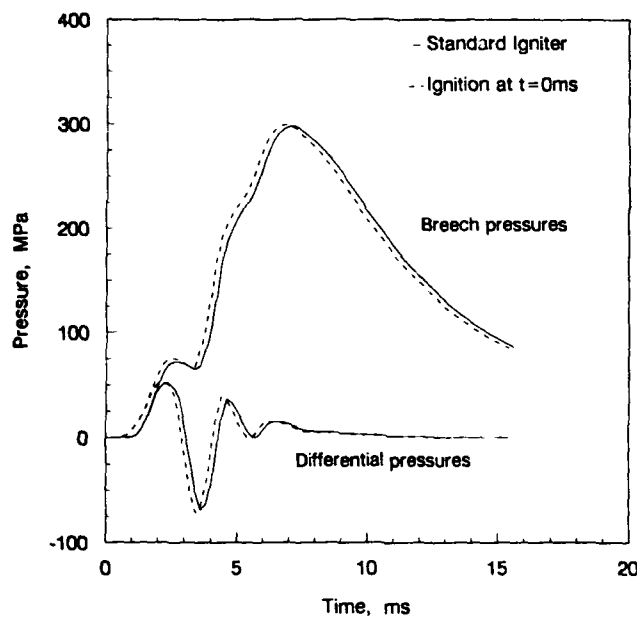


Figure 4: Breech- and differential pressure-time curves.

Figures 5a and 5b depict the results of the model calculations for igniters 1, 2 and 4 assuming that the whole case is filled by the propellant (i.e. with no filler element or spacer present). The use of the same charge weight generates an increased bed porosity which in turn decreases the flow resistance of the igniter products and results in the prediction of very low pressure differentials. It follows that the bed porosity is an important parameter which has to be taken into account when designing a charge. In reality however porosity of that order of magnitude can not be achieved due to settling of the propellant bed and creation of ullage. Horst and Gough [14] eliminated ullage and thereby reduced pressure differentials in 5"/54 ammunition. The techniques used were the attachment of a sheet of foam plastic to the inside of the case and the mixing of polystyrene granules with the propellant.

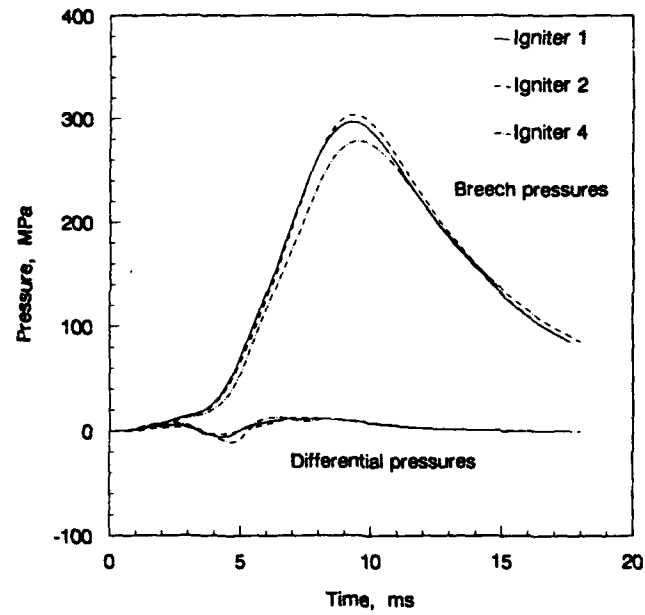


Figure 5a: Breech - and differential pressure-time curves.

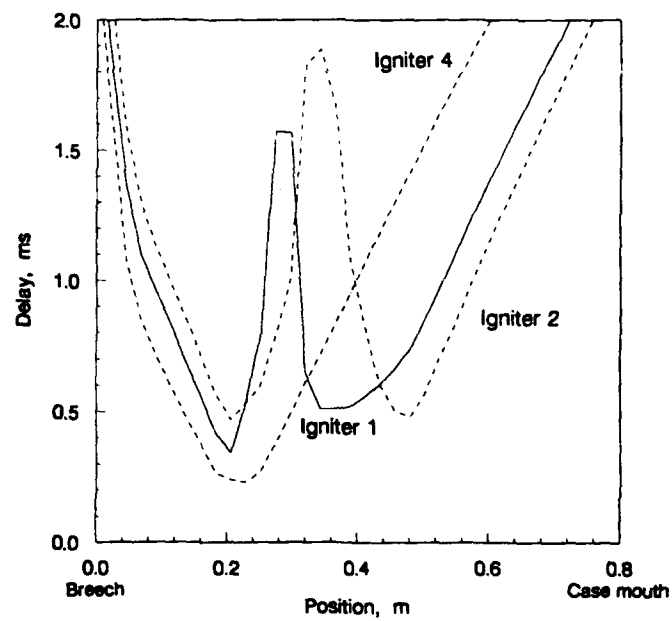


Figure 5b: History of flame spreading.

Decreasing the bed porosity from 0.52 to 0.33 results in increased pressure differentials as seen in Figure 6a. This result shows again that bed porosity is an important charge design parameter with regard to pressure wave development. The history of flame spreading (Fig. 6b) looked more erratic for the lower bed porosity of 0.33 than for 0.52 (Fig. 5b) which is due to the higher flow resistance. The porosity decrease was obtained by increasing the charge weight to 14 kg and to keep maximum pressures below 400 MPa it was necessary to reduce the impetus of the propellant to 658 kJ/kg. The pressure differentials for igniters 1, 2 and 4 are again very small for the cases depicted in Figures 5 as well as 6.

Alymeda [12] showed that one of the important parameters influencing the model predictions for differential pressures is the speed of compression wave. With conventional propellants the speed of this wave is around 5307 m/s [13] but Horst [15] suggested to obtain more realistic results in model predictions a compression wave speed of 1830 m/s should be used for LOVA propellants. Figures 7a-f show sample calculations using the different igniter discharge functions for pressure-time, differential pressure-time and flame spreading. The predictions for igniters 1, 2 and 4 (Fig. 7a) showed the first time a marked difference in pressure wave development. As expected the homogeneous discharge of igniter products over time and position using igniter 2 predicts the least severe pressure waves. Similar pressure wave amplitudes (Fig. 7c) were predicted for igniters 4, 5 and 8 which differed from each other by the discharge rate at the same bed location. As expected longer ignition delays were predicted for lower discharge rates. Large differences in the calculations were encountered when changing the discharge position as in Figure 7e. Igniter 6 (discharge at breech end) displayed the highest differential pressures, this simulates the case for a broken igniter tube. The porosity used for calculations displayed in Figures 7a-f was 0.43 due to instability of the code at lower porosities (0.33) under those conditions.

It is apparent that the model can be of some use for igniter design but the most reliable and precise predictions would require the use of a two dimensional modelling technique which allows modelling of the flame spreading in a radial direction.

The influence of initial burn rate on model predictions was investigated and the results are shown in Figure 8. Such predictions require accurate data on burning rate and it can be seen that if a constant pre-exponential factor is assumed, to yield "standard burning rates", the predicted result is quite different from the situation where the pre-exponential factor is not constant over the whole pressure range. In Figure 8 the low "initial burn rate" curves were generated using experimentally determined data on Australian LOVA propellant of 0.211 below 41.4 MPa and 0.4094 above 41.4 MPa. The case with the lower initial burning rate shows a longer ignition delay time and less severe pressure wave development.

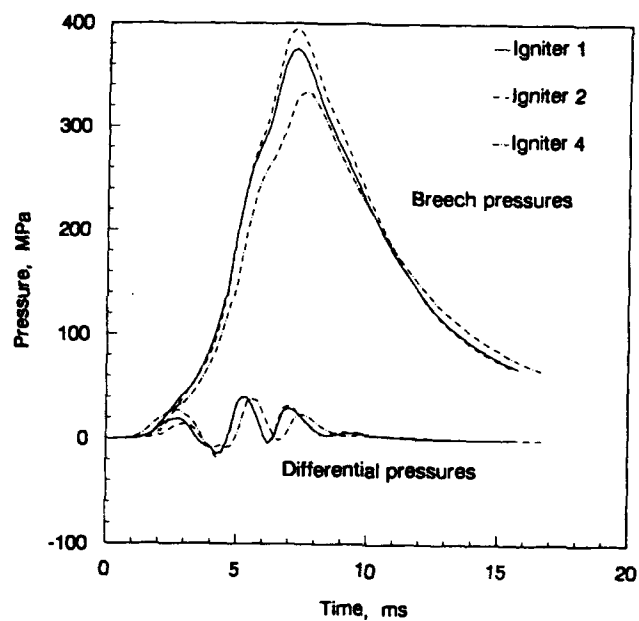


Figure 6a: Breech - and differential pressure-time curves.

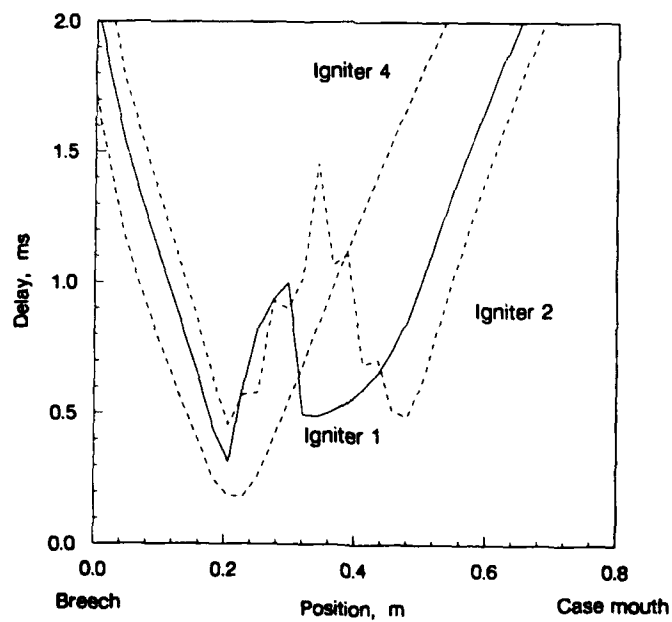


Figure 6b: History of flame spreading.

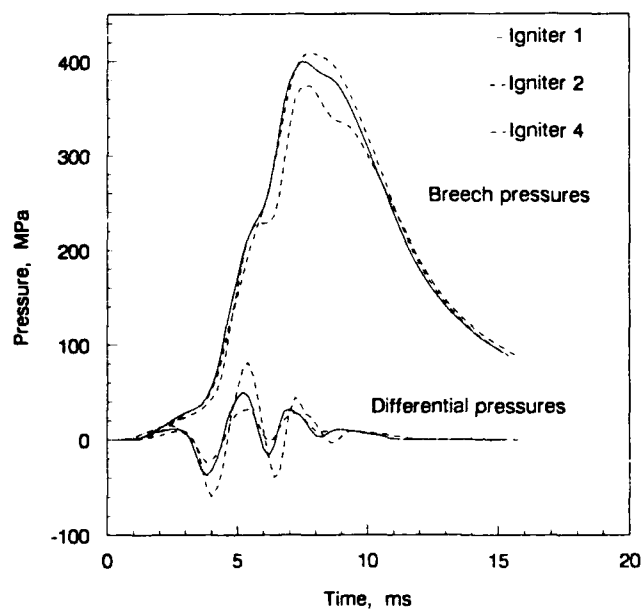


Figure 7a: Breech - and differential pressure-time curves.

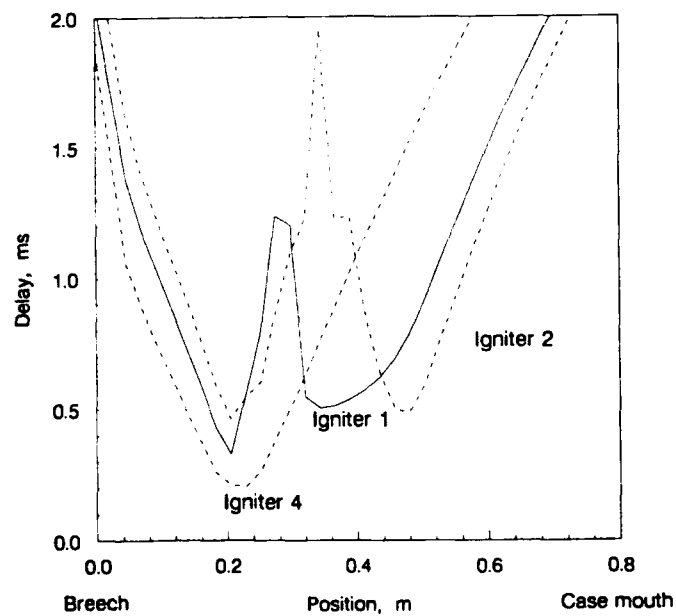


Figure 7b: History of flame spreading.

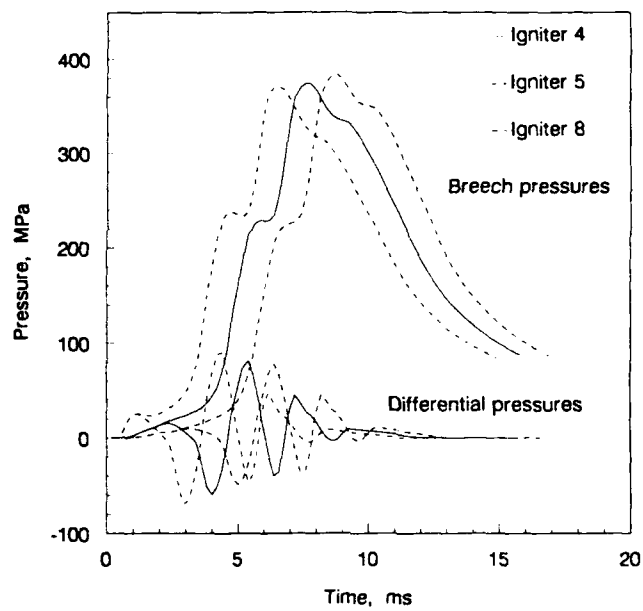


Figure 7c: Breech - and differential pressure-time curves.

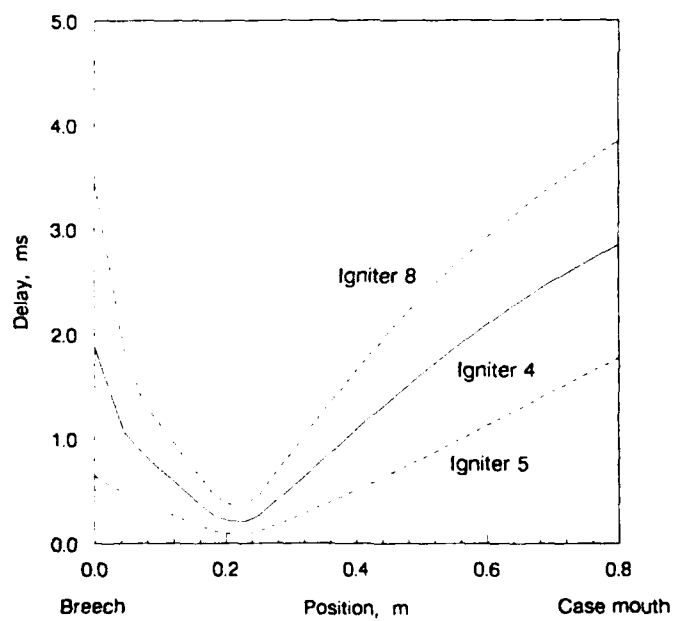


Figure 7d: History of flame spreading.

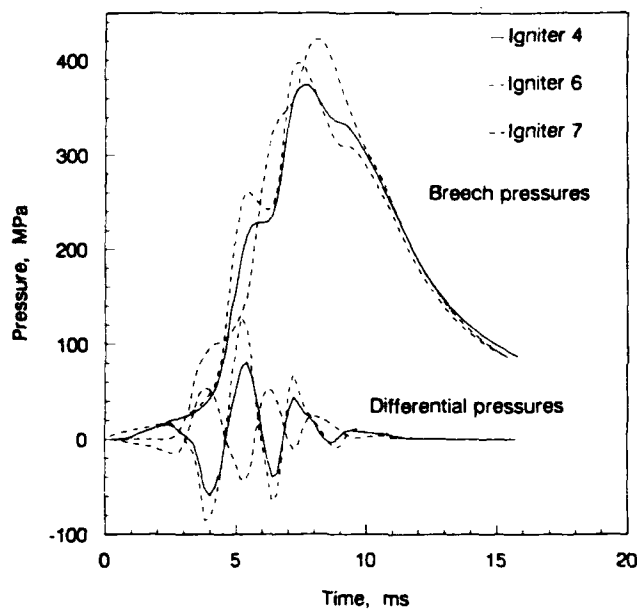


Figure 7e: Breech - and differential pressure-time curves.

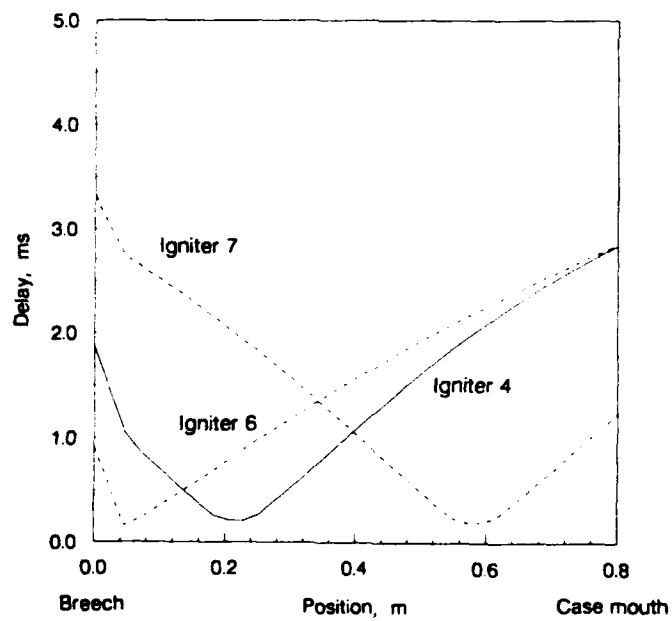


Figure 7f: History of flame spreading.

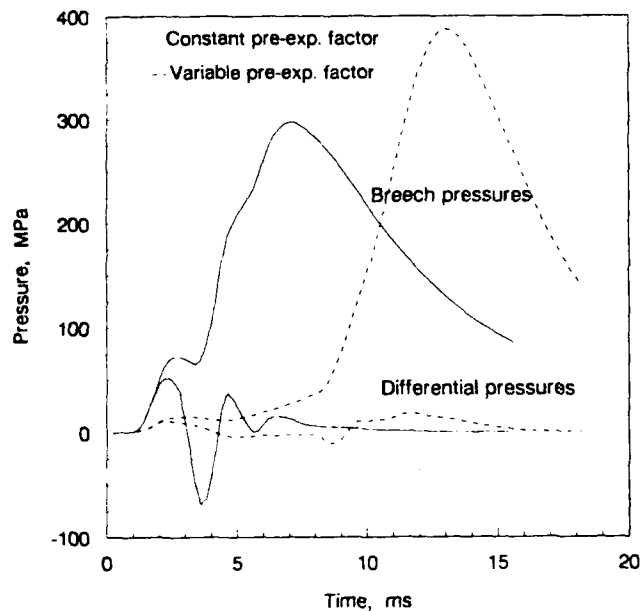


Figure 8: Breech - and differential pressure-time curves.

3. Influence of Kinetic Parameters on Modelling Results

Major discrepancies have been found in estimated and experimental flame spreading and in overall performance of LOVA propellant charges using the standard non-kinetic option of XKTC [3]. These can be overcome at least partly by the use of a kinetic sub-model which recognises that the energy liberation takes place in stages and that the first of these occurs near the surface with the formation of intermediate gaseous products. Subsequently the remaining energy is released during flame-zone reactions of the intermediates to final products. This process is modelled by Arrhenius reaction kinetics and is termed the one gas-phase reaction model. A more sophisticated approach, the two gas-phase reaction model, also includes a gas-phase reaction between intermediates and igniter gases. The following calculations have been conducted for standard charge configurations and a compression wave speed of 5307 m/s.

The simulations in Figure 9 have been performed using the three different kinetics options for XM39 LOVA. The relevant propellant data are listed in Table 1. The

theoretical predictions for the standard option without using the kinetic sub-model show the shortest ignition delay and highest build-up of pressure waves. Longer ignition delay times and less severe pressure waves were predicted for both kinetics options. The results for the one and two gas-phase reactions are nearly identical which is thought to be due to the use of the same kinetic parameters for the reactions between intermediates and igniter gases and intermediates and final products. The muzzle velocity predictions for these cases were 835.8 m/s for the non kinetic option, 779.5 m/s for the one gas-phase reaction and 782.6 m/s for the two gas phase reaction.

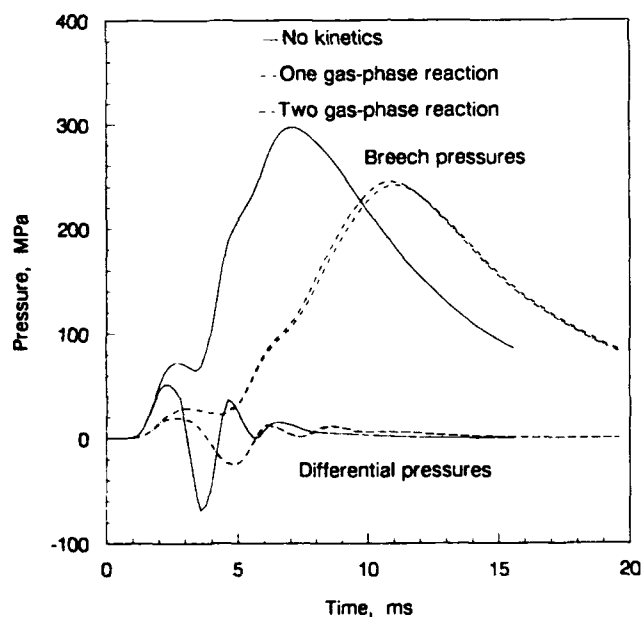


Figure 9: Influence of kinetics options on pressure-time.

Table 3 lists the results of model predictions using different activation energies and pre-exponential factors for the Arrhenius kinetics. As can be seen, lower pre-exponential factors result in lower maximum pressure, lower pressure differentials and lower muzzle velocities. Small changes in activation energy affect the maximum pressure and muzzle velocity predictions to a high degree. This can be also seen in Figure 10 where a 5% reduction in activation energy results in a 15% increase in maximum pressure and a 6.6% increase in muzzle velocity. Large differences in model predictions occur also when different fractions of energy are released during the gas-phase reactions. Currently no experimental firing results are available to verify any of these predictions. Experimental firings in a 40 mm gun using a variety of LOVA propellants will be carried out in the near future to validate and fine tune the model and establish kinetic options and parameters for the 5"/54 LOVA charge design.

Table 3: Parametric study of kinetics parameters

Kinetics Option	B(I) (m ³ /g.s)	E(I) (J/mol)	B(II) (m ³ /g.s)	E(II) (J/mol)	E _{react} /E _{total}	P _{max} (MPa)	V _{max} (m/s)	ΔP _{min} (MPa)	ΔP _{min} (MPa)
NO	-	-	-	-	-	297.50	835.80	-68.70	+51.30
one g-p	2.625E5	7.500E4	-	-	0.5	136.11	571.17	-23.38	+18.77
one g-p	5.250E5	7.500E4	-	-	0.5	241.60	779.50	-24.79	+19.49
one g-p	2.625E6	7.500E4	-	-	0.5	307.84	848.26	-42.68	+22.84
one g-p	5.250E6	7.500E4	-	-	0.5	297.65	838.90	-51.21	+32.62
one g-p	2.625E7	7.500E4	-	-	0.5	297.66	836.92	-61.17	+48.23
one g-p	5.250E7	7.500E4	-	-	0.5	297.85	837.80	-66.66	+49.57
one g-p	5.250E5	6.750E4	-	-	0.5	292.00	831.28	-27.42	+20.05
one g-p	5.250E5	7.125E4	-	-	0.5	278.24	814.29	-25.89	+19.71
one g-p	5.250E5	7.688E4	-	-	0.5	215.05	751.39	-24.40	+18.94
one g-p	5.250E5	7.875E4	-	-	0.5	152.21	643.03	-23.78	+18.82
one g-p	5.250E5	8.250E4	-	-	0.5	139.51	588.19	-23.52	+18.74
one g-p	5.250E5	7.500E4	-	-	0.2	282.28	819.20	-57.50	+40.42
one g-p	5.250E5	7.500E4	-	-	0.4	269.76	805.20	-36.90	+25.78
one g-p	5.250E5	7.500E4	-	-	0.6	111.25	487.23	-14.68	+14.19
one g-p	5.250E5	7.500E4	-	-	0.8	80.97	322.78	-4.50	+8.46
two g-p	5.250E5	7.500E4	2.625E5	7.500E4	0.5	243.77	781.47	-25.06	+19.58
two g-p	5.250E5	7.500E4	5.250E5	7.500E4	0.5	245.18	782.60	-25.28	+19.72
two g-p	5.250E5	7.500E4	2.625E6	7.500E4	0.5	255.03	790.59	-28.07	+20.64
two g-p	5.250E5	7.500E4	5.250E6	7.500E4	0.5	258.85	791.38	-31.80	+21.90
two g-p	5.250E5	7.500E4	2.625E7	7.500E4	0.5	271.71	802.85	-49.18	+35.33
two g-p	5.250E5	7.500E4	5.250E7	7.500E4	0.5	275.94	808.65	-54.30	+43.03

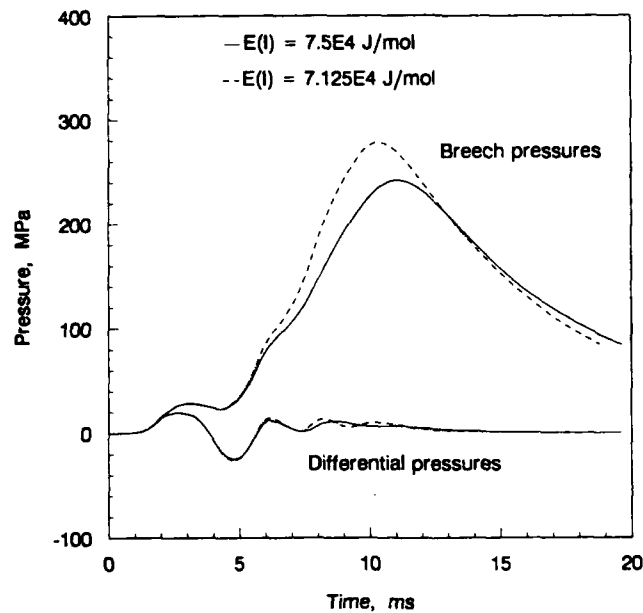


Figure 10: Influence of activation energy on pressure-time.

Ignition criteria are not well understood. XKTC nominates a grain surface temperature to specify when ignition occurs. To establish the value experimentally outside a gun chamber is very difficult since it not only depends on the heating rate of the propellant grain but also on the type of heating (conductive, convective, radiative). Figure 11 shows the model predictions for different ignition temperatures. To establish the sensitivity of the model to this parameter, calculations were conducted for a two gas-phase reaction scheme and ignition temperatures of 476 K and 556 K. As expected the higher ignition temperature results in a slightly longer ignition delay time. The overall interior ballistic behaviour however is very similar for both cases.

4. Conclusions

The study showed the various parameters which influence the XKTC model predictions and explored the limits of the code. To avoid pressure waves it is important to minimise ullage and maximise bed porosity. The igniter discharge function is also important but the XKTC code is not sufficiently sophisticated to provide detailed design criteria for igniters — a two dimensional model is needed.

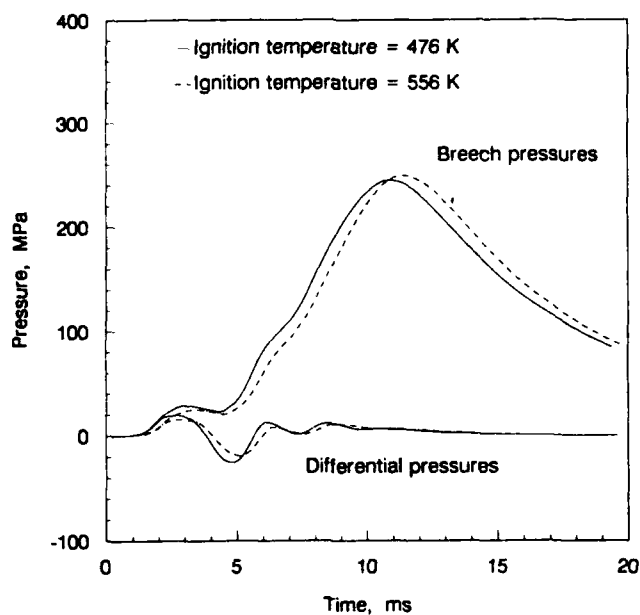


Figure 11: Influence of ignition temperature.

Substantial changes in the predicted interior ballistics were observed using the different kinetic options available in XKTC and the predictions were also found to be very sensitive to burning rate parameters.

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Influence of ignition related parameters and charge configurations on XKTC model predictions

AUTHOR(S)
Anna E. Wildegger-GaissmaierCORPORATE AUTHOR
DSTO Materials Research Laboratory
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ABSTRACT

A parametric study has been conducted to assess the influence of ignition related parameters and charge configurations on model predictions using the one-dimensional two-phase flow interior ballistics code XKTC. The investigation showed that the code is sensitive to charge configuration parameters such as bed porosity and ullage, and their effect on compression wave speed. Minimisation of ullage and maximisation of bed porosity reduce the probability of damaging pressure waves. Substantial changes in interior ballistic performance could be observed for the different kinetics options available in XKTC and for changes in kinetic parameters. Although the code is useful for igniter design, a two dimensional model is recommended for more realistic predictions.

Influence of Ignition Related Parameters and Charge Configuration
on XKTC Model Predictions

Anna E. Wildegger-Gaissmaier

(MRL-TR-92-31)

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