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REACTIVE FLOW MODELS FOR THE DESENSITISATION OF HIGH EXPLOSIVES

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Abstract

Mechanical desensitisation of explosives (e.g. by compaction) has important technological consequences for safety and performance. Many widely-used reactive flow models are not capable of reproducing the desensitisation observed in experiments such as measurements of double-shock particle velocity profiles. Improved models are under development, in which we intend to incorporate enough flexibility to reproduce experimentally observed shock desensitisation while retaining plausible and computationally practical physical models for the equations of state (unreacted, partially-reacted and products), equilibration processes and reaction rate. One application of experimental and reactive flow studies is to suggest ways of minimising the damage caused by explosives. Shock desensitisation on microsecond time scales may not be directly relevant to this application, but the reactive flow models deduced might indicate how and to what extent reaction can be influenced by manipulating the external environment.

Introduction

Desensitization of explosive by shock-compaction is a well-known phenomenon, for which the mechanism is not completely understood. The mechanism of shock desensitization may promote a more general understanding of the response of explosives to shocks. The state established by the first shock can be viewed as a unique initial state in the explosive, a state at relatively high density and at elevated temperature, limiting the variables which can affect the explosive's response to a second shock.

Hotspot removal, by compression, chemical damage, or thermal degradation of the hotspots is the usual mechanism cited to explain preshock desensitization.

Some workers report a time constant associated with desensitization, a time period after shocking during which the material exhibits no desensitization, or during which the degree of desensitization increases gradually. This time constant is assumed to be the time required to close or to damage the hotspots in the explosive.

Under the conditions of high compaction resulting from shock compression of an explosive, removal of voids from the material is a reasonable expectation. To the extent that these voids comprise the hotspots in the material, their removal suggests that the explosive should behave more like homogenous material. Data obtained from in-material gauges [1] suggest that initiation proceeds in a homogeneous manner after preshock compression of the explosive. In-material gauges record material response at the shock front, and also record velocities in the following flow where reaction is most evident during homogenous initiation.

Experimental observations of preshock desensitization are numerous. [1] Of these, two are studied here. Experiments done [2] on the TATB-based explosive EDC-35 record the

interaction of a shock (L) with a well-established propagating detonation (A). Data show the extinction of the detonation wave in the region where the shock has passed. These images show the full importance of the phenomenon in practical situations, and demonstrate the effectiveness of preshocking the material in hindering subsequent detonation of the preshocked explosive, even under the strong stimulus of a propagating detonation.

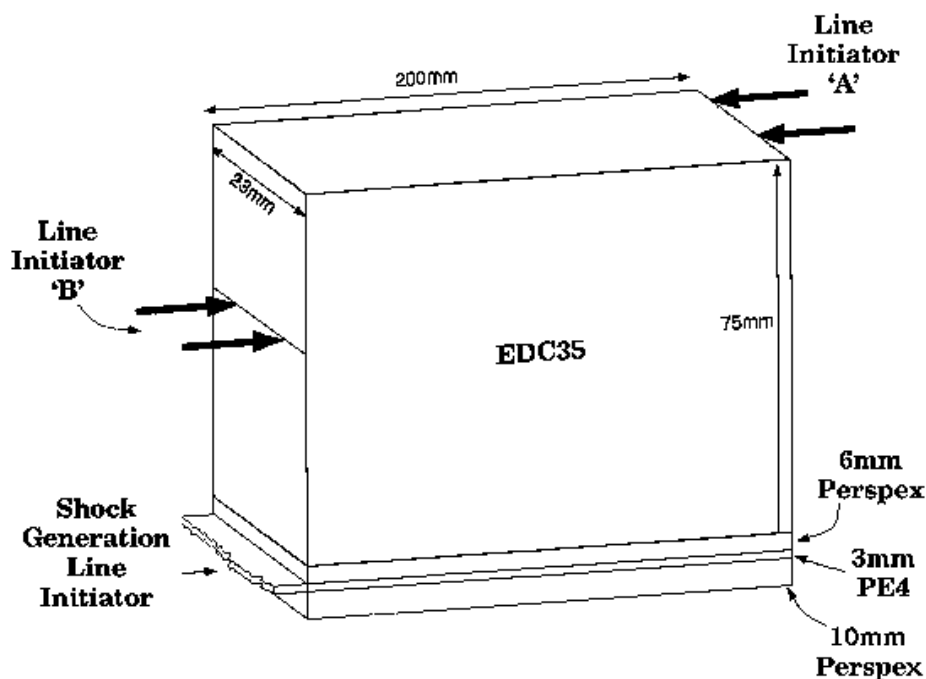


Figure 1. Schematic of multiple shock experiment observed with framing camera [2]

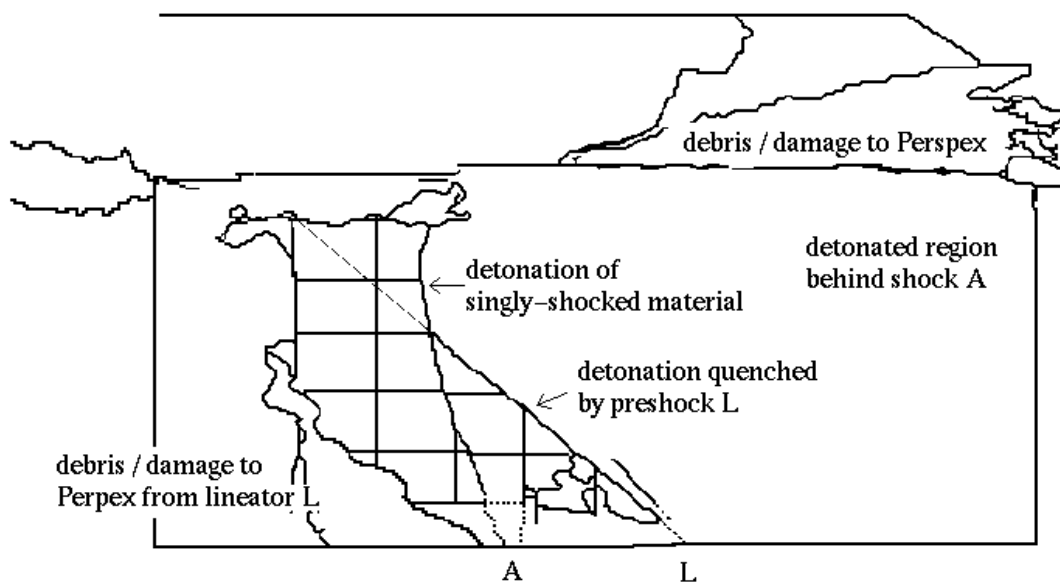


Figure 2. Selected frame from framing camera record of multiple shock experiment [2]

These spectacular results are difficult to model, as the waves are propagating in 3-D, pressures are difficult to estimate, particularly in the divergent geometry, and edge effects are uncontrolled.

A simpler case showing the same desensitization effect is examined in detail. This geometry provides a 1-D case with a planar and well-supported input wave, which simplifies the modelling. Shocks are generated by the direct impact of a projectile accelerated using a gas gun. Details regarding experimental technique can be found elsewhere. [3]

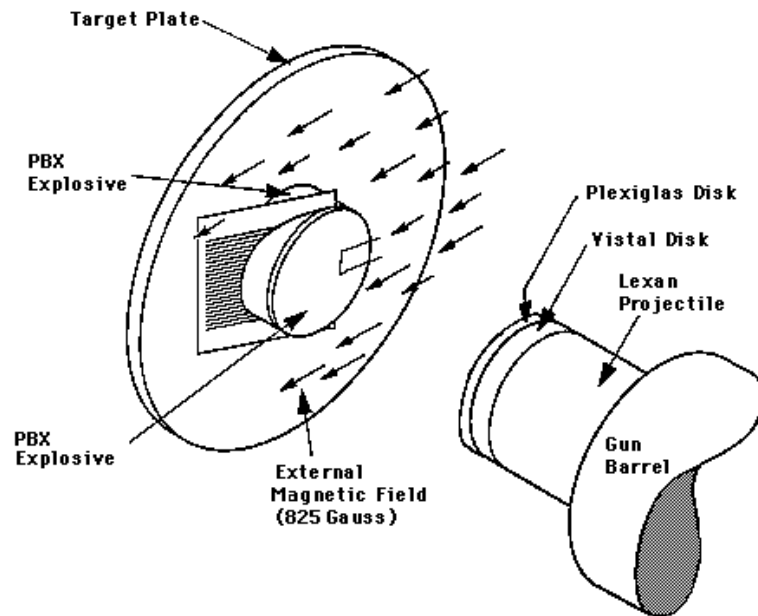


Figure 3. Schematic of gas gun experiment generating 1-D multiple shock data

The preshock is generated using a composite impactor consisting of a low impedance thin layer on the front surface of a high impedance (vial, amorphous sapphire) impactor mounted on the projectile. This low impedance layer generates the first shock, and shock reflection from the vial generates the second shock, as shown in the $x-t$ diagram in Figure 4. The impedance of the thin layer is chosen to match the impedance of the explosive target, to prevent multiple shocks or "ringing up." This projectile impacts a precisely machined flat explosive cylinder containing the gauges.

Particle velocity, u_p , is measured directly at 10 Lagrange positions, using ten nested magnetic gauges. Shock velocity U_s is obtained independently from time of arrival at the different gauges.[4] A stirrup gauge on the explosive surface records the profile of the input wave generated at impact. The error in particle velocity u_p is 1 to 2% depending on the level of noise in the signal.

Experiments have been done on PBX-9404 and PBX-9501, both HMX-based explosives. Explosive PBX-9501 is a plastic-bonded (PBX) composition consisting of 95% HMX, 2.5% estane, and 2.5% BDNPA/BDNPF.[5] PBX-9404 is a plastic-bonded composition consisting of 95% HMX, 3% nitrocellulose, and 3% CEF (chloroethyl phosphate). [5]

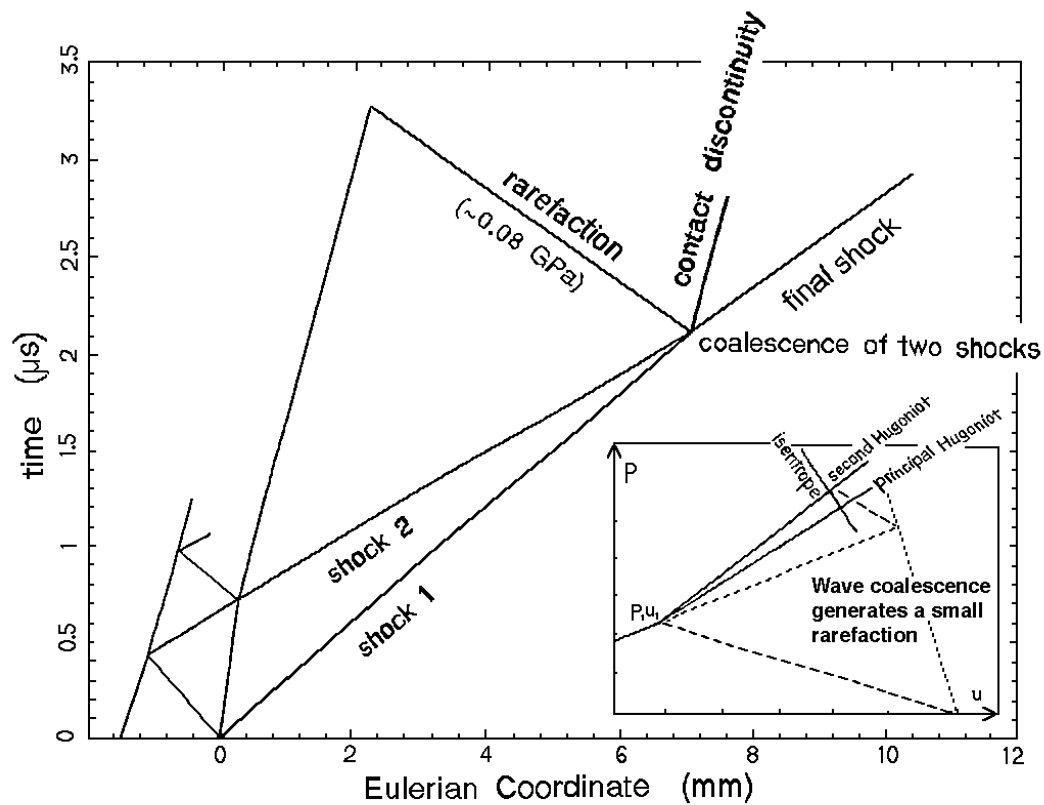


Figure 4. X-t diagram and P-u diagram showing input shocks and subsequent waves.

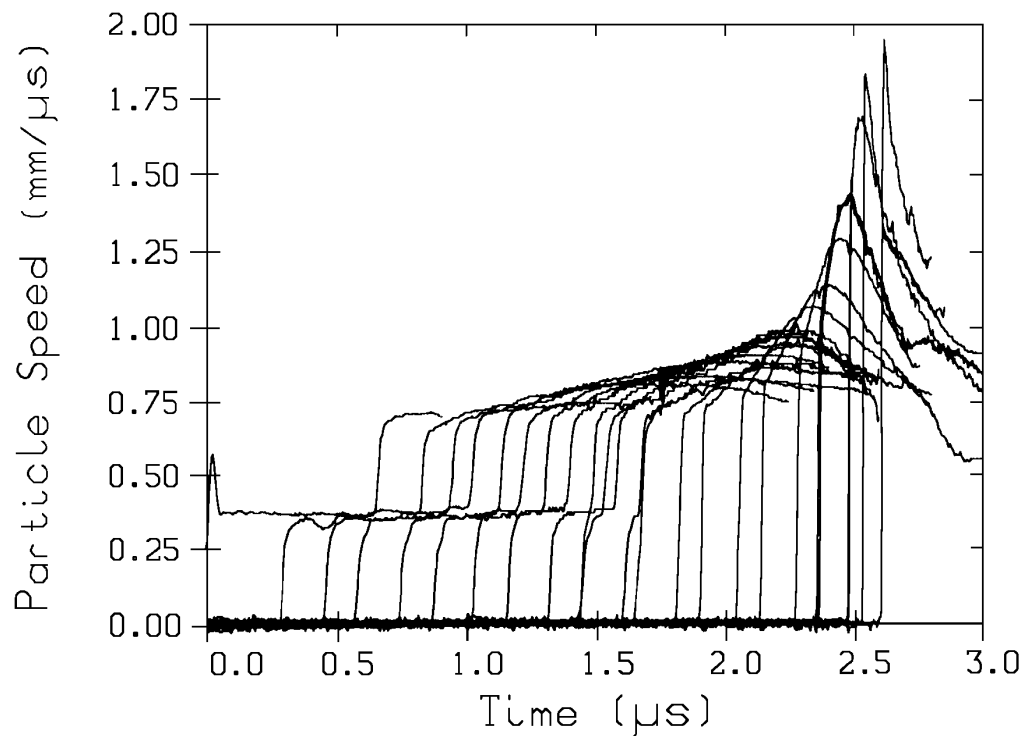


Figure 5. Gauge records showing initiation of PBX-9404.

Physical Mechanisms for Initiation

Mechanisms for the shock initiation of detonation can be affected by shock desensitization. Several recognized mechanisms are discussed below. Hydrocode calculations are used to estimate the effect of each in the context of desensitisation.

The reaction of hotspots and thermal reaction of bulk explosive are conveniently separated conceptually by considering two separate initiation mechanisms. Homogeneous initiation relies only on bulk chemical reaction, according to the uniform thermal state generated by the shock. Heterogeneous initiation allows production of localized regions of high temperature, "hotspots," where reaction rates can exceed the rates appropriate to the thermodynamic state of the bulk. Both homogeneous and heterogeneous initiation are mechanisms that have been observed in selected systems.

Hotspots are frequently assumed to be generated from small voids within the solid, which collapse suddenly during the passage of the shock, resulting in localization of deformation and hence localization of shock energy, resulting in an elevated local temperature. Several factors may affect the behavior of voids. The collapse will obviously vary according to the size of the void, relative to the mechanical properties of the surrounding material. The loading history will affect the rate of collapse in general.

Viscosity [6] of the bulk will affect the volume over which the distortion occurs: a low viscosity will permit distortion of a large volume, with the resulting energy deposition being reduced at any single location. In a highly viscous medium, more energy will be dissipated in a localized manner around the void, a phenomenon which might be considered to be the mechanical equivalent of adiabaticity. Similarly, thermal conductivity will reduce the localization of thermal energy. Over the short distances and with the high thermal gradients involved in shock desensitization, thermal conductivity may occur quickly enough to reduce reaction.

Experimental observations show that material of a very low porosity is more difficult to initiate, culminating in the phenomenon of "dead-pressing." The degree of localisation of energy depends on spatial variations in the response of the material to dynamic deformations. At the crudest level, the variations in response can be correlated with variations in mass density. Thus the hotspot initiation properties of material which has undergone a given loading history can be considered in terms of the instantaneous difference in density between bulk material and that in the "voids." In general, variations in material response allow a higher transient temperature to occur in localised regions, i.e. allow hotspots to form where high temperature provokes reaction at a high rate. In the absence of such density variation, reaction will commence at a lower rate, corresponding to the bulk temperature.

All of these hotspot mechanisms should depend on initial temperature. The exact response to initial temperature may serve as a distinguishing feature. A high initial bulk temperature permits less difference between the bulk and the hotspot temperature, affecting thermal conductivity and reducing the effectiveness of thermal adiabaticity. Similarly, at higher temperature, the material will generally soften, resulting in a reduction in "mechanical adiabaticity" or localization of energy, and a reduction in the heat generated in producing a given amount of shear. These effects compete with the increased Arrhenius rate to reduce hot-spot induced reaction, effectively increasing bulk (homogeneous) reaction and decreasing hotspot (heterogeneous) reaction. Thus after a preshock, the elevated temperature alone reduces the effectiveness of hotspots, while raising the Arrhenius rate. Regardless of damage to hotspots, the contribution of the Arrhenius rate may be enhanced.

Hotspots may take other physical forms. Shear bands that form in response to the shock are a mechanism for localization of the mechanical energy of the shock. Localization of energy on lattice defects will behave similarly. Formation of shear bands is greatest when the material, or a component, such as HMX, is stiff or brittle. A mechanism similar to shear is the homogeneous (molecule-level) reaction when a molecular crystal such as an explosive is distorted, resulting in interaction of packing layers of molecules. This distortion evidently produces non-equilibrium excitation of certain electronic or vibrational modes, resulting in dissociation and reaction of the molecules at the plane of distortion. This phenomenon is evident in PETN and HMX single crystals, in which initiation pressure depends on orientation of a single crystal. [7]

Dependence on grain-size has been extensively studied, and is a complex question. Grain size affects the density of potential hotspots, while reducing their size. Smaller voids are recognized to be ineffective in producing reaction. Rate-dependent strength makes smaller voids more difficult to compress. For hotspots, this means less deposition of energy. Because of the greater surface area to volume ratio of small hotspots, they cool faster, and distribute the localized energy over less material.

Desensitisation

A plethora of physical mechanisms has been proposed to account for desensitization of explosive charges by a preshock. Most commonly cited is the destruction of voids by compression, removing sites for formation of "hotspots." By definition, the initial shock is too weak to initiate a detonation in a distance comparable with the run distance expected on the second shock.

- **Void closure.**
On shocking, voids collapse in a certain time, producing a hot region and much smaller residual void. This modified microstructure is less susceptible to shock initiation, because of the smaller difference in densities, the difficulty of localising energy in a smaller void, and the softness of the bulk material at its elevated temperature.
- **Hotspot burn-out.**
If a little material reacts in the vicinity of hotspots caused by the preshock, the density difference between "voids" and bulk will be less, and thermal conduction from the hot products will cause further softening of the bulk material round about. Any solid material around the void will presumably be inert products not subject to reignition by subsequent heating at the void. On the other hand, the high pressure products are likely to disrupt the microstructure in the vicinity of the hotspots, possibly making the shocked explosive more sensitive, and engaging more unreacted material in any subsequent hotspot dynamics. [8]
- **Grain size reduction.**
Unless the preshock is very weak, it may have a significant "working" effect on the microstructure. After the passage of the preshock, the density of shear bands and the number of deformation twins and fractured grains may be substantially increased from the virgin explosive. These modifications can be regarded as a reduction in the effective grain size, with a concomitant difference in initiation properties. [9]
- **Bulk heating.**
The preshock raises the bulk temperature of the explosive. Viscosity and plastic flow stress generally decrease with temperature, so bulk heating will be decreased somewhat. Localized heating caused by a second shock may be substantially less than the heating caused by a single shock to the same pressure.

The effects described above are in general likely to be quite material-dependent. In the present work we apply them to one particular explosive (PBX-9404); we make no claim that our conclusions on the dominant mechanisms for the desensitisation of this material apply to all other compositions.

Reactive flow models

Models of material properties should ideally represent the actual physical processes in a realistic way, insofar as these processes are known. For simulations in the continuum approximation, the relevant processes are the mechanical behavior and chemistry at the microstructural level. Physically-based models can be expected to have a greater region of validity, and it is often possible to calibrate them against accurate static measurements, rather than varying parameters to match a dynamic simulation to an integrated experiment.

An ‘ideal’ reactive flow model, capable of investigating the initiation and desensitisation properties of a wide range of explosives, might contain the thermal and mechanical properties for each spatially distinct phase in the composition and a representation of several critical processes in the chemistry, sufficient to determine the rate-governing step in a range of scenarios. The mechanical properties might include the equation of state (EOS) and elastic-plastic behaviour, with a description of the evolution of the population of dislocations. The local state in each computational cell might describe the spatial distribution of each component of the composition, and the distribution of the thermomechanical state (density, temperature, elastic strain, dislocation density) in each phase. The use of some form of distribution might be used to represent the variation in particle size and in the temperature in bulk material near a hotspot. Each distribution might be a quantised population (e.g. considering the evolution of particles of a range of discrete sizes) or some smooth representation.

Models are becoming more sophisticated and representative with time, but we have not yet reached a state where a model of this detail can be countenanced for ‘engineering’ simulations of explosive systems. Apart from the expense of determining the material properties, the amount of data required to describe a dynamically-deforming system would use a prohibitive amount of storage and computational time.

In the present work we consider types of model which should provide enough freedom to model the initiation and desensitisation of many explosives, without adding too great an overhead for storage or computations. While simpler than the type of bottom-up microstructural model outlined above, the models used in this work at least address microstructural processes, without treating them fully. Initial values for most parameters were obtained from the composition, texture, and other measured properties of the unreacted explosive, rather than calibration against dynamic experiments.

There is a natural hierarchy of complexity in explosive models. For simple blast simulations it can be sufficient to treat the explosive as fully reacted at the outset. When more detailed information is needed on the motion of materials next to the explosive, programmed burn models can be used to describe the time at which each element of explosive is converted to detonation products, and hence deduce the loading history experienced by the adjacent materials when the explosive detonates completely. If the time at which each element of explosive detonates cannot be determined without a hydrodynamic simulation, the explosive state can be described by a single reaction progress variable (‘mass fraction reacted’), conventionally 0 for unreacted material and 1 for detonation products and representing the mass fraction of reaction products in any finite region of space. The reaction progress variable is coupled to the hydrodynamics by a reaction rate

law, a function of the local thermodynamic and/or microstructural state. For more complicated materials, several different species may be considered along with a set of reaction rates. The ultimate form of model here is finite-rate chemistry, although for solid explosives, microstructural effects may dominate.

Even a single reaction progress variable represents a significant increase of complexity over programmed burn, because at intermediate stages of reaction it is necessary (at least in principle) to consider the mechanical and thermal interaction between spatially-separate regions of unreacted material and reaction products.

In the present work, a slightly modified form of single parameter reactive flow was used. The continuum model described the local thermodynamic state (density and specific internal energy) for two materials, and the local volume fraction of each. The materials represent the unreacted explosive and the reaction products. The mass fractions can be calculated trivially from this information, to give 'standard' single parameter reactive flow. Porous materials can be represented by starting with a non-zero volume fraction of products. This is not a perfect model, because in general the contents of the pores will not contain material with the same density and energy as reaction products at the same pressure and temperature, but it is a reasonable model for pores containing low density gas.

Pressure and temperature were equilibrated explicitly according to a separate time constant for each. This produces an exponential approaches to mechanical and thermal equilibrium separately. 'Perfect' equilibration was enforced by setting the time constants to a small value.

Many forms of reaction rate can be and have been developed, notable examples being Arrhenius, Forest Fire and Lee-Tarver. The Arrhenius rate is probably the most physical representation of the chemical reaction process at the molecular level, but it is inappropriate for direct use in heterogeneous materials where the macroscopic reaction rate is dominated by effects such as grain burning.

To allow some of the other desensitisation mechanisms to be investigated, an extra term was added to the simple bulk reaction rates to estimate the different rates found in the region of a hotspot. For any given pair of reactant and product states and volume fractions, the volume of reactant affected by the state of the products was estimated from the hotspot surface area (a function of the reacted volume fraction and the number density of hotspots) and a length scale reflecting the hotspot volume (available heat and mechanical energy), and from the time scale for thermal equilibration. Some fraction of this volume of material (generally half) was allowed to react at a rate given by the state of the hotspot rather than the bulk of the unreacted explosive. The extra parameters in this model, the length and time scales, were treated as material constants. In principle, they could be considered as additional continuum variables and evolved according to other microstructural processes.

Comparison with Experiment

A Lagrangian hydrocode was used to simulate dynamic experiments, and hence allow the models to be evaluated against experimental data. The hydrocode used a finite difference representation of the continuum equations, integrating the hydrodynamics with a predictor-corrector scheme. Shock waves were stabilised with Wilkins' bulk artificial viscosity. Reaction was operator-split from the hydrodynamics and subcycled, using a forward-time integration scheme. The pressure and temperature equilibration scheme was also subcycled. Pressure equilibrium was approached by varying the volume fractions, allowing the higher-pressure component to do work on the other component. These density changes were assumed to be isentropic. Heat flow between the components was calculated

at constant density. (In other words, mechanical and thermal equilibration were operator-split from each other.) Material strength and heat conduction were not treated.

For the present work, the models were compared against a single 1-D geometry, the experimental geometry generating the data shown in Figure 5. The impactor consisted of ~2 mm Perspex (Plexiglas) and 11 mm Vistal mounted on a Lexan projectile. The projectile speed was 0.931 km/s. The target was PBX-9404.

EOS for the inert materials were taken from a Livermore compendium [10] and for the explosive, from a Livermore review [11].

The starting density of the explosive was assumed to be 1.843 g/cc. The theoretical maximum density of 1.872 g/cc implies that the porous and heterogeneous models had a void fraction of 1.5% at this starting density. The products EOS was found to give a reasonable starting pressure and temperature for a density of 0.001 g/cc and energy of 0.002 Mb.cc/g in the hotspot. (This is a reasonable model for air at STP.) A hotspot separation of 10 μm was assumed for area(volume) relation and length scale for the heterogeneous reaction model. This was intended as an order of magnitude estimate based on the grain size.

The simulations used a mesh size of 0.1 mm throughout; no systematic studies were performed of the sensitivity to mesh resolution, artificial viscosity, or other hydrocode parameters. The results described below should be regarded as preliminary and semi-qualitative.

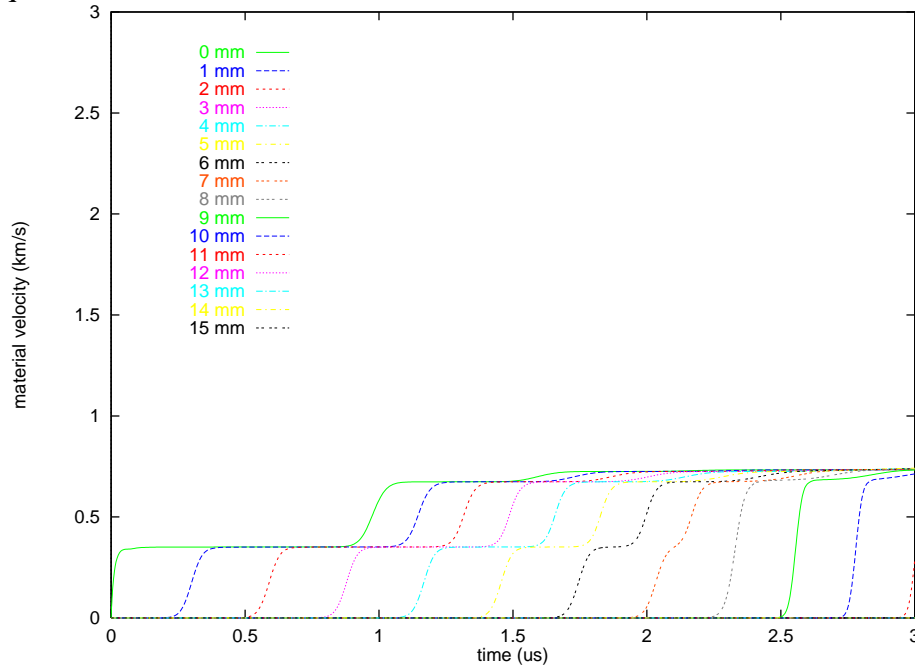


Figure 6. Gauge traces resulting when no reaction is permitted, “inert” model.

A simulation was performed with the reaction rate disabled. According to the EOS used, perspex (Plexiglas) was an imperfect impedance match for PBX-9404. The temperature behind each shock was predicted to be:

first	338 K
second	361 K

combined 417 K

If these temperatures are at all accurate, the difference between doubly and singly shocked material alone is enough to account for a large apparent desensitisation.

Using the Lee-Tarver reaction rate, initiation took place shortly after the shocks merged. A heterogeneous build-up was evident beforehand, quite unlike the experiment.

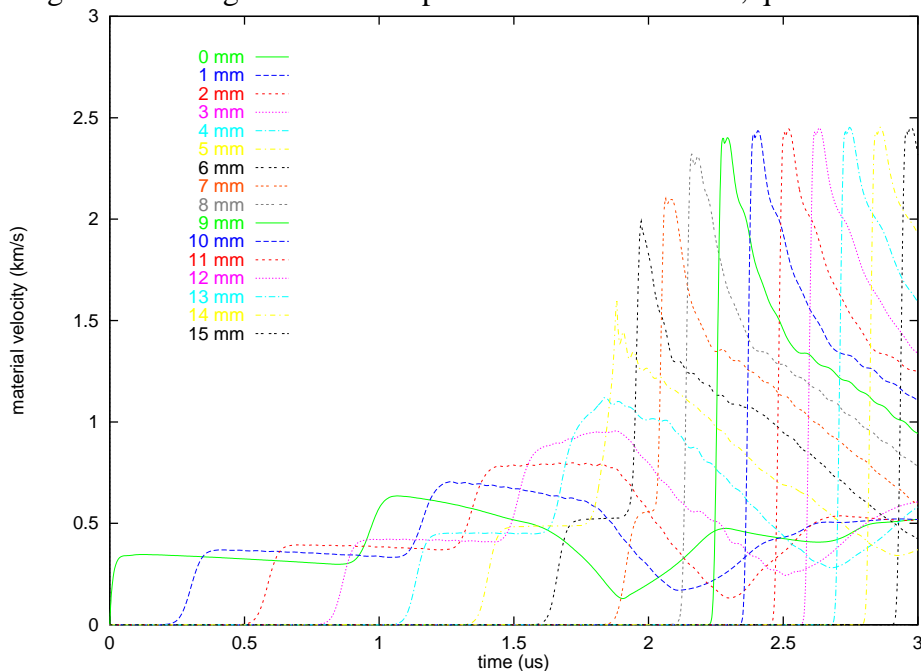


Figure 7. Gauge traces generated using Lee-Tarver ignition and growth model.

The Arrhenius activation energy and frequency factor were taken for HMX. [Gibbs80] In the hydrocode, the Arrhenius rate used a reference temperature rather than an energy; this was calculated by dividing the activation energy per molecule by Boltzmann's constant to obtain $T \sim 26621$ K. Dividing instead by the heat capacity, an explosion temperature of about 568 K is obtained. This is roughly comparable with the temperature of the reaction exotherm on the 1 atm isobar (~ 625 K).

Treating PBX-9404 as homogeneous and using the HMX values for the Arrhenius rate, negligible reaction was predicted in the system. Although Arrhenius rates are almost invariably used with a constant frequency factor and activation energy, in reality both are likely to depend on the thermodynamic state. The frequency factor is likely to increase smoothly with density, but to experience sudden changes across phase boundaries. (PBX-9404 is affected by the HMX phase change at ~ 480 K on the 1 atm isobar.) The activation energy is likely to change in a similar way, except that for explosives it is likely to decrease with density.

Temperatures predicted by Tarver's form of the JWL EOS, while not outwith the bounds of plausibility at low pressures, are likely to be inaccurate in the partly-reacted material and reaction products, and at higher pressures on the unreacted Hugoniot. This EOS is not thermodynamically consistent.

The sensitivity to activation temperature and frequency factor was investigated by performing calculations with different values for each. It was found possible to reproduce the time to initiation, although the profiles during build-up did not resemble the smooth rise

observed in the experiments. The adjusted values were much closer to the temperature deduced from the literature activation energy for PBX-9404 (~ 15800 K [12]), which is lower than that for pure HMX because of the nitrocellulose binder.

As predicted by comparing the temperatures behind the inert shocks, the effect of double shocking was to reduce the sensitivity to shocks at these pressures.

Detonation first occurred a short distance behind the combined shock. A second initiation site was predicted at a similar time at the impactor surface, where the explosive had been hot for the longest time.

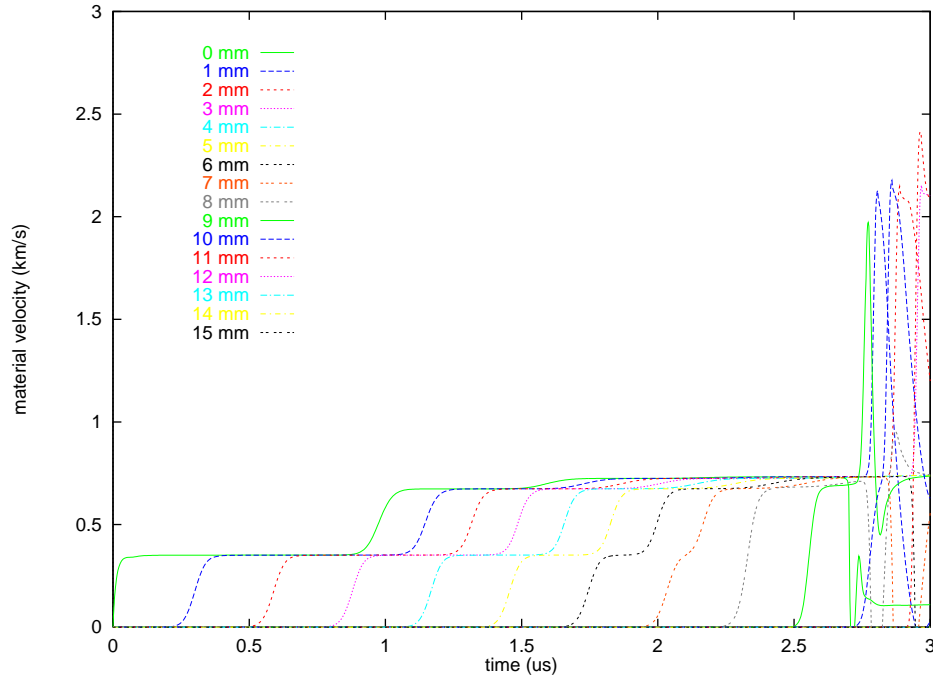


Figure 8. Gauge traces arising from reaction governed by unmodified Arrhenius behavior.

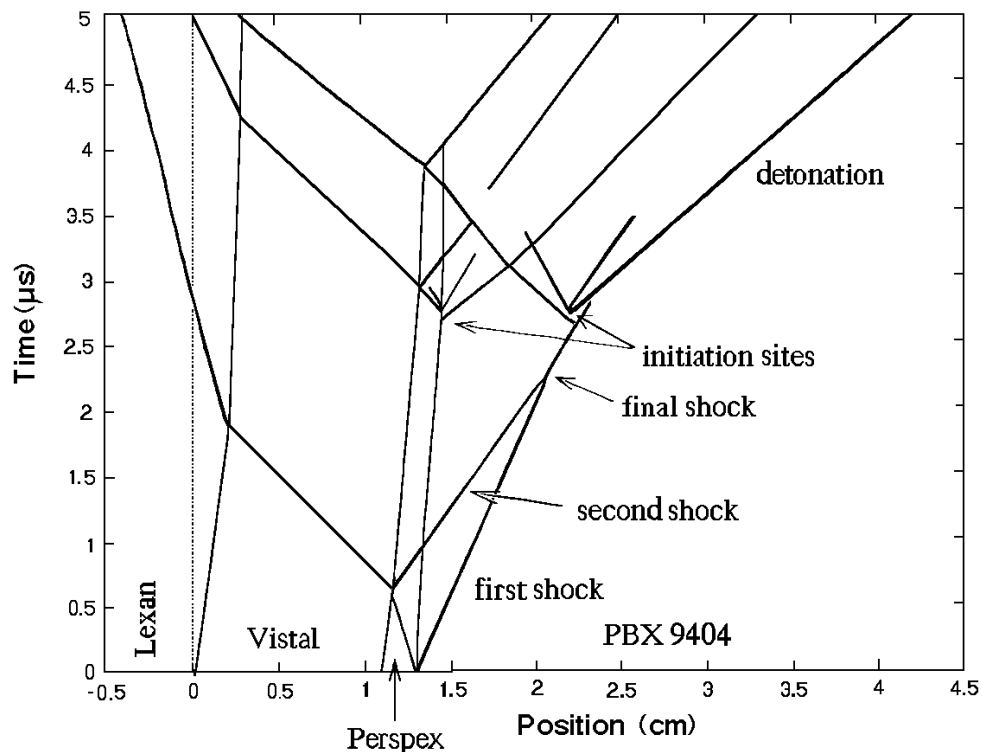


Figure 9. The x-t diagram calculated using unmodified Arrhenius rate shows development of reaction in material well behind the shock front.

Using the porous model, time to initiation was systematically less than for homogeneous material. However, the build-up profiles still did not resemble the measured profiles particularly well.

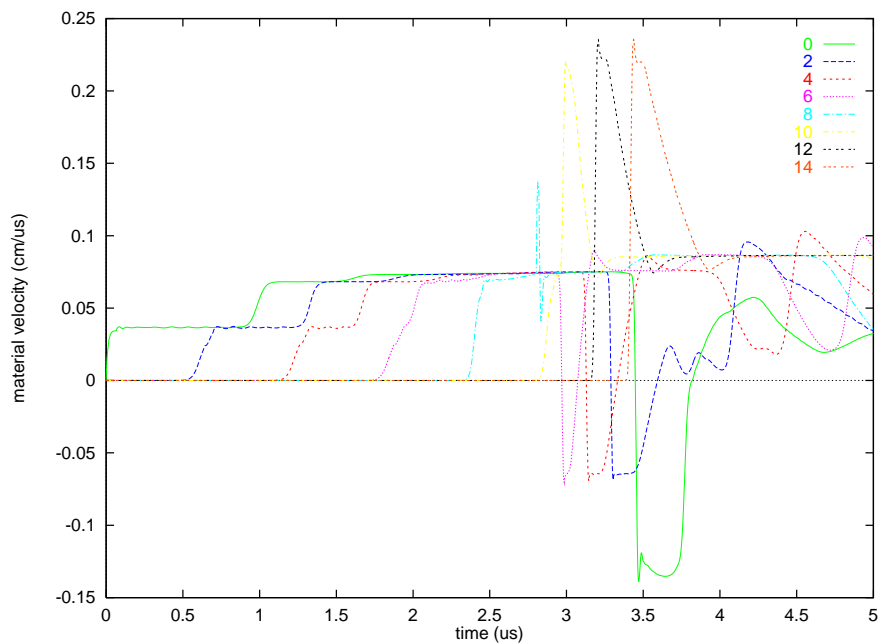


Figure 10. Gauge traces generated by a "Porous Arrhenius" reactive model, allowing pores to contribute thermal energy to the bulk without allowing reaction at pores.

Using the heterogeneous model, the time to initiation was systematically less than for the porous model. While still not an accurate representation of the experimental record, the profiles exhibited some evidence of a slower build-up. A more thorough study of the effect of equilibration and hotspot reaction parameters offers a reasonable possibility for matching the experiments quite closely.

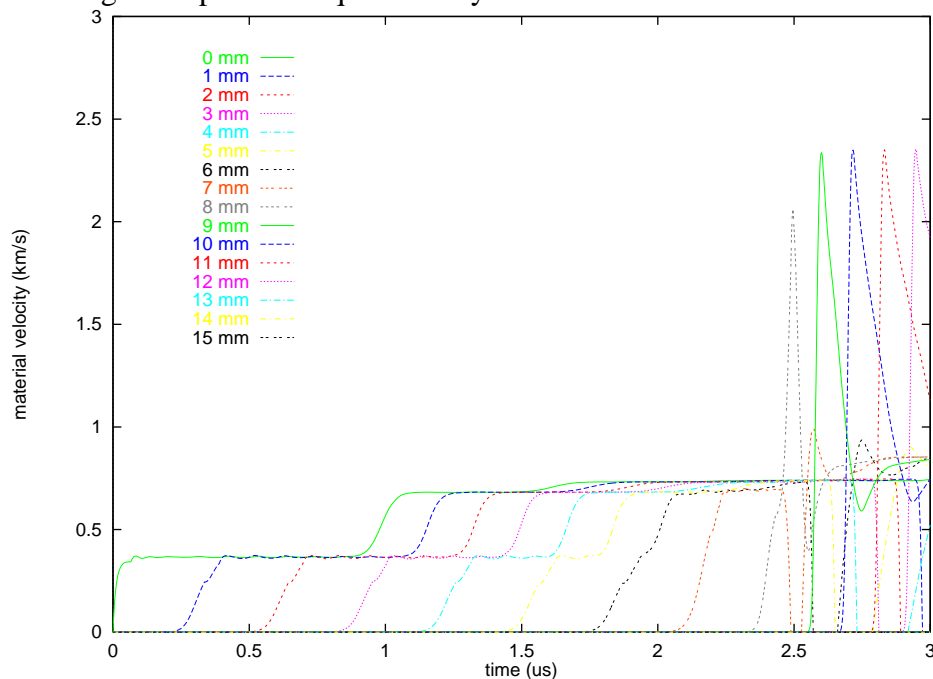


Figure 11. Gauge traces generated by “Heterogeneous Arrhenius” reactive model. Reaction at pores commensurate with heat from pore compression.

Table 1. Models, Temperatures, and Activation Energies, and Time to Initiation for Each

Model (A = pre-exponential factor)	Approximate Time to Initiation (μ s)
Lee-Tarver	1.9
Arrhenius ($A = 5 \text{ e}19 / \text{s}$)	
26621 K	-
15000 K	3.5
14500 K	3.0
14400 K	2.8
14300 K	2.7
14000 K	1.8
13300 K	second shock
Arrhenius ($A = 5.9 \text{ e}14 / \text{s}$)	
26621 K	-
9950 K	2.7

Arrhenius, porous (A = 5 e19 / s)	
26621 K	-
20000 K	-
17500 K	-
16000 K	4.6
15500 K	3.5
15000 K	2.9
14900 K	2.8

Arrhenius, heterogeneous (A = 5.9 e14 / s)	
26621 K	-
13300 K	3.6

Arrhenius, heterogeneous (A = 5 e19 / s)	
26621 K	-
16500 K	2.4
16000 K	1.7

(entries marked as '-' showed no significant reaction in the explosive during the 5 μ s of the simulation)

Minimising explosive damage

In principle, desensitisation is of interest as a way of reducing the damage caused by unwelcome explosive devices. The relevance and effectiveness of any desensitising mechanism depends on the definition of 'damage' - which may subsume the principles of operation of the device and the environment in which it is placed.

A certain amount of chemical energy is present in an explosive, and short of physically removing explosive material it is difficult to envisage a general way to reduce the total energy released following thermal or mechanical attack. However, if the time scales for reaction were altered sufficiently, released energy could be coupled to surrounding structures in a more benign way.

Although striking desensitisation effects can be seen on short time scales, the use of shock waves to 'make explosives insensitive' in any long-term sense is clearly largely impractical. Voids are likely to re-open after the passage of a shock wave, and the stresses caused by interacting rarefactions can open up more spaces than were initially present. In compensation, the re-expanded material will remain warmer for some time; this should make the explosive softer and hence less prone to initiation by plastic work. The success of this type of strategy is material-dependent, and also depends on the device geometry since a desensitising shock could reflect from a high impedance surface and cause initiation directly.

The value of the work presented here lies in clarifying the effective desensitizing changes produced in the explosive by the compressive shock. An understanding of the active factors would clarify not only avenues of desensitizing alteration, but would also illuminate the mechanism of initiation, suggesting approaches not directly related to compression.

The shock desensitization observed here, while probably irrelevant for long-term desensitisation, could conceivably have applications where it is desired to disrupt the detailed propagation of a detonation wave in a body of explosive. However, this scenario assumes that a way can be found to synchronize the quenching shock with the detonation wave. An explosive train might be used to generate the shock from the detonation itself rather than attempting to arrange an electrical link.

Fundamental data and physically-based models are of particular value in this field. Candidate methods for desensitising - whether by dynamic means or by altering a composition - typically involve a wide range of materials and states. Physical and performance data may be scarce for some of these systems. Models developed with consideration for the underlying physical processes occurring in an explosive are far more likely to be applicable to new situations - and hence provide a predictive capability - than are restricted empirical models.

Conclusions

Shock desensitisation is a real effect, on microsecond time scales at least. The behavior observed exhibits a mixture of homogeneous and heterogeneous features.

The Lee-Tarver reactive flow model produces reasonable build-up shapes, but does not reproduce the desensitisation observed in PBX-9404.

Temperature has a substantial effect. A homogeneous Arrhenius model exhibits desensitisation simply because of the lower temperatures generated by compressing to a given pressure through two shocks rather than one. From a simple chemical kinetic point of view, this reduced temperature is enough to account for the observed desensitization. However, the particle velocity profiles immediately prior to initiation were not in agreement with the experiments. The Arrhenius terms alone are evidently insufficient to adequately describe the experimental phenomena.

A heterogeneous (porosity) model was described which does not require any field parameters in addition to the single-parameter representation of reactive flow. This model was used to investigate the properties of Arrhenius-based heterogeneous reactive flow, attractive because of its relatively sound physical / chemical pedigree. Porosity provides a mechanism for adding thermal energy. A simple porosity model provides only bulk heating to support Arrhenius reaction, while a porosity model with enhanced reaction in the heated region around a hotspot provides additional sources of reaction.

Models with porosity indicate that the incorporation of additional microstructurally-based processes allowed the "bulk" Arrhenius parameters to be used with successively less adjustment to match the double shock run distance. With the inclusion of reaction at pores, energies of activation closer to the measured values [12] could be used. The detailed features of the experimental build-up profiles were not reproduced, with the model showing too sudden a growth of reaction once initiation occurs. It is likely that a more thorough study of the time scales associated with thermal and mechanical equilibration should improve the accuracy of the models. The models used here had short equilibration times.

The efficacy of the Arrhenius model in predicting desensitization, and the requirement of some homogeneous terms to match the experimental data are consistent with mechanism inferred from analysis of the data alone [1], that the shock compacted material shows behavior that is close to homogeneous, i.e., the reaction is dominated by the bulk thermal Arrhenius reaction. However, neither the data records nor the modelling are con-

sistent with strict Arrhenius behavior, but require some contribution from hotspot reaction to produce the observed profiles.

This small example suggests the possibility that performance of any explosive system can be modified by outside influences, and that thinking of the initiation as an adjustable ratio between homogeneous (bulk chemical) and heterogeneous (hotspot) reaction may be a fruitful avenue.

This shock desensitisation effect is far from a panacea for disabling explosive devices. However, models which predict shock desensitisation are likely to elucidate mechanisms by which more practical schemes for deliberate desensitisation might be developed.

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