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TITLE: THERMAL INITIATION CAUSED BY FRAGMENT IMPACT ON CASED EXPLOSIVES

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Thermal Initiation Caused by Fragment Impact on Cased Explosives

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ABSTRACT

Numerical calculations have been used to predict the velocity threshold for thermal initiation of a cased explosive caused by fragment impact. A structural analysis code was used to determine temperature profiles and a thermal analysis code was used to calculate reaction rates. Results generated for the United States Air Force MK 82 bomb indicate that the velocity threshold for thermal initiation is slightly higher than that for the shock-to-detonation process.

INTRODUCTION

Detonations of cased explosives (e.g., conventional bombs) may be caused by the impact of metallic fragments. If several bombs are stored close together, the accidental detonation of one bomb (donor) may produce fragments that cause other bombs (acceptors) to detonate. The design of safe storage configurations requires knowledge of the threshold for detonation caused by fragment impact.

Previous studies (Chick and Macintyre, 1985; Howe, et al. 1981; James, 1988) have determined velocity thresholds for fragments with enough energy to cause shock-to-detonation transitions (SDT). A fragment impact that severely deforms the explosive can also cause thermal initiation. If the explosive is confined, a deflagration-to-detonation transition (DDT) may follow. The purpose of the work described in this paper was to develop a procedure for determining the conditions for thermal initiation of bombs caused by fragment impact.

PROBLEM STATEMENT

The size and velocity of fragments created by a donor bomb depend on the geometry and the properties of the high explosive and inert materials used. The example considered here is the United States Air Force MK 82 bomb filled with 80/20 Tritonal. The detonation of this bomb creates fragments as large as 38 by 250 mm with a thickness of about 6 mm (Lucht and Hantel, 1989). Fragment velocities can exceed 2 km/s. The physical setup for this problem is shown in Fig. 1. We assumed that the fragment is sufficiently long that a two-dimensional approximation is satisfactory.

A fragment impact causes deformation of the shell and Tritonal (80/20 wt% TNT/aluminum) and an increase in temperature of the material near the point of impact. The higher temperatures may cause significant reaction rates in the Tritonal. If the temperatures are sufficiently high, the reaction rates will reach levels at which energy is generated faster than it can be transferred away by conduction and a thermal explosion (thermal initiation) will result.

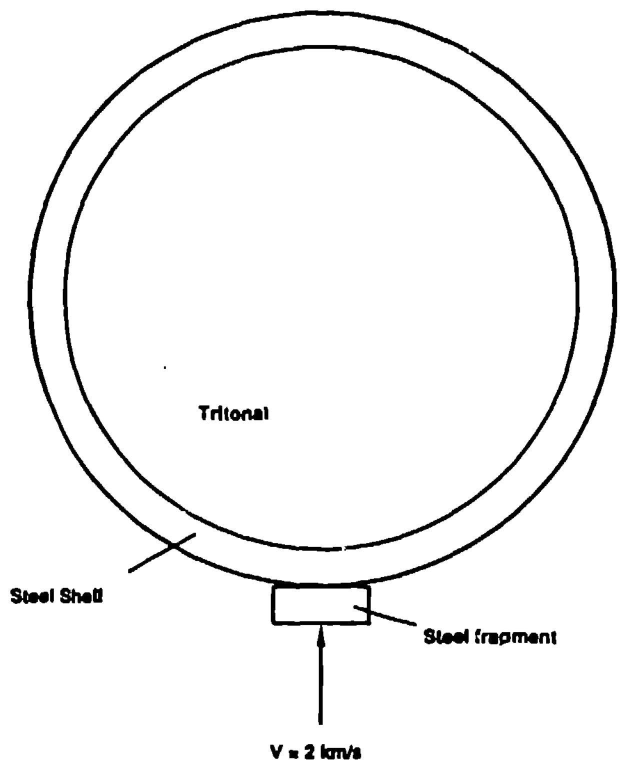

Fig. 1 - Impact of a fragment on an acceptor bomb.

Because no currently available code has the capability to efficiently perform the entire analysis, the problem was divided into two parts. First, a structural analysis code was used to perform the impact analysis and to determine the energy deposition rates and resulting temperatures. Then a thermal analysis code that has an Arrhenius burn model was used to determine whether thermal initiation would occur.

IMPACT ANALYSIS

The code selected for performing impact analyses was EPIC2 (Johnson and Stryk, 1986), a two-dimensional, Lagrangian, finite-element code developed at Honeywell, Inc. for the United States Army Ballistic Research Laboratory. This code calculates local temperatures using a Mie-Gruneisen equation of state. It uses an eroding slide line formulation to calculate penetration and has been used to perform accurate simulations of a wide range of impact problems for low to moderate projectile velocities.

An approximate analysis was used to predict the variation of melting temperature with pressure. It indicated that the Tritonal would remain in the solid phase during impact for the range of velocities considered here. We therefore use the properties of solid Tritonal for the impact calculations performed by EPIC2. The effect of this choice will be discussed later.

Tritonal properties are listed in Table 1. The density, specific heat, volume expansion coefficient, and Gruneisen coefficient were taken from Gibbs and Popolato (1980). The thermal conductivity was computed based on appropriate weighting (Jakob, 1957) of the thermal conductivities of aluminum and TNT.

TABLE 1. TRITONAL PROPERTIES

Mass/thermal properties	
density (g/c^3)	1.72
specific heat (cal/g·K)	0.31
thermal conductivity (W/m·K)	1.473
volume expansion coefficient (K^{-1})	4.2X10^{-3}
initial temperature (K)	294.3
melting temperature (K)	355.4
Strength properties	
shear modulus (GPa)	0.868
yield stress, (MPa)	13.79
hardening coefficient, (MPa)	0.0
hardening exponent,	1.0
strain rate coefficient, C_3	0.0
softening exponent, m	1.5
Equation of state	
K_1 (GPa)	7.508
K_2 (GPa)	-1.519
K_3 (GPa)	284.96
Gruneisen coefficient, Γ	1.31

The Hugoniot pressure in EPIC2 has the form

$$P_H = K_1 \mu + K_2 \mu^2 + K_3 \mu^3 \ .$$

The constants K_1, K_2, and K_3 are determined by curve-fitting the actual Hugoniot pressure vs density variation for Tritonal. The bulk modulus at a pressure of 1 atmosphere is equal to the first Hugoniot pressure coefficient, K_1. Poisson's ratio for explosives is about 0.44. These values were used to calculate the shear modulus.

The yield strength used in EPIC2 has the form

$$\sigma_y = (C_1 + C_2 \varepsilon^n)(1 + C_3 \ln \dot{\varepsilon})(1 - T^{*m}) \ ,$$

where C_1, C_2, C_3, n, and m are material constants, ε is strain, and T^* is a dimensionless temperature defined as $(T-T_R)/(T_M-T_R)$ where the subscripts R and M refer to room and melting conditions, respectively. The values used in EPIC2 for a "generic explosive" are C_1 = 13.8 MPa (2000 psi) and $C_2 = C_3 = 0$. These values were selected for the base case. The value of the softening exponent, m, used in the code is 0. We selected a value of 1.5 as being more representative of explosives. Sensitivity studies discussed in a later section indicate that the results are rather insensitive to the yield strength.

The Base Case

A simulation was performed for the case shown in Fig. 1. Results are summarized in Figs. 2 and 3. The distorted grid is shown in Fig. 2. The line y = 0 is a line of symmetry. The upper half of the bomb is omitted because effects in that region are negligible for the time span of interest, and as shown by preliminary calculations, that region can be omitted with no appreciable effect on calculated temperatures in the impact region. The grid contains 3126 nodes and 5944 elements. A simulation using approximately twice as many nodes gave nearly identical temperatures and pressures. A typical simulation of the first 2 µs after impact requires approximately 3 min of central processor unit (CPU) time on a Cray X-MP computer. The steel shell and the Tritonal near the point of impact are badly distorted. Some of the shell and fragment elements have been removed, indicating some erosion of the surfaces. The shell remains essentially intact and is not penetrated by the fragment.

Figure 3 shows the temperature-vs-time profiles for the three nodes in the Tritonal closest to the steel/Tritonal interface on the z-axis. The temperature profiles peak at a value above 1090 K and then drop to a nearly constant value near 550 K at $t = 20$ µs. The pressure profiles (not shown) reach a maximum value of 160 kbar about 3.7 µs after impact, then decrease after the pressure pulse has passed. The temperature distribution in the Tritonal at $t = 20$ µs is shown in Fig. 4. The temperature is above 560 K in a region approximately 5 mm thick.

The effect of conduction is not included in these calculations. A first-order analysis indicated that the conduction rate is negligible, compared with the energy deposition rates caused by compression and shear deformation, in the short time span considered here, because of the low thermal conductivity of the Tritonal.

Sensitivity and Parametric Studies

Because there is significant uncertainty in some of the mechanical properties of Tritonal, a series of simulations was performed to determine the sensitivity of the temperature field to the variations of those properties. Calculations were performed using values of the shear modulus 25% lower and 25% higher than the value listed in Table 1. The maximum temperature at $t = 20$ µs was within 1 K of that calculated for the base case. The peak temperatures differed by no more than 5 K from the base case values. Similar calculations were made to determine the effect of varying the yield stress, C1. Again, a 25% variation of C1 caused less than 1 K difference in the temperatures. The softening exponent m was also varied. A value of $m = 0$ gave temperatures within 5 K of the values obtained using $m = 1.5$. The temperature calculations are therefore found to be relatively insensitive to strength parameters.

There is some question about whether the Tritonal will be in the liquid or solid phase as it is shocked to high pressures. No data for liquid Tritonal were found, but data for both solid and liquid TNT are available. The base case was run using data for solid TNT and for liquid TNT. The maximum temperature was 130 K higher and the temperature at $t = 20$ µs was 40 K higher for the liquid TNT. It is therefore possible that the temperatures computed using properties for solid Tritonal may be low by 130 K for impact velocities of 2 km/s.

Simulations were performed to determine the effect of fragment velocity on Tritonal temperatures. Results are summarized in Table 2 where T_m is the peak Tritonal temperature, T_{20} is the spatially-maximum Tritonal temperature at $t = 20$ µs (the quasi-steady condition), P_m is the peak pressure, and X is the corresponding run to detonation distance (Gibbs and Popolato, 1980).

THERMAL ANALYSIS

The thermal analysis was performed using the EXPLO code (Jaeger, 1981). EXPLO is a one-dimensional finite-difference code applicable to slabs, cylinders, and spheres. It has an Nth-order Arrhenius burn model and thermal conduction calculation with a variable property and phase-change capability. The material library in EXPLO was revised to include property data for Tritonal.

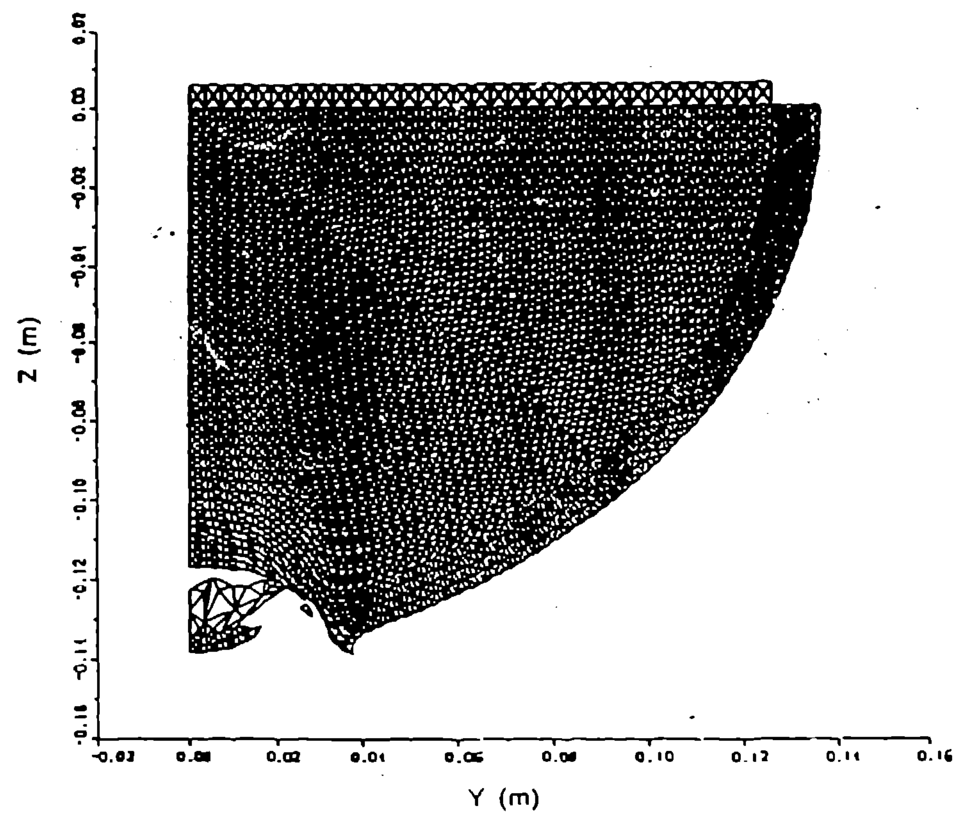

Fig. 2 - The grid at t = 20 μs.

TABLE 2. RESULTS OF PARAMETRIC STUDY

V (km/s)	T_m (K)	T_{20} (K)	P_m (kbar)	X (mm)
1.00	500.	358.	54.	44.0
1.25	610.	395.	76.	18.7
1.50	750.	440	100.	9.4
1.75	905.	500.	127.	5.2
2.00	1090.	550.	160.	2.9
2.50	1485.	675.	217.	1.4

The high-temperature regions in the Tritonal, calculated with EPIC2, can be approximated as slabs that have thicknesses of a few millimeters. Simulations were performed using EXPLO to determine the thermal response of Tritonal for various thicknesses and initial temperatures. The face at $x = 0$ is assumed adiabatic, and the interface at $x = S$ loses heat by conduction to the semi-infinite region ($x > S$) that was initially at room temperature. If the initial temperature is high enough, conduction is not sufficient to remove the energy being generated by the reaction and the temperatures increase without bound causing a thermal explosion (thermal initiation) that may transit to a detonation.

Results of these EXPLO calculations for Tritonal are shown in Fig. 5 where the time to ignition is plotted as a function of the reciprocal of the initial temperature. Note that there is a critical temperature for a slab of given thickness below which thermal initiation will not occur. For temperatures well above the critical temperature, the time to ignition is controlled almost entirely by the reaction rate.

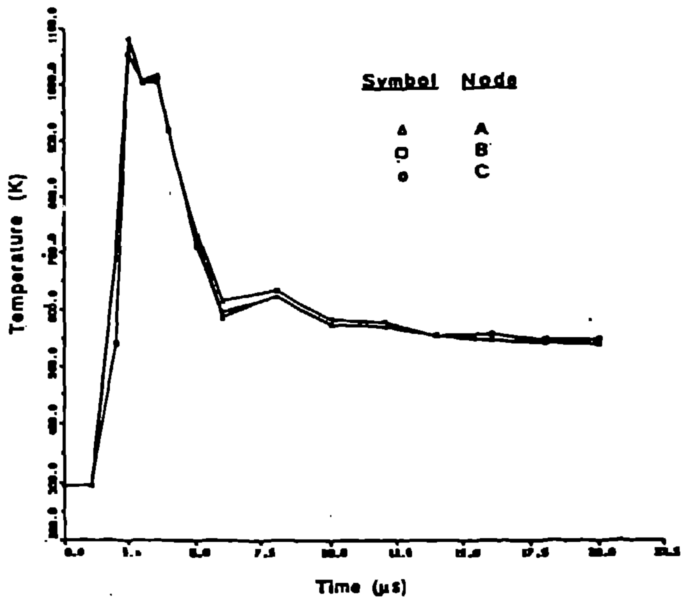

Fig. 3 - Temperature vs time profiles for the base case.

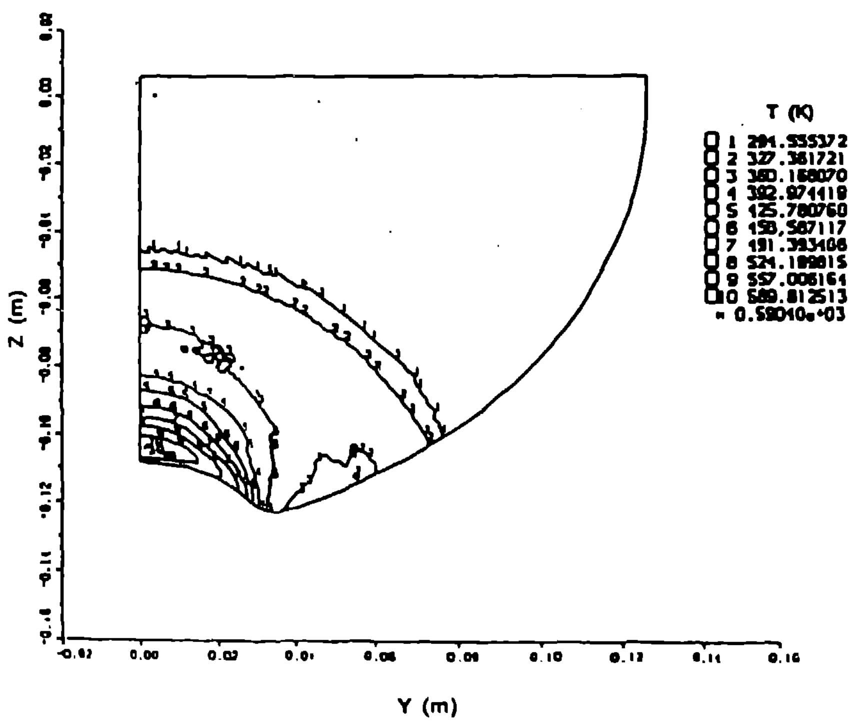

Fig. 4 - Temperature contours in the Tritonal at t = 20 μs for the base case.

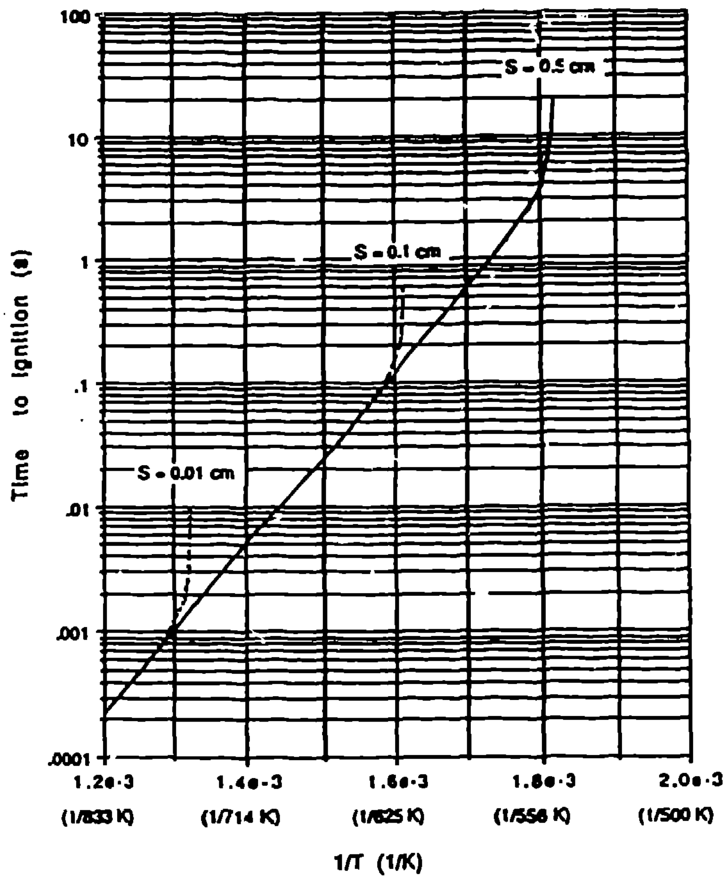

Fig. 5 - Ignition times for Tritonal slabs, low temperatures.

The conduction effect becomes negligible and the thickness of the slab is unimportant. For temperatures higher than 800K and slabs thicker than 0.01 cm, the time to ignition in μs may be computed from $\log_{10} t = 6452/T - 5.39$, where T is the temperature in K.

These results may be applied to the temperature fields discussed previously. An examination of the temperature-vs-time profile of Fig. 3 suggests that two areas should be investigated. The first is the sharp peak that occurs as the pressure wave passes. The width of the peak is rather small but the temperature is extremely high. The character of the peak was investigated by running the simulations with greatly increased print frequency in the region of the peak. Results of that calculation indicate that the temperature of a 1-mm-thick region remains at or above 1000 K for 1.5 ms. Results of the EXPLO calculations indicate that those temperature levels will not cause thermal initiation.

The other region of the temperature-vs-time profile that should be investigated is the quasi-steady region that occurs after the pressure wave is well past, that is at t = 20 μs. Although those temperatures are much lower, they persist for a relatively long time. The temperature contours shown in Fig. 4 indicate that the temperature is in the range of 557 to 590 K in a region that has a thickness of about 5 mm. The curve in Fig. 5 shows a critical temperature of 550 K for a 5-mm-thick slab, indicating that thermal initiation would occur in that region.

Application of the thermal analysis results to the temperature data produced by the parametric study using EPIC2 indicates that thermal initiation caused by the temperature peak will occur for velocities of about 2.1 km/s. The residual temperature effect will cause thermal initiation for velocities slightly below 2.0 km/s.

SUMMARY

An analysis has been performed to determine the minimum velocity at which a shell fragment from a donor bomb can cause thermal initiation in an acceptor bomb that suffers a direct impact. That value is approximately 2 km/s. It should be noted, however, that the quasi-steady temperatures are somewhat underestimated because the partial reaction that occurs at the peak pressure adds some thermal energy that is not accounted for in the thermal calculations for late times (20 ms). This consideration, along with other uncertainties in the analysis suggests that the threshold velocity may be as low as 1.7 km/s.

A separate analysis using a code that has a shock to detonation model would be required to determine the threshold impact velocity necessary to cause SDT. Typically, SDT will occur when the run to detonation distance, X, is less than about 10 to 20 mm. It appears (see Table 2) that a thermal initiation transiting to a detonation will not occur at impact velocities lower than those for which a shock to detonation would occur.

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