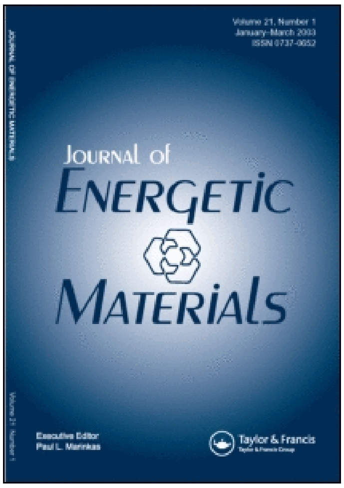

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Temperature effects on the performance of a complete explosive device

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TEMPERATURE EFFECTS ON THE PERFORMANCE OF A COMPLETE EXPLOSIVE DEVICE

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ABSTRACT

The sensitivity of hexanitrostilbene to flyer plate impact in the temperature range -65 C to 65 C has been investigated. It was found that as temperature decreases the mean firing energy of the flyer plate gradually increases. The increased energy requirement is attributable to the reduction in the shock sensitivity of the high surface area hexanitrostilbene acceptor explosive. The explosive response was found to depend on the viability of the hot spots formed and on a temperature dependent reaction rate. The electrical performance of a small flyer plate generator appears to have been unaffected over the temperature range.

INTRODUCTION

An explosive device that can reliably operate over a wide temperature range has broad appeal. When that device employs only secondary explosives, the appeal is greatly increased. A flyer plate generator coupled with hexanitrostilbene (HNS) explosive forms the basis of such a device.

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There are many potential applications for this type of explosive device. For example, in mining, explosive devices are expected to perform at the very high ambient temperatures that exist down bore holes. At the other extreme, low temperature operation is required in extraterrestrial environments. Between these extremes lie many other applications. An understanding of the effect of temperature on the sensitivity of the explosive and on the performance of the associated flyer plate generator is therefore critical to the implementation of a successful design.

The effect of temperature on the ignition and growth of detonation in heterogeneous solid explosives has been investigated by several authors. Urtiew et al [1] studied LX-17 (92.5%/7.5% TATB/Kel-F) under sustained shocks and found that at low temperatures the explosive ignites and burns more slowly than at room temperature. Roth [2] has shown that the sustained shock sensitivity of HNS decreases as temperature falls.

Gilman [3] and Schwarz [4] both showed that as temperature decreased HNS shock sensitivity to thin flyer plates decreased. For Gilman the decrease occurred below approximately -70 C, while for Schwarz the decrease was monotonic from 100 C.

Using thin flyer plates against RX-26-AF (46.6%/49.3%/4.1% TATB/HMX/Estane) Lee et al [5] discovered that at -80 C, slow reaction rates enable side rarefactions to partially quench a detonation wave. This effect appeared to be related to the specific surface area (SSA) and the pressing density. Lower density, finer particle size pure TATB exhibited no such temperature dependence.

Campbell [6] showed that the velocity of detonation of PBX-9502 (95%/5% TATB/Kel-F) was dependent on temperature and charge diameter. Hutchinson et al [7] have found a similar trend for EDC35, another TATB based explosive. The data indicated that at large charge diameters the detonation velocity fell as the temperature was raised and that at small charge diameters the detonation velocity fell with the temperature. It was suggested [6] that at large diameters, this result was due to the effect of temperature on density while at small diameters the result was due to the effect of temperature on the reaction rate.

The critical diameter of an explosive is also temperature dependent. For pressed TNT [8] and PBX 9502 [6] the critical diameter increases as the temperature decreases. Jackson et al [9] have shown that the detonation front in TATB exhibits greater curvature or less divergence as the temperature decreases (divergence and curvature being inverse descriptions of the same phenomenon). It is therefore not surprising to find that divergence of the detonation wave decreases near the critical diameter [10].

Although explosive performance clearly varies with temperature, the effect depends on a number of factors including the method of initiation. In this paper the performance of a complete explosive device (electrical and explosive) over the temperature range -65 C to 65 C is addressed.

In the following sections the design of the thermally controlled experiments is described, the results are provided, and the effect of temperature on explosive sensitivity and on the electrical performance of the flyer plate generator are discussed.

EXPERIMENTAL

The acceptor explosive chosen for this work was HNS. Fine particle HNS was pressed into pellets of 85%, 90% and 95% theoretical maximum density (TMD). The pellets were approximately 4 mm in diameter and 2.5 mm in length. The powder had a measured SSA of about 12 m^2/g.

A small flyer plate generator was employed to propel a thin flyer plate at the explosive. The explosive samples were placed at the end of a barrel. An explosively operated switch was employed to discharge the capacitor. Bridge sizes were 125 µm, 250 µm, and 375 µm.

The current through the bridge and the voltage across the bridge were monitored during the firings. In addition, the breakout of detonation at the end of the acceptor pellet was observed by a piezoelectric detector. The piezoelectric detector was also employed to measure the time of flight of the flyer plate through the barrel when no explosive target was present.

The complete explosive device together with all probes was placed inside a thermally insulated firing box. Low temperatures were achieved by adjusting the quantity of dry ice admitted into the firing box. High temperatures were achieved by use of a hot plate. In both instances an internal fan was employed to reduce temperature gradients within the box.

The high temperature tests were limited to 65 C due to concerns about the stability of the explosively operated switch at higher temperatures. The explosive switch contains lead azide and RDX and is initiated by a match head. The low temperature limit of -65 C was just within the capability of the dry ice.

The temperature was monitored by two independent type K thermocouples [11]. One thermocouple measured the air temperature near the explosive pellet. The other thermocouple was embedded in an explosive simulant and also placed near the explosive pellet. When these two thermocouples displayed the same temperature readings, thermal equilibrium within the test chamber was assumed to have been achieved. Thermal equilibrium usually required a conditioning period of about twenty minutes. When the embedded thermocouple reached the desired temperature the explosive switch was operated.

Both the explosive and electrical performance of the device were assessed. Explosive performance was based on the firing energy required to initiate the explosive. The firing energy was adjusted in accordance with the Bruceton technique [12] to determine the point at which 50% of the explosive pellets detonated. All pellets were employed once only. The mean firing energy ($E_{50\%}$) for the explosive device was determined with 95% confidence. In those instances where the number of shots was limited to about 10, due to the limited quantities of explosive available, an estimate of $E_{50\%}$ was made. In all other cases the $E_{50\%}$ value was calculated from approximately 20 shots. The electrical performance was based on circuit ringdown measurements and flyer plate velocity calculations.

Table 1 shows the calculated circuit resistance and inductance from a sample of less than five ringdown measurements each, conducted at -65 C and 65 C at a firing voltage of 1433 V. The values at 20 C are also given for comparison. The inductance and peak current are practically independent of temperature. Resistance appears to be affected by temperature.

TABLE 1. Comparison of Calculated Circuit Characteristics as a Function of Temperature.

Temperature (C)	Inductance (nH)	Resistance (mΩ)	Peak Current (A)
20	12.2	59	3875
-65	12.4	61	3734
65	13.6	88	3831

A previously introduced [13] empirical relationship between the transit time of the flyer plate through the barrel and the firing voltage has been modified to include data for -65 C and 65 C. The revised equation for transit time, valid for temperatures from -65 C to 65 C is:

$$t = 162.6e^{-0.00237(V-708.4)} + 70.5 \qquad (1)$$

where t is the transit time and V is the firing voltage. Figure 1 is a graph of the relationship showing data points from -65 C to 65 C. Temperature appears to have no effect on the transit time of the flyer plate.

By employing equation (1), the breakout time and the length of the explosive pellet, an estimate of the excess transit time of the detonation wave [13] was determined. The excess transit time is shown in Table 2 as a function of temperature. No corrections for pellet shrinkage or growth are included in these estimates.

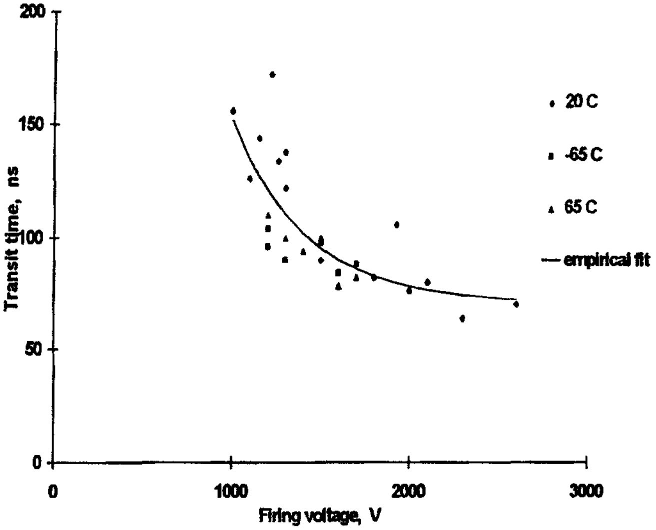

FIGURE 1

Empirical relationship between the transit time of the flyer plate through the barrel and the firing voltage over the temperature range -65 C to 65 C.

TABLE 2. Excess Transit Times at Various Temperatures for HNS.

Temperature, C	%TMD	Excess transit time, ns
-65	90	25±16
65	90	7±8

Figure 2 shows the range of the relative $E_{50\%}$ as a function of temperature for HNS pressed to 85% and 95% TMD. Linear regression lines are also shown to highlight the trend. The data are normalized to $E_{50\%}$ for room temperature, 90% TMD explosive, and for 250 μm wide bridges.

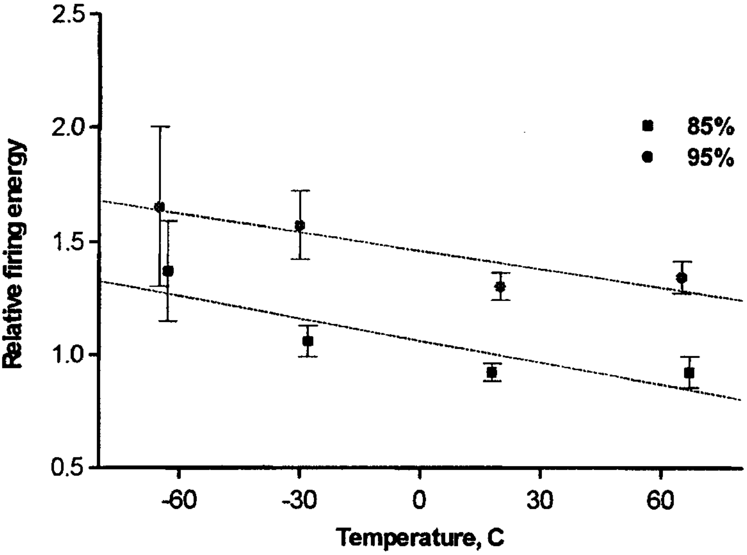

FIGURE 2

Normalized mean firing energy levels ($E_{50\%}$) for HNS at 85% and 95% TMD over the temperature range -65 C to 65 C. $E_{50\%}$ levels are generally quoted with 95% confidence intervals.

In Figure 3, the relative $E_{50\%}$ as a function of bridge widths at 20 C and -65 C is shown. The data is normalised as per Figure 2.

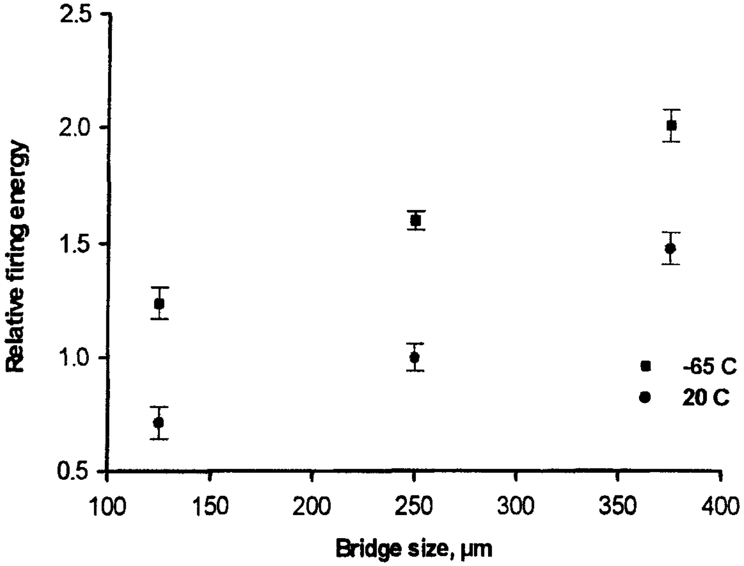

FIGURE 3

Normalized mean firing energy levels ($E_{50\%}$) for HNS at 90% TMD as a function of bridge size and temperature. $E_{50\%}$ levels are generally quoted with 95% confidence intervals.

Figure 4 shows a comparison between the current and voltage traces for a bridge burst at 20 C and 65 C conducted at the same firing voltage. Figure 5 shows a similar comparison at -65 C and 20 C at a different firing voltage. Bridge burst is assumed coincident with the peak in the voltage record.

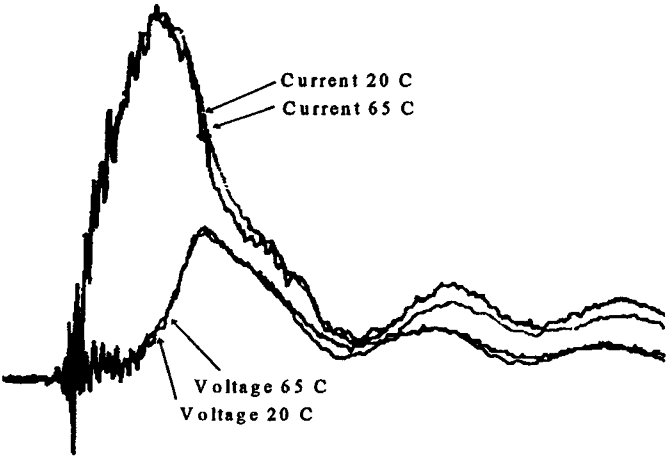

FIGURE 4

Typical bridge current and voltage records taken at 20 C and 65 C.

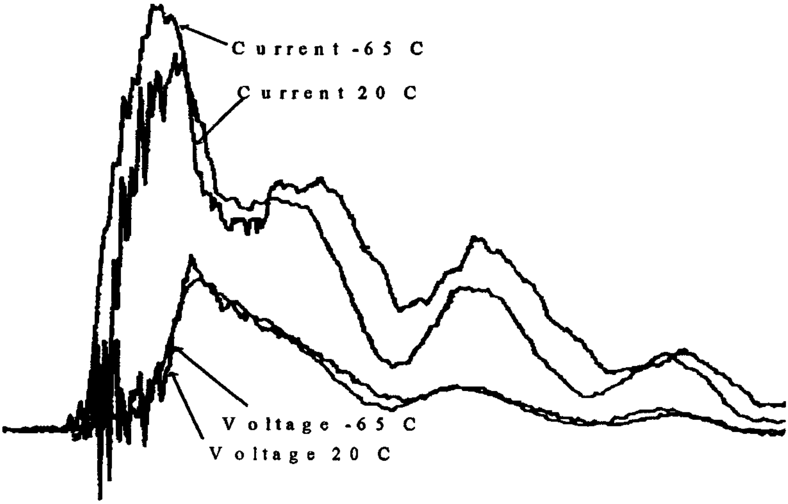

FIGURE 5

Typical bridge current and voltage records taken at -65 C and 20 C.

DISCUSSION

The ringdown method of assessing the dynamic circuit resistance and inductance only provides an estimate of the value of each parameter. Resistance estimates are often particularly variable, varying by up to 20%. For this reason, the changes seen in Table 1 are taken to indicate that the electrical performance of the circuit is relatively unaffected by the temperature change. Certainly, no gross changes in performance are evident.

Another test of the effect of temperature on the electrical performance of the circuit is provided by the current and voltage traces recorded up to bridge burst. Although the measured current and voltage vary from shot to shot, the similarity shown in the records up to bridge burst (as indicated in Figs. 4 and 5) suggests that the electrical performance is probably independent of temperature.

At first, this result may seem surprising given that as the temperature decreases the DC circuit resistance decreases and therefore the electrical performance of the flyer plate generator may be expected to change. The DC resistance at an ambient temperature is found to have an insignificant effect on circuit performance due to the dynamic resistance changes that occur during the bridge burst. Before discharge, the circuit has a low resistance. As the current rises, the total circuit resistance also rises due to the increased bridge resistance. The rapid change in the bridge resistance (from 0.030 Ω to 1 Ω approximately) and the effect this has on the circuit performance turns out to be far more significant than the milliohm resistance change due to the ambient temperature. An interesting consequence is that the switch performance must therefore also be independent of the temperature.

An important indicator of the electrical performance of the flyer plate generator is the burst current density (j_b). The j_b is related to the peak flyer plate velocity through the electrical Gurney model [14]. Electrical Gurney model parameters [15] were employed to determine flyer plate velocities at the different temperatures shown in Table 3. The calculated flyer plate velocities assume that the models have no temperature dependence. This is a valid assumption as the measured transit times of the flyer plate through the barrel show no temperature dependence.

Table 3 is divided into two parts; A and B. Part A provides a comparison between calculated flyer plate velocities at -65 C and 20 C. Both calculations are based on data with a firing voltage equal to the $E_{50\%}$ of 90% TMD HNS at -65 C and collected at either -65 C or 20 C. Similarly in part B, calculations were based on firing voltages equal to the $E_{50\%}$ of 90% TMD HNS at 20 C and collected at either 20 C or 65 C. The comparisons within parts A and B show an almost identical velocity confirming that there is no difference in the electrical performance of the flyer plate generator with temperature. Any changes in the performance of the explosive device can therefore be attributed to the explosive. Table 3 also indicates that 3.93 mm/μs and 2.99 mm/μs provide good approximations of the mean flyer plate velocity for initiation of the HNS at -65 C and 20 C respectively.

The excess transit times (t_e) shown in Table 2 increase as the temperature decreases. Allowing for explosive pellet contraction or expansion in the calculations of t_e reveals that an underestimation of t_e occurs at low temperatures and an overestimation occurs at high temperatures. Thus the difference in t_e shown in Table 2 should probably be greater.

The change in t_e with temperature indicates that the explosive may take longer to build up to detonation as the temperature decreases. This suggests that there may be a temperature dependent reaction rate governing the build up process in HNS just as has been found in LX-17 [1] and RX-26-AF [5].

TABLE 3. Calculated Flyer Plate Velocity as a Function of Temperature.

	Calculation conducted at Temperature, C	Flyer plate velocity, mm/μs
Part A	-65	3.93
Based on 90% TMD HNS at -65 C	20	3.88
Part B	20	2.99
Based on 90% TMD HNS at 20 C	65	3.05

It is known that the reaction rate affects the divergence of the detonation wave [9]. As the temperature decreases the divergence decreases [9] and the failure diameter of the explosive increases [8,6]. The failure diameter is described as the diameter of an explosive below which a steady detonation wave cannot propagate. The minimum spot size is the minimum area of an explosive that must be ignited in order for a detonation to grow to steady state. Although not synonymous, failure diameter and minimum spot size are closely related and therefore the minimum spot size for initiation is also expected to increase as the temperature decreases. An indication that the minimum spot size is being approached is provided by an abrupt increase in the flyer plate velocity required to initiate the explosive as the flyer plate diameter decreases [9].

The minimum spot size can be probed by shock initiating the explosive target with smaller and smaller diameter flyer plates. The results of such an investigation are shown in Figure 3 where a constant energy difference between the $E_{50\%}$ values at -65 C and 20 C for each bridge size is indicated. Given that the electrical performance of the flyer plate generator is independent of temperature, it seems reasonable to expect that the extra energy at the lower temperature is required to initiate the HNS sample. Therefore the kinetic energy of the flyer plate must be greater at -65 C than at 20 C by an amount equal to this constant energy difference. The proportional change in the velocity of the flyer plate (δv) is given by:

$$\frac{\delta v}{v} = \frac{\delta E}{2E} \qquad (2)$$

where v and E are respectively the flyer plate velocity and mean firing energy at 20 C and δE is the difference between the mean firing energies at -65 C and 20 C.

Employing (2) and the data of Figure 3 shows that the velocity increases by approximately 17%, 30% and 35% (for bridges 375 μm, 250 μm, and 125 μm respectively) as the temperature decreases. The increase in velocity, as a function of flyer plate size, indicates that the minimum spot size is being approached, however, it is still less than 125 μm at -65 C. Although the measured increase in excess transit time (Table 2) provides evidence for a temperature dependent reaction rate, the present data cannot be employed to show that the minimum spot size increases as the temperature decreases.

The actual flyer plate velocity for the 250 μm bridge at -65 C can be estimated from the data of Figure 3 and Table 3. Table 3 indicates that the mean flyer velocity for initiation of 90% TMD HNS at 20 C is approximately 2.99 mm/μs. Employing (2) gives an incremental velocity of 0.9 mm/μs and therefore a mean firing velocity of 3.89 mm/μs at -65 C. This is in good agreement with the estimate supplied in Table 3.

Figure 2 shows that there is a tendency for $E_{50\%}$ to increase as the temperature approaches -65 C. This increase, also shown by Schwarz [4], indicates that fine particle HNS becomes more difficult to initiate as the temperature decreases.

The shock initiation process in a heterogeneous explosive such as HNS is governed by the number and size of the generated hot spots. The hot spots may be produced as a consequence of: void collapse, jetting, and frictional heating. Whatever the mode, at low initial temperatures, the viability of the generated hot spots is dependent on the quantity of heat lost to the surrounding medium [5]. In addition, as the temperature decreases, the HNS target contracts increasing the density. The increase in density results in a lower number density of smaller voids and hence smaller potential hot spot sites. As the hot spot size decreases, the amount of explosive that may be decomposed also decreases. To increase the volume of explosive that may be decomposed, the temperature of these hot spots must be increased. Increasing the shock pressure generates hotter hot spots [16]. These hot spots are able to grow to sufficient size and decompose sufficient material to build a detonation wave before the arrival of the lateral rarefaction waves [5,17]. Thus to achieve initiation at low ambient temperature, the shock pressure and therefore the firing energy must be greater than at high ambient temperature. Thus the trends shown in Figure 2 are expected.

At a fixed temperature, as the density decreases, the number density and size of the voids increases. The larger generated hot spots decompose more of the explosive resulting in an increased shock sensitivity [17]. Thus the general decrease in $E_{50\%}$ with decrease in density shown in Figure 2 is also expected.

CONCLUSIONS

Over the temperature range -65 C to 65 C, the explosive device firing energy was found to depend on temperature. As the temperature decreased, a steady increase in the mean firing energy was obtained for each of the HNS samples.

The temperature dependent performance of the explosive device has been successfully separated into electrical and explosive response. The monitored discharge current and bridge voltage, the flyer plate transit time and calculated flyer plate velocity all indicated that the electrical performance of the flyer plate generator did not vary with the temperature. The explosive shock sensitivity, however, decreased as the temperature decreased. The reduction in sensitivity is related to the increased difficulty in generating sustainable hot spots and to a temperature dependent reaction rate. The minimum spot size for the 12 m^2/g HNS was found to be less than 125 μm at -65 C.

Optimum explosive device design must incorporate the change in sensitivity of the explosive to ensure that reliable performance over all operating temperatures is obtained.

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