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Measurements of the Dielectric Properties of Thin High-Explosive Samples Using a Parallel Plate Test Fixture

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Abstract

This report presents results of a study of the dielectric properties of several high explosive materials, including Composition B, C-4, Detasheet, Semtex 1A, Semtex 1H, and Semtex 10. The capacitance and dispersion of samples up to ten mm thick were measured at 24 and 65°C using a parallel plate test fixture. In this configuration, capacitance is proportional to the real component of the complex dielectric constant (or permittivity) of the material, while the dispersion is equal to the imaginary component of the dielectric constant divided by the real component. Measurements were performed at two temperatures to determine whether these dielectric properties might be used to monitor moderate temperature changes within these materials using an external fringing field capacitor. It was found that the real dielectric constant of the high explosives generally changed by only about 1% on heating from 24 to 65°C, and that the externally measured capacitance is therefore not a reliable parameter for monitoring temperature changes in these explosives. Temperature-based changes in the dispersion were often 20% or greater, and for several materials (e.g., Composition B, Detasheet) the temperature and dispersion showed good correlation as the temperature of the explosive was cycled up and down. It is thus possible that for some high explosives the externally measured dispersion is a useful parameter for monitoring temperature changes. However, other factors may limit the usefulness of this technique, including the need to have the plates of a fringing field capacitor in direct contact with the high explosive to obtain measurements, and the limited penetration depth of the fringing field into the explosive material.

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Introduction

Varied applications exist in which it would be useful to infer spatial temperature gradients and temporal temperature changes within bulk explosive materials based on external measurements. Several experimental techniques and material properties might form the basis of such measurements. In an ongoing study at Sandia National Laboratories, several types of measurements have been attempted, including dielectric, ultrasonic, and seismic measurements. This report discusses in detail measurements of the dielectric properties of several high explosives and benign dielectric materials. Measurements have been performed primarily at room temperature (24°C) and at 65°C, these temperatures being representative of the temperature range of interest for the intended applications.

There has been very little previous work on the dielectric properties of explosives. A literature search at the beginning of this project (2010) found only a single reference, a paper published at Picatinny Arsenal in 1963 [Walbrecht 1963]. Walbrecht's study includes measurements of the dielectric properties of plastic bonded explosive (PBX), TNT, Composition B, Baratol, and Octol. However, it contains no data on the temperature dependence of the dielectric properties; all measurements were performed at room temperature, recorded as 75°F (23.9°C). Walbrecht's study includes some data on the frequency dependence of the real component of the dielectric constant, k (referred to in the present report as ε'). The value of k was found to decrease with increasing field frequency for all explosives studied, with the effect being much more dramatic for TNT than for the other explosives investigated. Attempts made to obtain additional information on the dielectric properties of explosives included Google searches, discussions with explosives experts at Sandia and Los Alamos National Laboratory, and searches of non-public data compilations such as the Lawrence Livermore National Laboratory Explosives Database. The lack of existing data on the dielectric properties of explosives is striking. Therefore, investigation of the temperature dependence of the dielectric properties of explosives represents fundamentally new science.

Experimental Details

Figure 1, below, illustrates the parallel plate test fixture used in the present study, an Agilent model number 16451B, serial number MY44100681. This test fixture was connected to an Agilent E4980A LCR Meter which measured the capacitance and dispersion of a solid sample inserted between the parallel plates. Measurements were performed with a field frequency of 1MHz and an applied voltage of 1V. Prior to performing measurements the capacitance of a 2 mm air gap between the plates was measured to serve as a calibration point.

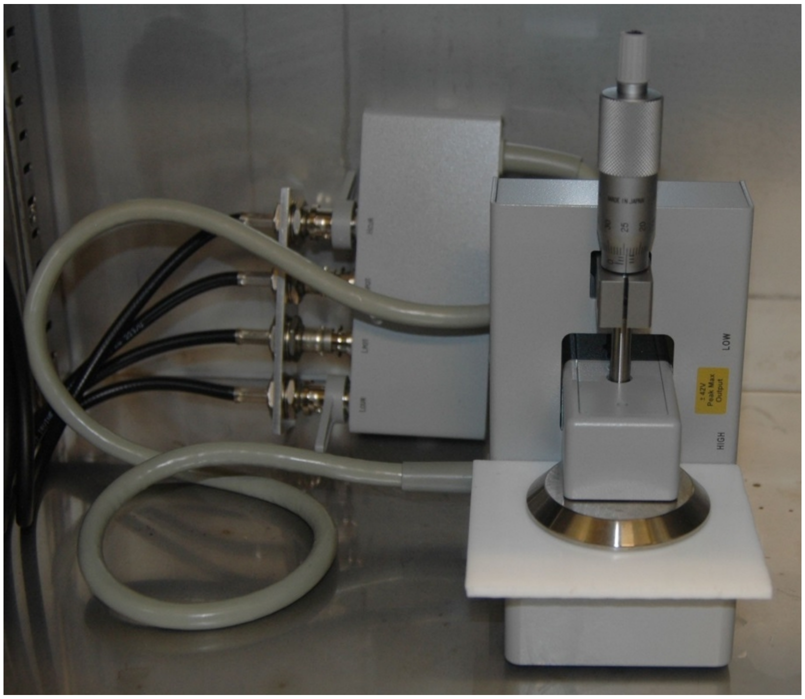

Figure 1. Parallel Plate Test Fixture with Dielectric (Teflon) Sample

Measurements were performed with both benign dielectric materials (shown in Figure 2, below) and explosives. In the studies performed with benign dielectric materials, the measured capacitance of the 2 mm air gap was within 1% of the theoretical value of 5.021 pF, which is obtained by setting ε’ of air equal to one in equation (1), below. However, in the studies with explosives, which were done at a much later date, the 2 mm air gap capacitance value was approximately 5% lower at 4.75±0.05 pF, indicating that the thickness of the air gap was actually ca. 0.1 mm greater than the value of 2.00 read off the calibration knob on the parallel plate test fixture. The thickness (d) of each explosive sample studied was read directly off the calibration knob on the test fixture; 0.1 mm was then added to correct for this calibration problem.

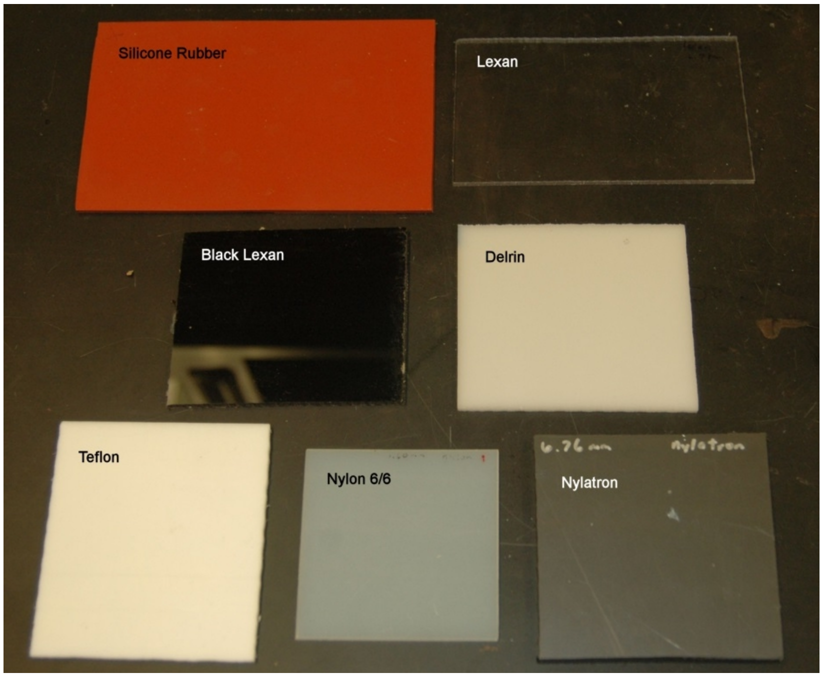

Figure 2. Benign Dielectric Materials Tested

Table 1, below, provides a list of the high explosives studied, the sample thicknesses, the Sandia TU numbers, and the sources from which these materials were obtained. Precise dates of manufacture are unknown but all samples were obtained prior to July, 2008. The Comp B and detasheet samples, with fixed thicknesses, were the thinnest samples available. The C-4 and Semtex samples had to be molded into "pancakes" for measurements in the parallel plate test fixture; the thickness values provided are not fixed but representative.

Table 1. Explosives Investigated and Sample Thicknesses

Explosive	Thickness	Sandia TU Number	Source
Composition B	9.5 mm	123970	Accurate Energetics Systems, LLC
C-4	5.5 mm	125722	Holston Defense Corporation
Detasheeet	2.2 mm	125808	North American Explosives (NAX)
Semtex 1A	6.4 mm	125773	Explosia a.s
Semtex 1H	7.3 mm	125774	Milspec Industries Inc
Semtex 10	5.6 mm	125772	Milspec Industries Inc

Samples were heated in a temperature-programmed Thermotron Industries S-1.2-3200 test chamber (Figure 3) that contained the parallel plate test fixture.

Figure 3. Environmental Test Chamber

The real component of the complex dielectric constant, ε’, is related to the measured capacitance by

(1) $\varepsilon' = Cd/A\varepsilon_0$,

where C is the capacitance in F, d is the sample thickness in m, A is the test fixture plate surface area in m^2, and ε_0 is the permittivity of free space, 8.854×10^{-12} F/m. The parallel plate test fixture had a plate radius of 19 mm, corresponding to a plate area A of 0.001134 m^2. This equation holds rigorously only for plate diameters sufficiently large compared to the sample thickness d. The sample thicknesses used were the thinnest available, but in some cases the calculated ε’ values may contain some error due to the sample thickness.

The complex dielectric constant ε* is given by

(2) $\varepsilon^* = \varepsilon' + i\varepsilon''$,

where ε” is the imaginary component of the dielectric constant and i satisfies $i^2 = -1$. Finally, the dispersion D is given by

(3) $D = \varepsilon''/\varepsilon'$.

Thus measured capacitance values can be converted to ε’ values and dispersion values can be used to derive ε” once ε’ is known.

Measurements of the Dielectric Properties of Benign Materials

Because working with high explosives and, in particular, heating them above room temperature, requires extensive preparation and safety documentation, a decision was made to first study the dielectric properties of several benign dielectric materials. The measurement methods could therefore be practiced and optimized before the measurements with explosive materials commenced. The benign materials chosen for study were silicone rubber, clear lexan, black lexan, Delrin, nylon, nylatron, and Teflon, and all of these were obtained from McMaster-Carr. All samples were nominally $^1/_8$ in (3.175 mm) thick. Table 2, below, provides ε' values for each of these materials at 24, 45, and 65°C that were calculated from the measured capacitance values at a 1 MHz field frequency.

Table 2. ε' Values of Benign Dielectric Materials

Material	24°C	45°C	65°C	% Change, 24 to 65°C
Si rubber	3.11	3.04	2.98	4.18
Clear lexan	2.69	2.72	2.76	2.60
Black lexan	2.70	2.72	2.77	2.59
Delrin	3.26	3.29	3.35	2.76
Nylon	3.24	3.57	4.17	28.70
Nylatron	3.52	4.19	5.80	64.77
Teflon	2.05	2.05	2.05	0.00

From Table 2, it can be seen that clear lexan and black lexan show identical ε' values within experimental error, as might be expected. Nylon and nylatron show much larger changes with temperature than the other materials. Delrin shows temperature dependence similar to the lexan samples, while Teflon shows no temperature dependence at all in the range studied. Silicone rubber is the only material where ε' decreases with temperature, and the relative change is larger than that in all other materials except nylon and nylatron. The results indicate that the temperature dependence of ε' can vary widely for different dielectric materials, and it is therefore difficult to use these results to predict specific dependence for any particular explosive material.

Table 3, below, shows similar data on ε" values of the benign materials, calculated from the corresponding ε' and D values. For all materials, the temperature dependence of ε" is substantially greater than that of ε'. While there is considerable variation among the materials, these results suggest that ε" (or dispersion) will be a better parameter for monitoring temperature changes in dielectric materials that ε' (or capacitance). There are, however, likely to be larger errors associated with the ε" values, as evidenced by the poorer agreement of values for the two types of lexan in Table 3 compared to Table 2.

Table 3. ε" Values of Benign Dielectric Materials

Material	24°C	45°C	65°C	% Change, 24 to 65°C
Si rubber	0.0367	0.0180	0.00378	89.70
Clear lexan	0.0629	0.0677	0.0869	38.16
Black lexan	0.0694	0.0593	0.0787	13.40
Delrin	0.0289	0.0151	0.0133	-53.98
Nylon	0.0959	0.228	0.592	617.3
Nylatron	0.188	0.545	1.467	780.3
Teflon	0.0148	0.00101	0.00207	-86.01

Capacitance Measurements and ε' Values for High Explosives at 24 and 65°C

Table 4 provides ε' values for the various explosives studied at 24 and 65°C. These values are derived from the measured capacitance for a 1 MHz, 1 V applied field using equation (1), above. The first set of values listed for detasheet were obtained after stabilization at 24°C for 18 hours and at 65°C for 5.5 hours, while the second set was obtained after stabilization periods of only ca. 30 minutes. The close agreement of these two measurement sets led to the conclusion that a 30-minute stabilization time was adequate, so in all experiments with the other explosives, stabilization times ranged from 30 to 60 minutes. Also listed in Table 4 is the percent change in ε' upon heating from 24 to 65°C. This percent change in ε' upon heating is always positive and always small, varying from 0.41% for C-4 to 1.71% for Semtex 1H. This change was often largely irreversible; the ε' value did not drop back all the way to the initial 24°C value with any of these explosives when the sample was cooled to 24°C. The increase in ε' appeared to be completely irreversible with detasheet and Semtex 10, mostly irreversible with C-4 and Semtex 1H, and mostly reversible with Composition B and Semtex 1A. Overall, the changes in ε' observed for these explosives upon heating are even smaller than those that were observed with the benign dielectric materials.

Table 4. ε' Values of High Explosives

Explosive	24°C	65°C	% change, 24 to 65°C
Composition B	3.151	3.184	1.05
Detasheet	3.267	3.310	1.32
Detasheet	3.278	3.326	1.46
C-4	2.906	2.918	0.41
Semtex 1A	2.573	2.615	1.63
Semtex 1H	2.753	2.800	1.71
Semtex 10	3.512	3.534	0.63

The ε' value of 3.151 reported here for Composition B at 24°C and 1 MHz is in good agreement with the previous study by Walbrecht. In that study, the temperature was 23.9°C and the applied field frequency varied from 25 Hz to 0.1 MHz. Measured ε' values were 3.804 at 25 Hz and 3.297 at 0.1 MHz for a sample 1.03 mm thick. Extrapolating Walbrecht's data to 1 MHz yields an ε' value of approximately 3.24, which is approximately 2.8% higher than the value measured here. The large thickness (9.5 mm) of the Composition B sample used in this study may account for part of this difference. It is also possible, given that Walbrecht's report was published in 1963, that there were differences in the chemical or physical makeup of the Composition B used in the two studies.

Dispersion Measurements of High Explosives at 24 and 65°C

Since ε' of the high explosives was found to vary so slightly with temperature, the next logical step was to investigate variation of the dispersion. In these experiments, the high explosive was placed in the parallel plate test fixture within the Thermotron chamber, and the temperature was cycled between 24 and 65°C. The emphasis was on observing whether or not the dispersion changed in a consistent manner that could be correlated with temperature, and not on measuring the precise value of ε". The Thermotron chamber temperature was first set at 24°C, and the temperature was cycled up or down every 30-60 minutes while the dispersion values were recorded.

Figure 4, below, shows the correlation between temperature and dispersion for a Composition B sample subjected to such a temperature cycle. It is immediately apparent that there is excellent correlation between the temperature and the dispersion. The dispersion is initially ca. 0.003 at 24°C, then rises to greater than 0.005 when the temperature is raised to 65°C. Upon cooling back to 24°C it drops to below 0.002, then rises to ca. 0.0046 when the temperature is raised again, with a final drop to ca. 0.0015 when the temperature is lowered a final time. Although the absolute dispersion values at each peak and trough of the cycle vary, the consistent increase of the dispersion when the temperature is increased is clear. Note that the increase in the dispersion value lags the increase in temperature during both heating cycles, likely because the temperature measured is the temperature of the interior of the Thermotron test chamber, not the temperature of the Composition B sample. When the test chamber temperature is increased, it probably takes some additional time for the entire sample to reach the same elevated temperature, causing the dispersion value to rise less quickly than the test chamber temperature.

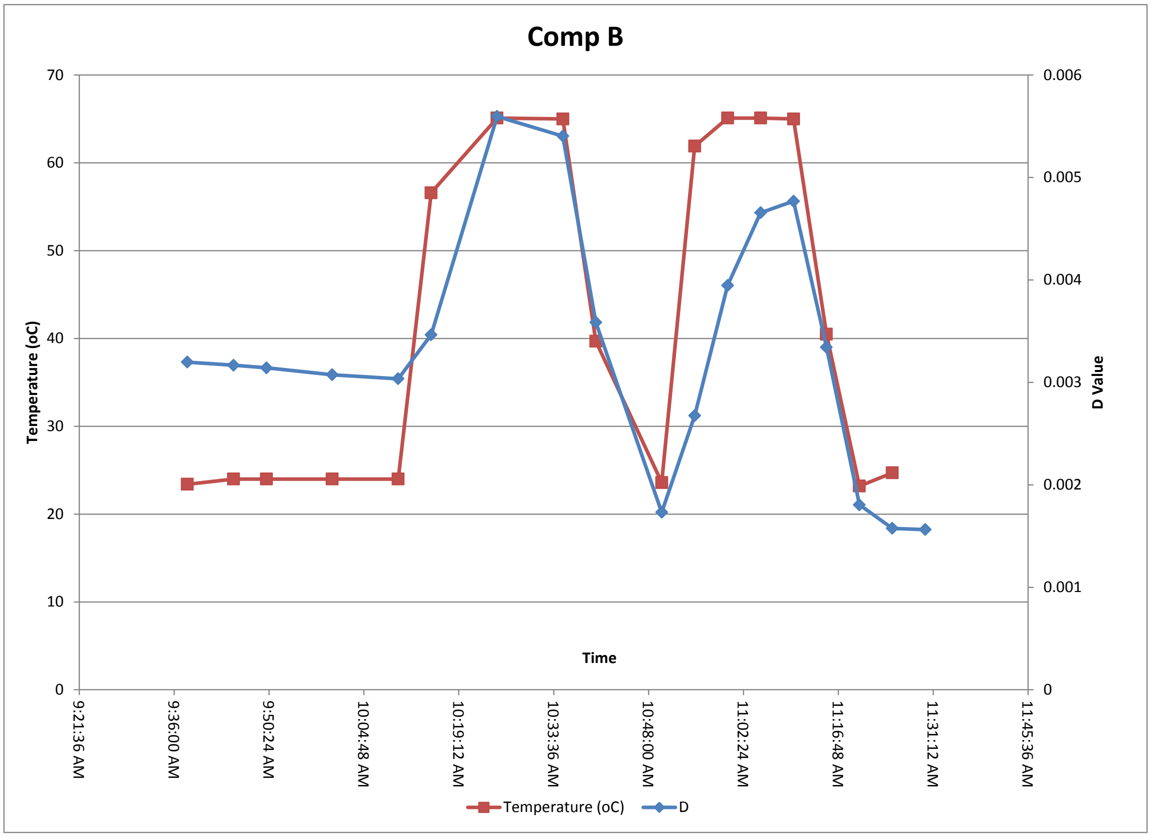

Figure 4. Composition B, Test 1

This dispersion experiment was repeated a week later with another Composition B sample, with results shown in Figure 5, below. The same pattern of increasing dispersion when the temperature is increased is readily apparent. The primary differences are that the first increase in the dispersion upon heating to 65°C is quite small, and the dispersion values in general tend to be lower. However, this data set also supports the idea that external monitoring of the dispersion might be used to detect temperature changes in Composition B.

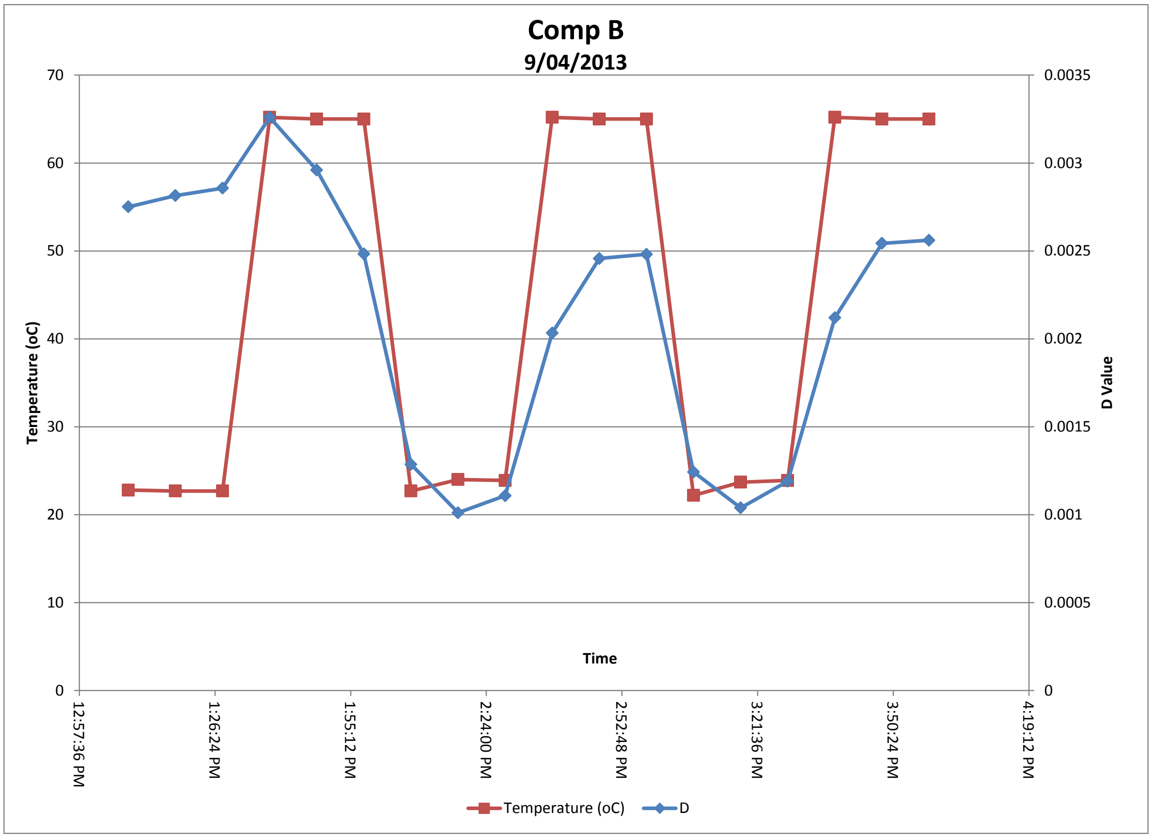

Figure 5. Composition B, Test 2

Figure 6, below, shows a similar plot for detasheet. With this PETN-based explosive there is also a strong correlation between the observed dispersion values and the test chamber temperature. In this case the dispersion decreases when the temperature increases, with values of approximately 0.0022 at 24°C and approximately 0.0018 at 65°C, a change of about 22%. The dispersion change appears to be reversible with temperature for the approximately 30-minute time intervals investigated. Once again, the dispersion change lags the measured temperature change considerably, probably because the temperature of the explosive material does not change as quickly as the chamber temperature.

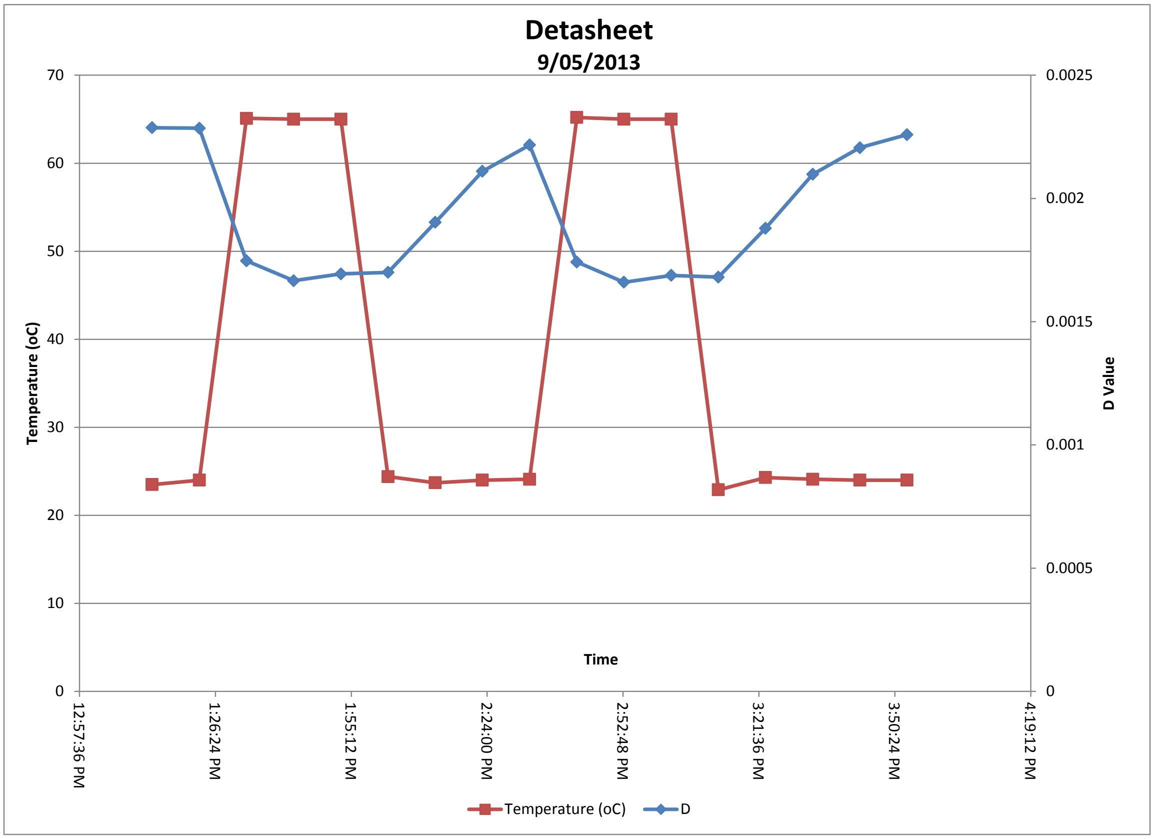

Figure 6. Detasheet

Figure 7, below, plots the temperature and dispersion correlation for C-4 plastic explosive that is approximately 94% RDX by weight. As with Composition B, the dispersion of C-4 increases with temperature, which is not surprising since RDX is the largest component of both materials. The change of dispersion with temperature is readily apparent, with the magnitude being approximately 20%. Again, a time lag between the change in chamber temperature and the change in the dispersion value is obvious.

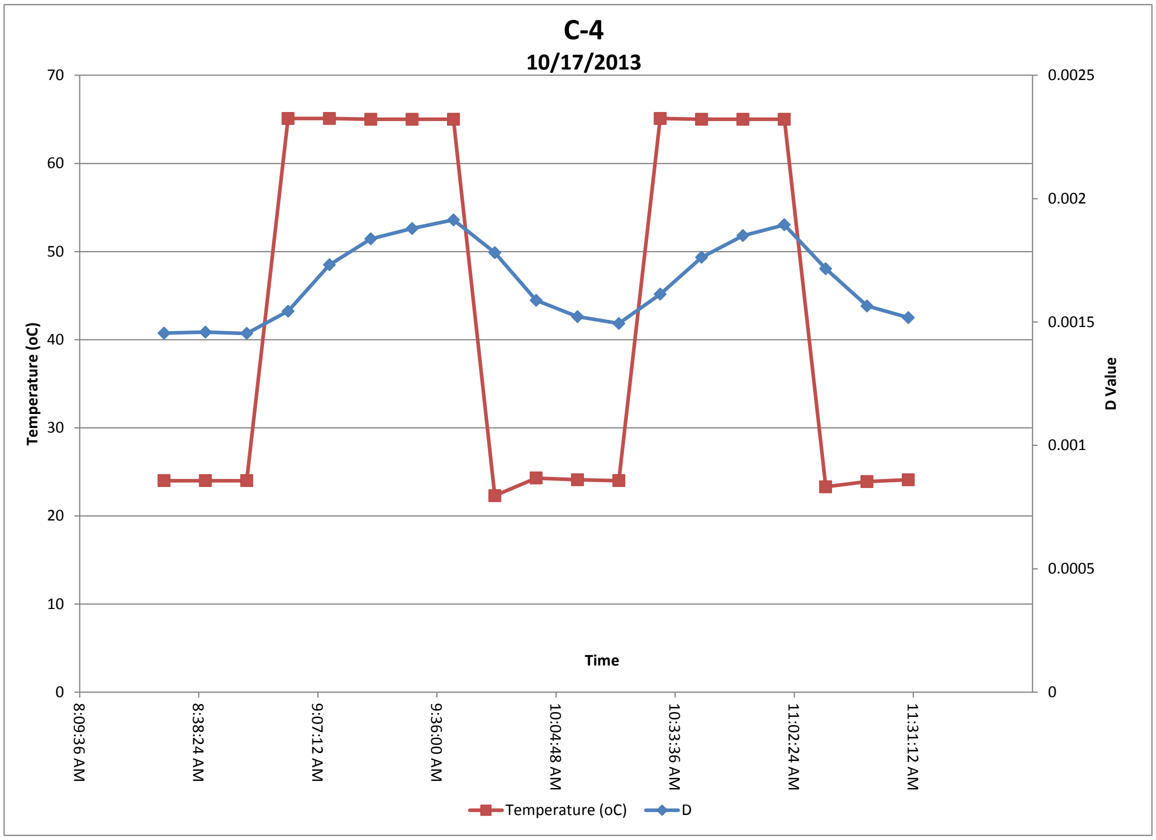

Figure 7. C-4

Figures 8, 9, and 10, below, show measurements of the dispersion of Semtex 10, Semtex 1A, and Semtex 1H, respectively, as the temperature is cycled between 24 and 65°C. Laboratory analysis using liquid chromatography showed that the Semtex 1A and Semtex 10 contain only PETN, while the Semtex 1H contains both PETN and RDX.

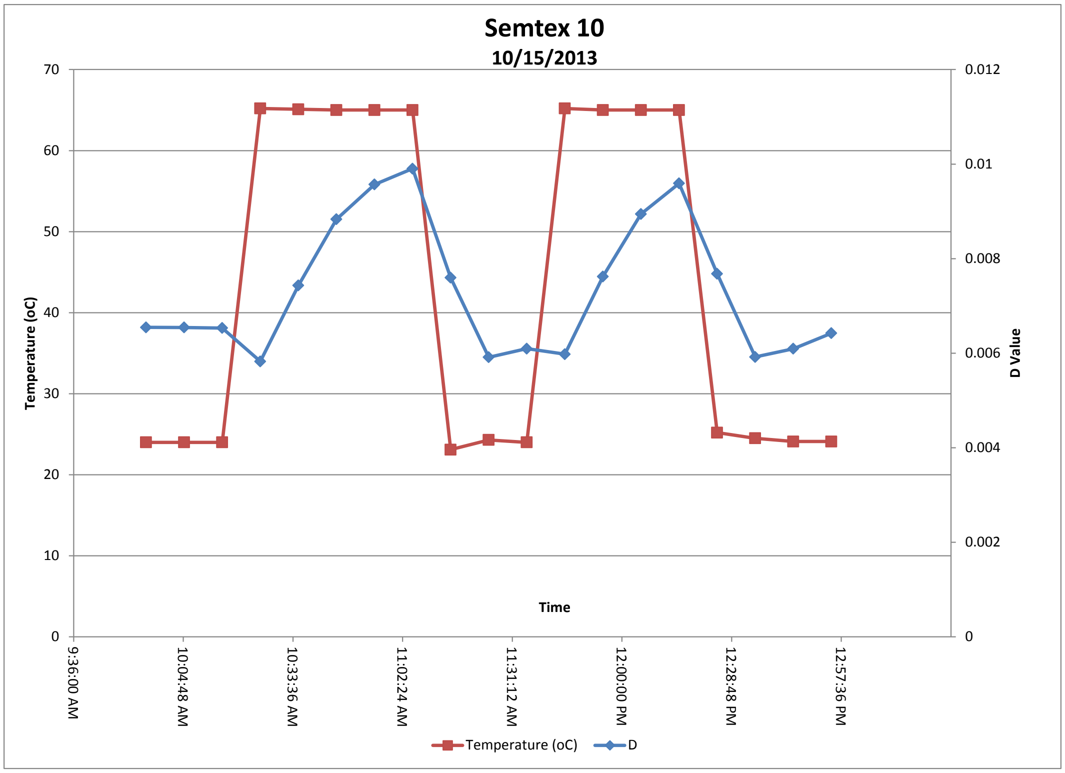

Figure 8. Semtex 10

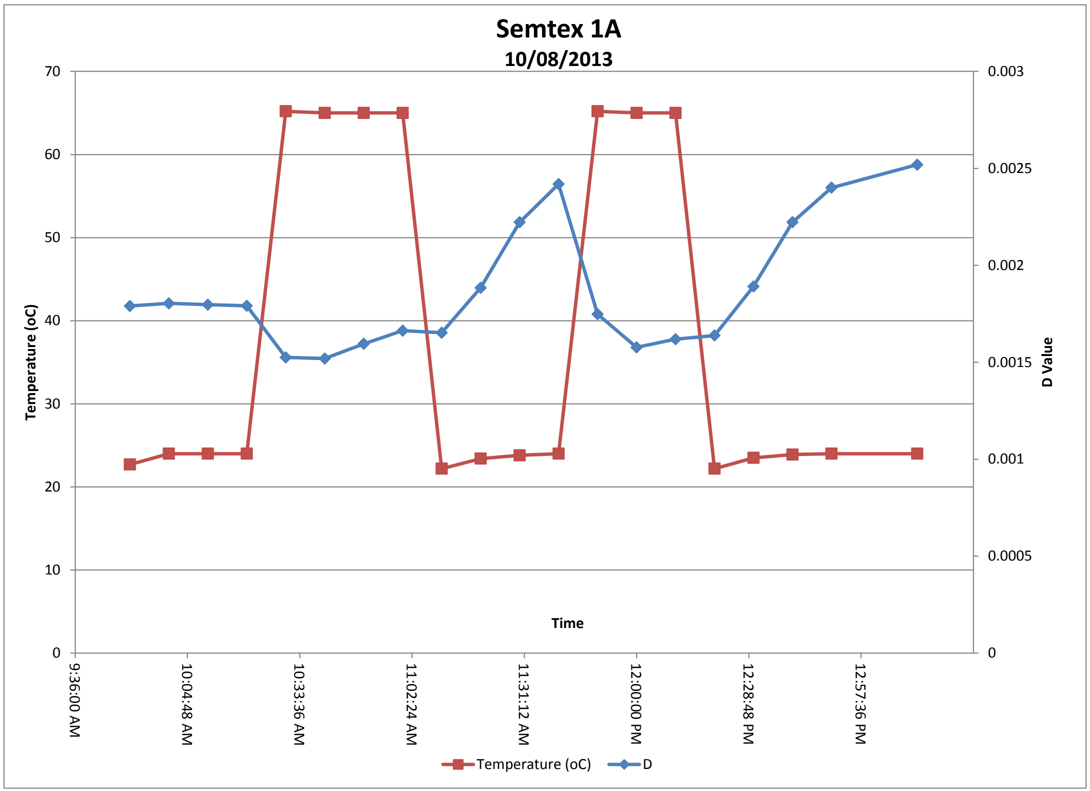

Figure 9. Semtex 1A

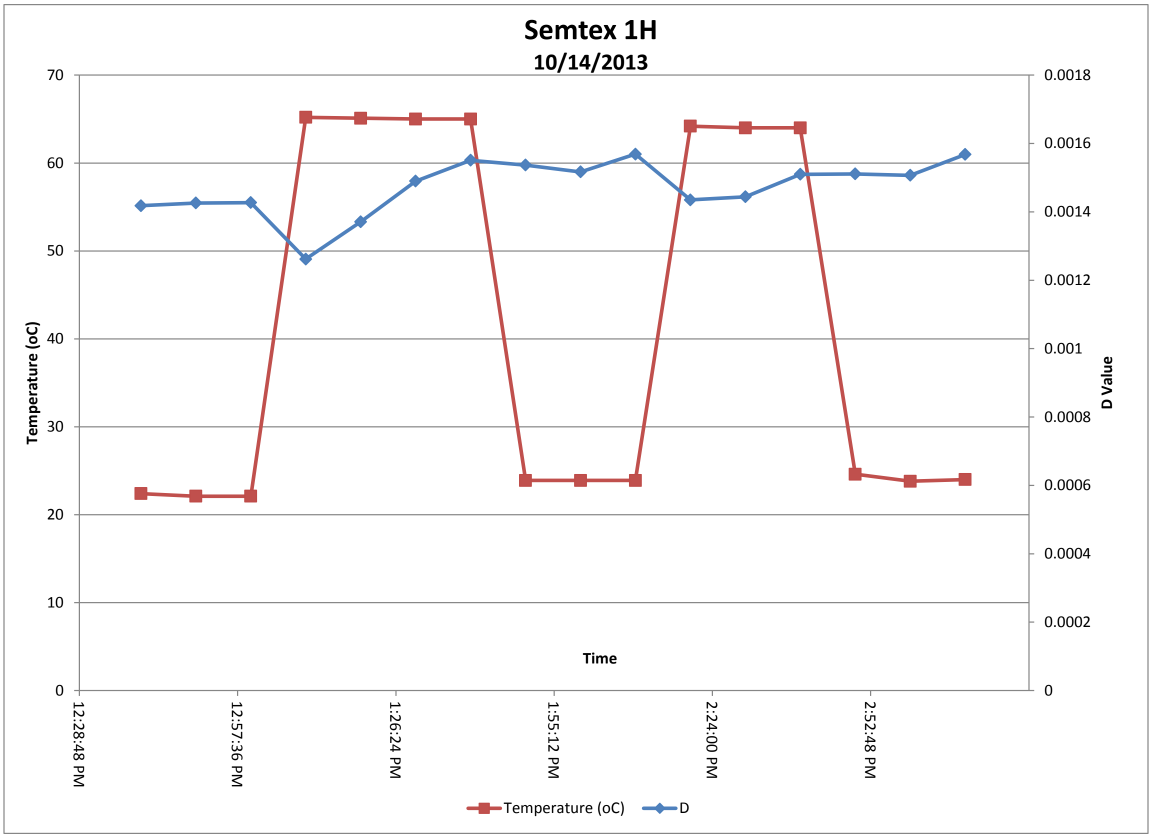

Figure 10. Semtex 1H

The weight percentages of these explosives in each type of Semtex are provided in Table 5, below. Semtex 10 and Semtex 1A show fair correlation of dispersion with temperature, though the behavior of Semtex 1A during the first heating cycle appears somewhat anomalous. Semtex 1A shows a decrease of the dispersion value with temperature, while Semtex 10 shows the opposite effect. Once again the dispersion changes lag the changes in chamber temperature. In the case of Semtex 1H, there appears to be little change in dispersion with temperature, the dispersion value remaining relatively constant at 0.0014-0.0015 during the temperature cycling.

Table 5. Liquid chromatography analysis of the content (weight percent) of PETN and RDX in different types of Semtex used in this study

Semtex Type	Weight % PETN	Weight % RDX
Semtex 10	82.2	No detection
Semtex 1A	79.3	No detection
Semtex 1H	46.0	37.3

Practical Implications

Overall, the results obtained in this study suggest that ε’, the real component of the complex dielectric constant, is not a useful parameter for monitoring temperature changes or temperature gradients within high explosives. This observation applies to the 24 to 65°C temperature range investigated, but it is likely also to apply to moderately higher temperatures provided no phase change such as melting occurs. For the six high explosives studied, the change in ε’ on heating from 24 to 65°C varied from only 0.41-1.71%, with the value always increasing with temperature. Changes of less than 2% are unlikely to be reliable indicators of temperature change because such changes may be difficult to distinguish from baseline drift; the temperature change required to produce a clear change in ε’ is too large for most practical applications.

In contrast, changes in the measured dispersion of these high explosives over the same temperature range are typically on the order of 20% or higher, suggesting that dispersion may be a useful parameter for monitoring temperature changes in these materials. The exception was Semtex 1H, which showed very little change of dispersion with temperature, a fact that may be related to the composition of this material that has approximately equal amounts of PETN and RDX. For Composition B, C-4, detasheet, Semtex 10, and Semtex 1A, changes in the dielectric dispersion are clear upon heating from 24 to 65°C, and the changes appear to be completely reversible.

While the dielectric dispersion of these explosives changes enough with temperature to be of some practical interest, there are other factors that may limit the use of dispersion measurements. The two primary issues are the need for direct contact with the high explosive material and the penetration depth. Measurement of the dispersion of a dielectric material with a thickness greater than approximately 10 mm requires the use of a fringing field capacitor (see Figure 11, below) where the two capacitor plates lie in the same plane, rather than a parallel plate capacitor as used in the tests described in this report. This fringing field geometry, in turn, requires the plates of the capacitor to be placed directly on the dielectric material, with no intervening air or other materials in order to obtain accurate measurements.

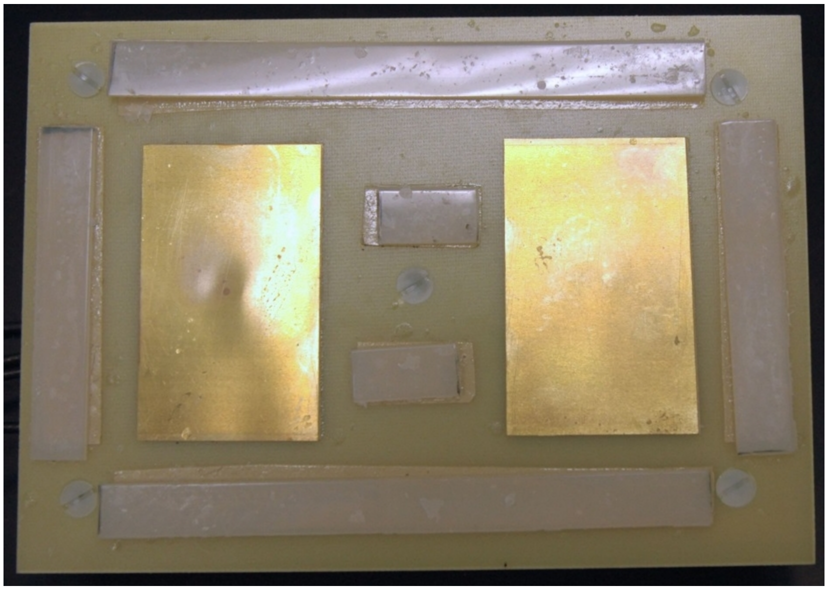

Figure 11. Fringing Field Capacitor

Additional experiments performed as part of the present study have shown that the penetration depth associated with a fringing field capacitor is approximately equal to the plate separation of the capacitor. Thus, for example, the fringing field will penetrate approximately 6” into the dielectric material if the plates are 6” apart. These relatively shallow penetration depths limit the technique to samples whose depth is less than 2 times the distance between the dielectric probes if full characterization of the object under test is desired.

Reference

Walbrecht, E. E. *Dielectric Properties of Some Common High Explosives*, Picatinny Arsenal, Dover, NJ, May 1963.

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