4.4 CONCLUSIONS

4.4.1 ESD ignition sensitivity

The measurement and prediction of the ignition by electrical discharges is a complex subject which spans the disciplines of chemistry, physics and electronics. A phenomenal amount of research effort has been directed over the last century towards quantifying the sensitivities of different materials (usually in terms on a minimum ignition energy) and elucidating the processes involved in the ignition and developing models describing the ignition in terms of measurable parameters. Theories and models are now available dealing with the ignition of fuel–air mixtures, but have yet to be wedded to a theory of discharge incendivity. A model of initiator explosive or pyrotechnic dust ignition by electrical discharges is as yet elusive.

The consensus is that ignition of all these systems depends on raising a critical sized ignition zone of the reactants to the self–sustaining combustion temperature. In the case of a burning fuel–air mixture, a critical size kernal must be heated to the flame temperature. In the case of a decomposing initiator explosive, a hot spot of critical size must be formed. In a pyrotechnic system, the melting of one of the reagents in a minimum volume of material mixture is may be the critical criterion. Similar criteria may exist for other combustion systems. The critical ignition zone size is defined by the conditions where the energy evolved by the reaction exceeds the energy lost to the surroundings. Energy must be supplied by the discharge in a form which initiates the reaction processes. The minimum quantity of energy required for ignition under optimum conditions is known as the minimum ignition energy. The size of the critical ignition zone is defined by the heat losses, (defined largely by the physics of the system), the chemical reaction thermodynamics and rate of reaction. Heat is lost to the surroundings by electromagnetic radiation, conduction, convection, diffusion, acoustic wave or other mechanisms.

Heat is required to raise the temperature of the critical ignition zone to the ignition temperature, and heat this is supplied by the discharge and the reaction processes within the ignition zone. If the reactant is in solid form, heat of fusion or vapourisation may be required before the reaction can proceed. The rate of energy generation by the reaction is governed by the energy produced per unit of reactant and the rate the reaction is able to proceed. The rate may be determined by mass transport or other limiting phenomena.

It is usually assumed that all the energy in the discharge contributes to the ignition process. The discharge energy must be transferred into the reacting material by heat conduction, radiation, convection, acoustic shock wave, direct ohmic heating or other mechanism. The efficiency of these processes is not well understood. In practice not all discharges act as good heat sources. The discharge energy is necessarily supplied by an electrical circuit, often from a known amount of energy stored electrostatically (charge in a capacitance) or electrokinetically (current flow in an inductance). A third method is to produce the discharge from voltage pulse applied to the electrodes. The efficiency of the energy transfer from the storage element to the discharge energy neither constant nor well defined, and often must either be measured or assumed.

For thermal ignition to occur, the discharge must thermalise, ie begin to act as a heat source. Energy developed as active chemical species, light, or acoustic energy may also affect on the ignition process, or may be converted to heat by some means. Initially, heat is generated as an electron gas emitted from the cathode. Later in the discharge ohmic heating of the plasma may be dominant. When cathode and anode spots are formed, heat is lost in vapourising the electrode material, but ejected electrode material could itself act as a heat source to the reagents. The presence of certain materials (eg solid particles) in the discharge path can interfere with discharge processes by modification of the primary or secondary emission characteristics, or by acting as a heat sink, or by obstructing or modifying the discharge path.

A discharge deposits energy into the discharge channel in as little as 10^{-8}s or greater than 10^{-3}s. The duration of the discharge has been widely regarded as being an important parameter in the ignition of dust clouds and layers, although in the last decade optimum durations have been also found for gas mixtures. The discharge energy is the integral of the discharge power over the duration of the discharge, and so energy, power and duration are inherently linked. An optimum range of discharge power (rate of energy input) is easily argued. A high power (short duration) may lead to the generation of a shock wave with energy losses and the displacement of fuel from the discharge region. If power is too low (long duration) the energy losses may not be sufficiently exceeded and the reaction temperature not attained. It is more consistant with the ignition energy philosophy to observe heat pulse parameters such as power and heat pulse duration, rather than the voltage or current waveform as has normally been practiced. Results based on the heat pulse may be more easily compared than when other definitions are used, especially when the waveform is poorly defined. Discharge current is important, however, in that the nature and geometry of the discharge are linked with this parameter. The author therefore considers that discharge power, linked with the discharge current and type may be primary parameters in the description of incendivity.

Discharge power is a function of discharge current, an easily measured parameter. Hence the discharge current linked with other conditions as the basis for comparison of the incendivity of discharges. Three types of ignition characteristic were identified from ignition results from the literature. Sensitive ignition regions were often correlated with discharge currents below 10^{-1}A and the cessation of sensitivity was identified with the reduction of discharge current below about 10^{-3}–10^{-4}A. Some of these results have been confirmed experimentally in this work, but warrant further investigation to verify these findings for different materials. Discharges below 10^{-1}A are more likely to be glow–like than arc–like. Thus there is evidence that some powder layer materials are more sensitive to glow–like than arc–like discharges. Evidence for this behaviour was observed in pulse discharge ignition of SR10 pyrotechnic. The capacitive discharge ignition characteristic was consistent with one of the three ignition characteristic types. The author proposes that the 10^{-1}–10^{-4} range of discharge currents should always be investigated in dust layer ignition experiments.

It is certain that energy is not the only criterion in ignition of a dust layer. Even if it were, it is difficult to determine an "absolute" minimum ignition energy, rather than a local minimum due to particular conditions. The ignition curve is better represented by a multidimensional surface, with a dimension for each factor. The number of factors is high in a complex system such as a pyrotechnic. The attempt to prove that an ignition energy is the true minimum value is an impossible task.

There are few standards laid down for ignition sensitivity testing of combustible systems. Those that there are tend to be vague or poorly defined in areas such as the definition of discharge waveforms, test conditions and ignition criteria. The discharge circuit or measurement techniques may not be defined. The consensus of the literature is that such parameters are important factors in the incendivity of the discharge.

Sensitivity parameters suitable for easy application to hazard assessment in the field may not be those of great interest in ignition research and modelling. These two functions have been confused in the past, which led to proliferation of test methods. The results were often not comparable for this reason, although this factor was not necessarily apparent. There is a need for a rationalised sensitivity test strategy aimed at simplification of hazard assessment. In contrast, research and modelling will always require experiments designed to elucidate their specific areas of interest.

Despite the difficulties, the concept of ignition energy remains a useful tool in describing the hazard potential of a sensitive material. It is proposed that the term "minimum ignition energy" remains of theoretical interest, but a different term would better represent the the measured values used in ignition hazard assessment. The term acts as a guide to the user as to the level of safety precautions required for the protection of personell and property, and it is important to be aware that an ignition could occur if a more favourable set of conditions than the test conditions were produced. The term "minimum ignition energy" is unfortunate in this context and conveys a false air of authority. The term "Standard ESD Ignition Energy" is offered for consideration. This represents an ignition energy value obtained under well defined standard conditions. In addition, it is suggested that a 50% ignition threshold is adopted for this test as the threshold level obtainable most efficiently. The new term might then be abbreviated "$SESDIE_{50}$". This terminology recognises that in order to elucidate low ignition probability or conditions other than standard, further tests would be required. The fact that this is indeed the current situation is not clear from the current use of the MIE term. It is argued that the $SESDIE_{50}$ term is more consistent with a safety philosophy.

Various workers have quoted "MIE" in terms of stored energies or discharge energies for ignition. It is argued here that the capacitive stored energy for ignition is the most appropriate parameter for ignition hazard assessment. Stored energies are more easily assessed in practical hazard situations. A simplified capacitive discharge test equipment could easily be developed for sensitivity testing, perhaps in many cases by adaption of existing apparatus. The decision not to calculate the discharge energies leads to a very simple apparatus of high reliability. An important development would be the control of discharge current (by inclusion of series resistance). This is already common practice. The sensitivity parameter could then be quoted as a function of discharge peak current. In a practical situation, assessment of the voltage and resistances possible in the hazard would give at least an indication of the discharge currents and type of discharge to be expected.

The assessment of sensitivity of a complex system such as a pyrotechnic dust is frought with difficulties. Even the decision as to whether an ignition has occurred is open to interpretation! There is much work to be done in overcoming these difficulties. Added to this is the conflict between the need to minimise the number of trials and the need for a large number of trials for statistical purposes and to investigate the many factors. The author suggests that a multi level standard may prove a useful approach. For example, a first level would give basic sensitivity classification. This level represents a basic test applied to all potentially hazardous materials, yielding a sensitivity figure (eg $SESDIE_{50}$) qualified by other data. A second level of tests would give extended sensitivity data with greater statistical certainty, and might be applied where the first level test indicated a more hazardous material. A third level would give special information, perhaps tied to the specific operating and storage conditions of the material.

4.4.2 Capacitance and pulse discharge ignition energy measurements

In this work apparatus was developed for capacitance discharge and pulse discharge ignition energy measurements in the low microjoule energy region. A lower limit to IE measurements exists due to energy was stored in the electrode gap and size capacitance at breakdown. A typical lower limit was around 0.5μJ for an electrode capacitance of 1pF with a breakdown voltage of 1kV. Low energy discharges may not thermalise if a critical charge density in the discharge is not achieved.

In a pulse discharge, breakdown was preceded by a displacement current due to the charging of the electrode gap capacitance. Displacement current was proportional to gap capacitance and dV/dt, and caused a small increment in the discharge energy calculation, equal to the electrode stored energy. This was an advantage in low energy ignition work. In a capacitance discharge, the energy stored in the electrode gap capacitance on breakdown was not measured.

In both capacitance and pulse discharge waveforms, an impulse was associated with the wavefront, due to discharge of the electrode capacitance. The peak could be <5ns in duration and have an amplitude (10–100A) an order of magnitude greater than the main discharge current flow. The peak current value and duration was dependent on the electrode capacitance.

The useful applied voltage was limited for both capacitance and pulse discharge systems due to digitising resolution. Glow-like discharges were better resolved than arc-like due to their higher discharge voltage drop (circa 400V against circa 50V). Higher voltages could thus be used in glow-like discharge experiments.

Both pulse and CD techniques were useful in characterisation of sensitive materials. Pulse techniques may be particularly useful as a research tool as waveform characteristics could be better controlled. CD systems also have the advantage of simplicity which makes them perhaps better suited to routine measurements, particularly if discharge enrgy calculation is not required. Ignition tests indicated that the two techniques yield broadly similar results and may be useable interchangeably under certain conditions.

The pulse generating apparatus and energy measurement system could repeatably produce and measure near rectangular discharges having energies in the range 5–50μJ. The short (120ns) pulse breakdown voltage in hydrogen-air mixture and air was higher than the dc value. Breakdown voltage was reduced by introduction of ions into the interelectrode space by corona discharge. This was a useful technique for reducing gap stored energy when testing gas mixtures. Fast rise exponential decay discharges (similar to a CD waveform) with energies up to a few millijoules and durations in the 10^{-6}–10^{-3}s range were also produced. The discharge current and hence rate of energy input was largely controlled by series resistance and pulse voltage. Pulse voltage could be varied independently of the discharge gap as long as the breakdown value was exceeded. In gas discharges and arc–like discharges through powder the current pulse waveform followed the applied voltage waveform. For these discharges the duration was independent of other parameters. Glow–like discharges through a dust layer had a variable waveform and duration. A definition of duration based on the heat pulse was felt to be more useful than a definition based on the current waveform. At low discharge currents ($<10^{-3}$A) the discharge current could assume a pulse train form.

Capacitance discharge measurements were sensitive to the accuracy of the measured values of capacitor voltage at breakdown, and storage capacitance. Certain capacitor types (notably ceramic) were found to store greater amounts of charge than was expected from the zero bias capacitance value, and these were unsuitable for use. Stray capacitance could be a serious limitation on stored energy unless care was taken in circuit design. Capacitance discharge energy could be reduced by including significant circuit resistance. This altered the circuit decay time constant and hence waveform duration. Additionally, the waveform could change between oscillatory, unidirectional and pulse train forms. The circuit series resistance in a capacitive discharge system had a strong effect on spark ignition energy, waveform duration, and peak current in the discharge. The discharge power dissipation was found to be a function of the peak current in the discharge. Peak current was a function of the breakdown voltage and series resistance, except in the oscillatory and pulse train forms. Waveform duration, peak current and power at peak current were interdependent with capacitance, breakdown voltage and resistance.

Step changes observed in the capacitive and pulse discharge current waveforms around the 10^{-1}A current level were consistent with a change between glow–like to an arc–like discharge forms. Higher power dissipation per unit current was achieved in the glow–like state associated with lower currents. This is probably due to a higher cathode fall in this type of discharge. In capacitance discharges for discharge currents either side of the transition region, the power H_d' approximately followed the relation $H_d' \alpha I^n$, with values of n in the range $1 < n < 3.5$ for air. Transition behaviour was observed in both air and powder discharges. The discharge power decayed with the discharge current, but discharges with different series circuit resistances did not exhibit the same dissipation at a given discharge current. The characteristic was determined by the at peak current. The effective discharge resistance at peak current I_{dp} was an inverse function of I_{dp}. Peak current was slightly less than the value V_B/R_r. Additionally, at low capacitance values the capacitor voltage could drop significantly from the breakdown value by the time the peak current was reached. The power dissipation at peak current was nearly proportional to I_{dp}.

The ignition energy of 30% H_2–air mixture was found to be 22μJ using a 120ns pulse and 0.6mm discharge gap and 20μJ using a capacitance discharge in a 0.7mm gap using a circuit resistance of 359Ω. These ignition energy values found are comparable to those quoted in the literature. Thus both apparatus produced reasonable ignition energy results. Many of the experimental results (for example the pulse discharge result $H_d \alpha R_s^{a}$) were consistent with Priede's assertion that $R_d \alpha I^{-n}$. This supported the view that the discharge was essentially a current controlled phenomenon. The variable $a = -(2-n)$ was a weak function of the interelectrode gap. The 120ns pulse discharge energy could be approximated by the relation

$$H_d = K_2 \, 10^b \, d \int_0^T I_d^{-a} \, dt$$

The variables K_2, a, b probably depend on experimental apparatus and conditions.

The waveform of a discharge from the human body skin at V_B>350V featured a fast wavefront and slower near-exponential decay, and could be modelled by a conventional CRL model. If the discharge occured from a metal object in contact with the skin then a fast impulse was associated with the wavefront, which may have nanosecond duration and peak current an order of magnitude or more higher than the main discharge. Modifications to the CRL body model were proposed to account for these impulses. Waveforms similar to the human body discharge above the Paschen minimum could be produced by both capacitive and pulse techniques.

Discharges from the skin of a human body at a potential of less than the minimum breakdown potential of air (circa 350V) were not those expected from a simple CRL model. Discharges from a negative finger produced long duration slowly fluctuating waveforms, wheras dischages from a positive finger showed a train of fast pulses. Neither of these types of waveform was produced by the capacitive or pulse discharge apparatus.