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Accidental initiation of condensed phase explosives during road and rail transport

P.A. Davies

DNV Technica, Highbank House, Exchange Street, Stockport, Cheshire, SK3 OET, UK

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Abstract

An important issue, with regard to hazard/risk assessment of explosives transport, is one of identifying and quantifying stimuli which can cause explosives to initiate. This paper identifies these stimuli for road and rail transport environments together with a number of useful data sources. It is concluded that fire and impact are the most likely sources of explosives initiation.

1. Introduction

Explosives sensitivity testing is primarily performed so as to classify explosives into various hazard divisions and compatibility groups. The need for such classification has culminated in a variety of tests and a wealth of published data, some of which enables judgments to be made on the vulnerability of explosives to various stimuli which can be encountered during road and rail transport.

A comprehensive reference of data and tests pertinent to commercial explosives is given by Macek [1], whereas the Sensitiveness Collaboration Committee [2] have compiled a full list and description of tests relative to military explosives. In addition, the United Nations (UN) Committee of Experts on the Transport of Dangerous Goods recommend a number of tests and criteria suitable for classifying both commercial and military explosives [3]. The tests are published as a handbook companion to the UN recommendations on the Transport of Dangerous Goods [4].

It is generally accepted that under normal transport conditions, explosives can be conveyed with little risk of initiation [5]. Normal conditions refer to usual transport environments where extremes of heat, shock and vibration, etc., are not encountered. However, vehicular accidents can have the potential to cause initiation of explosives, either by introducing stimuli or amplifying normally passive environments. Typical

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initiation stimuli, being either accident induced or passively present, have been identified here and are discussed below.

2. Shock and vibration

Shock is defined as a sudden and severe non-periodic excitation of an object. Most available data quantify shock in terms of acceleration in an identical manner to that found in vibration measurement. Unlike shock, vibration is often described as a periodic oscillating motion. However, in normal transport environments both shock and vibration tend to be characterised by non-periodic oscillations accompanied by changing amplitude. Therefore, shock and vibration are effectively identical, since high amplitude short term vibration, as experienced in vehicular accidents, can also be classed as shock.

During transit, and under normal transport environments, heavy goods vehicles (HGVs) are subjected to maximum shocks [6] of approximately 100 m/s^2. It should be noted here that such measurements are often expressed in terms of "g" where g refers to acceleration due to gravity (e.g. in this case of 100 m/s^2 equates to approximately $10g$). Provided packages are secure, such shock levels are very unlikely to cause initiation. However, it has been known for structures attached to road and rail vehicles to experience excitations above those of the transporting vehicle [6]. Excitations of the order of 200 m/s^2 have been recorded for loads carried by HGVs, whilst the HGV itself has experienced much lower shock levels. There is no evidence to suggest that shock amplification is a new phenomenon. Although large excitations are not commonplace, shock amplification is considered part of the normal transport environment. As a consequence of this, it is thought that shock amplification has little effect on transport incidents involving explosives.

Sensitivity of explosives to shock has been analysed since the early 1930s when Muraour [7] devised a rudimentary test known as the "Gap Test". From its infancy it has grown to become one of the main internationally recognised sensitivity tests. A shaped charge known as the "acceptor" is separated from the "donor" charge by an inert barrier of thin metal or plastic strips, typically 0.25 mm thick. Both the donor and acceptor geometries are fixed, the only geometric variable being gap thickness. Consequently, shock sensitivity is measured in terms of gap thickness; the smaller the gap the less sensitive is an explosive, and vice-versa. The thickness of the gap is determined when the acceptor has a 50% chance of detonating.

Results gained from shock sensitivity tests are of little use for the provision of "real life" sensitivity quantification. This is because the stimuli used are idealised and their rates of input far too large compared with those experienced in vehicular accidents [8]. As a consequence of this, shock sensitivity test results are of little value except as a means of comparing the relative shock sensitivity of explosives. Typical Gap Test results for various explosive materials are listed in Table 1. Further information on the concepts of shock sensitivity, current testing procedures and equipment can be found in [9].

Table 1
US Naval laboratory gap test[a]

Material	Cast or pressed	Density (g/cm^3)	Gap thickness (cm)
RDX	pressed	1.640	8.20
Pentolite	cast	1.684	6.70
Tetryl	pressed	1.615	6.63
Comp. B	pressed	1.663	6.05
Comp. A	pressed	1.590	5.34
Comp. B	cast	1.704	5.24
TNT	pressed	1.569	4.90
Amatol	cast	—	4.12
TNT	cast	1.600	3.50
Tritonal	cast	1.750	2.90

[a] Source: Macek [1].

Although it is difficult to determine precise shock levels for explosives during conveyance, it is generally agreed that those shocks and vibrations experienced under normal transport environments are insufficient to cause explosive initiation [5, 6]. However, it is thought that shock and vibration resulting from vehicular impacts could attain suitable magnitudes to cause initiation. It is considered, that in vehicular accidents shock/vibration stimuli, sufficient to cause initiation, are accompanied by impact stimuli of magnitudes so great that initiation is much more likely as a result of impact. In addition to this, shock/vibration stimuli are difficult to distinguish and measure separately and therefore, initiation is commonly assumed to occur as a result of impact.

3. Impact

Impact can be defined as the collision of a single moving object with another moving or stationary object. Such impacts are absent in the normal transport environment. However, impact usually occurs in vehicular accidents. Collisions with other moving vehicles may cause direct and/or indirect collision of the explosives under conveyance. Direct collision refers to actual contact between explosives and the offending vehicle(s), whereas indirect collision refers to contact between separately packaged explosives and/or ancillary equipment and/or interior parts of the transporting vehicle. A similar analogy can be expressed for single vehicle accidents involving impact, such as, collisions with unyielding objects and structures.

Although it is thought that impact initiation is thermal in origin, why explosives ignite (sometimes) as a result of impact is not fully understood. On the basis of thermal initiation caused by the creation of localised thermal energy, known generally as "hot-spot" generation, energy transferred during impact must be greater than or equal to the Arrhenius energy of activation [6, 10]. In this instance Arrhenius energy is the energy required to cause a small amount of explosive to decompose. It is believed that impact causes this decomposition by creating "hot-spots" above the explosives initiation temperature. This is thought to occur as a result of (a) friction between grains of explosive and/or grit particles; (b) adiabatic compression of small air cavities; (c) viscous heating caused by rapid extrusion; and (d) localised adiabatic deformation of thin layers of explosive as a result of mechanical failure.

A full account of these initiation mechanisms is given by Bowden and Yoffe [10], Heavens and Field [11] and Field et al. [12].

Upon decomposition by one or more of the above heat generation mechanisms, additional energy is liberated which activates neighbouring material and so propagates a sustained reaction. There is a tendency for such exothermic reactions to become faster and rapidly increase the rate of heat production which ultimately leads to deflagration or detonation. For solid explosives the area over which energy is delivered appears to be an important criterion [6]. If the area is too small, neighboring material will not receive sufficient energy to cause further decomposition and therefore explosion will not occur. Initiation energy for solid explosives tends to be recorded on a per unit area basis (J/m^2). By contrast, liquid explosives, including slurries and pastes, tend not to be critically dependent on the area over which energy is delivered [6]. The reasons for this are not fully understood. For liquid explosives there is a tendency for energy to be recorded and measured in terms of energy per unit time (J/s).

Impact testing is well established as a standard explosives sensitivity test, although it is often acknowledged as a crude art rather than an exact science. This statement can be inferred from typical hammer impact tests, as described by Macek [1] and Bowden et al. [13], and from "Susan" impact tests described by Parzel and Ward [14]. Unlike the determination of shock sensitivity, where event initiation can be related back to a pure shock wave, impact initiation can be attributed to many factors. Such factors are in the main attributable to impact velocity, pressure, friction, viscous heating and explosive fluidity. Many more problems accompany impact testing. However, those mentioned above serve to demonstrate the complexity surrounding impact sensitivity testing and measurement. An in-depth discussion of the problems associated with impact testing is given by Macek [1] and Marshal et al. [15].

The most common impact sensitivity test consists of a hammer of known weight being dropped from a pre-determined height onto an anvil layered with powdered explosive. The distance between the hammer and explosive (height) is recorded as that distance which results in a 50% chance of detonation. The weight of the hammer is recorded and together with the height, which is found effectively by trial and error (through the Bruceton Staircase technique), both are used as a measure of impact sensitivity. Since detonation is extremely rare during testing, an event is deemed to occur when an appreciable amount of noise, gas, odour, smoke or other suitable by-product is observed. Unfortunately, the results obtained from impact tests are of limited value, except as a means of ordering explosives sensitivity to impact and highlighting the risk of impact initiation. Typical impact test results for various explosive materials are listed in Tables 2 and 3.

Table 2
US Naval laboratory impact test[a]

Material	Height[b,c] (cm)
PETN	13
RDX	24
HMX	26
Pentolite	38
Tetryl	38
Comp. A3	60
Comp. B	60
Tritonal	107
Amatol	116
TNT	200
Ammonium nitrate	> 320

[a] Source: Macek [1].
[b] 2.5 kg hammer, 35 mg sample.
[c] Height, 50% chance of detonation/event.

Table 3
Fall hammer impact sensitivity[a]

Explosive	Height[b,c] (cm)
Gelignite	5–10
Nitroglycerine[d]	20–30
RDX	25–30
Ammon gelignite	30–40
PETN	60–80
RDX/TNT	80–100
TNT[d]	160–200
TNT	> 200

[a] Source: Bowden and Gurton [13].
[b] 0.5 kg hammer.
[c] Height, 50% chance of detonation/event.
[d] Powder.

Results of Susan impact tests are detailed in Table 4. Essentially, the test was devised to help determine the initiation vulnerability of explosives in aircraft accidents. A steel projectile loaded with 0.45 kg of explosive is propelled at various speeds into unyielding surfaces. The results of such tests indicate that explosives have a range of probable impact initiation speeds and that some explosives are much more sensitive than others. More importantly, the results indicate that a number of explosives can be initiated by impact at speeds which can be experienced in severe vehicular collisions. The report [14] from which the Susan test data are taken (and detailed here in Table 4) states that “a blanket assumption cannot be made that all warheads have survived a 15 m/s [34 mph] impact”.

Table 4
Impact initiation of explosives: Susan tests[a]

Explosive	Impact speed (m/s)		Mean p^o (kN/m^2)[b] at 3.05 m
	Initiation	Survived	
PBXN-105	52	32	1.1
EDC 38	65	78	8.1
OCTOLITE 70/30	66	62	51.8
CTX-1	67	51	19.6
EDC 29	77	66	12.6
EDC 37	79	80	4.1
EX 62	80	51	11.9
EDC 24	84	64	2.0
HMX/TNT 85/15	86	98	50.3
CW3	89	50	3.2
EDC 15	90	53	15.7
TORPEX 2A	98	87	0.7
HMX/POLY 85/15	120	89	3.6
RGPA TYPE 2	140	82	2.4
RDX/TNT 60/40 A	143	87	7.0
RGP	154	82	2.0
BX4	156	118	5.5
TORPEX 4D/TF	185	135	9.3
RDX/WAX/A1 2B	203	114	9.0
PE4	228	125	8.7
EXC 35	246	157	3.0
CPX 200/M5	285	108	26.6

[a] Source: Parzel and Ward [14].
[b] p^o = peak overpressure.

It is important to note that vehicular collisions at such an impact speed (15 m/s) or greater are not uncommon. Evidence to support this stems from data collected by the author [16–18] on HGV and freight train (FT) speeds, upon and prior to collision. However, as can be seen from Table 4 all explosives tested by the "Susan" technique survived impacts far greater than 34 mph (15 m/s), in fact far greater than 120 mph (54 m/s).

From the discussion given above it is thought here that regardless of energy absorption by vehicles during collision and protection offered by packaging, etc., certain vehicular impacts are capable of initiating a number of military and commercial explosives.

4. Friction

Friction sensitivity of explosives has been investigated by many researchers since the late 1930s [13, 19]. Many tests have been devised, the most common ones being

Table 5
Friction sensitivity[a]

Explosive	Torpedo friction[c,d] (cm)	Friction wheel[c,d] (kg)
RDX	10–20	—
Gelignite	40–60	4
PETN	35–40	10
RDX/TNT	40–45	—
Ammon gelignite	40–60	30
TNT	80–120	>50
TNT[b]	100–120	>50
Nitroglycerine[b]	>150	>50

Values given are those which may cause an event. The chance of an event is not given.
[a] Source: Fordham [20].
[b] Powder.
[c] 1 kg at 80°.
[d] 0.5 m/s.

the Torpedo Test, Friction Wheel and Sliding Friction Test. Sensitivity testing by the aid of a friction wheel has been established for many years [20]. Simply, a small amount of explosive is smeared on the surface of a rotating disc on which rests a rod which can be varied in weight. The higher the speed of rotation and the greater the load before initiation the less sensitive is an explosive. In comparison, the sliding friction test essentially consists of a pendulum, anvil and plate. The plate is layered with explosive and the pendulum designed so as to slide the anvil over the plate perpendicular to the force vector and at a pre-set constant velocity. Initiation is detected by observation or with the aid of an infra-red analyser which can detect small amounts of decomposition gases. Typical friction test results are listed in Table 5.

Results gained from friction tests provide a measure of friction sensitivity which can be loosely extrapolated to frictional forces experienced in transport environments. For example, Hercules Inc., USA [21] through the Allegancy Ballistics Laboratory (ABL) have employed a sliding friction machine to determine whether explosives can be initiated by friction under normal transport environments. The results, which are detailed in terms of combined pressure and velocity, confirm that normal transport environments do not provide sufficient frictional stimuli to initiate explosives. Hercules suggest that loads experience velocities far below 3 m/s and pressures of 2.8×10^8 N/m^2 or more are unlikely to be encountered. To support their claim they found that the most sensitive explosive tested, Gel-Power A-2 slurry, at 3 m/s required a pressure of 3.7×10^8 N/m^2 to commence initiation.

Frictional stimuli are inherent in impact initiation. It is considered that in transport environments frictional stimuli are largely a result of severe vehicular collisions, and are therefore often masked by impact stimuli. One initiation mechanism associated with friction and impact is "stab-initiation". However, it can be argued that stab-initiation is basically a frictional stimulus [22]. For example, a metal rod piercing and passing through an explosive may cause a thin layer of explosive to adhere to the rod surface. This can cause frictional rubbing between the adhered layer and surrounding explosive resulting in localised heat generation. Such an initiation mechanism in an accident environment would require large impact forces sufficient to breach vehicle bodies, packaging and casing, etc. As a consequence of this, it is generally thought that stab-initiation is as much (if not more) an impact stimulus as it is a frictional stimulus. Similarly, frictional/impact initiation stimuli are possible from crushing effects caused by vehicles or wagons passing over explosives strewn across road or track. Again such initiation mechanisms, if credible, are likely to involve severe vehicular collisions or severe impacts to the explosives involved.

In the absence of impact stimuli capable of initiating explosives, frictional stimuli may attain sufficient magnitude to cause initiation. Such frictional initiation, under certain conditions is possible from the stimulus of sliding frictional force. This is measured as the force required to overcome resistance to horizontal motion and is recorded in terms of normal force per unit area (N/m^2). For explosives to be initiated by sliding frictional force during transit, a spillage of explosive requires a "rubbing" velocity [6] of approximately 3 m/s between package/equipment and explosive. Such action can produce "hot-spots" of sufficient temperature to cause thermal decomposition and hence, initiation. Incidents resulting from such action are unlikely (though not incredible). This is because packaged explosives rarely lose their integrity and cause spillage when exposed to normal transport environments. In addition, unless acted upon by large external forces, load movements are subjected to velocities far below 3 m/s. Large forces resulting in load velocities above 3 m/s are possible from vehicular accidents. However, it is unlikely that vehicular accidents other than collisions involving severe impacts will cause packages to lose their integrity, thereby subjecting explosives (possibly) to sliding frictional forces above 3 m/s. Furthermore, it is thought that severe collisions are more likely to cause initiation through impact than friction.

5. Thermal energy

The majority of explosives can be initiated by thermal stimuli. Initiation occurs when an exothermic reaction is realised and the rate of heat generation is much greater than the rate of heat loss. The critical temperature above which explosion occurs is dependent not only on explosive composition but also explosive geometry and length of exposure to thermal stimuli. In addition, Arrhenius activation energy, thermal conductivity and heat capacity, to name just a few, are contributing factors which affect thermal sensitivity of explosives. Thorough analyses of these factors and the techniques required to determine sensitivity are given by Longwell [23] and Anderson [24].

Determination of critical explosion temperature is mainly performed using thermal "cook-off" techniques. These usually involve the immersion of small amounts of explosive in molten solutions [25], the employment of differential scanning calorimetric equipment, where exothermic onset temperature is evaluated, or by the adoption of differential thermal analysis [26, 27].

Table 6
Ignition temperatures of explosives[a]

Explosive	Ignition temp.[b] (°C)	Minimum hot-spot temperature for initiation by:	
		Friction (°C)	Impact[c] (°C)
Tetrazene	160		400–430
Mercury fulminate	170		500–550
Tetryl	180		
Nitroguanidine	185		
Nitrocellulose	187		
Nitroglycerine	188	450–480	
PETN	205	400–430	400–430
RDX	213		
TNT	240		
Lead styphnate	250	430–500	500–550
HMX	300		
Lead azide	350	430–500	500–550

[a] Source: Bowden and Gurton [13].
[b] The Royal Military College of Science.
[c] Impact initiation in the presence of grit.

Results gained from thermal sensitivity tests are dependent on factors particular to each individual test. However, the results are useful in providing a guide to thermal stimuli which are capable of initiating explosives. It is apparent from the results given by the US Army Material Command [25] that explosives are extremely unlikely to be initiated by thermal stimuli when exposed to normal transport environments. This point is tentatively supported by the high temperatures required to initiate explosives. For example, TNT requires a temperature of 465 °C sustained for a minimum of 10 s or 520 °C for 1 s to undergo initiation [6]. In comparison, a typical Hercules manufactured dynamite when subjected to a temperature increase of 10 °C/min yields an onset exothermic temperature not much greater than 145 °C. Unfortunately, Kloeber et al. [6] have not expanded upon these results. The quantity and geometry of explosives used and the source of heat are not detailed. Therefore, the applicability of these results, with respect to the quantification of thermal sensitivity, is not clear.

Ignition temperature for a number of explosive materials under various conditions is given in Table 6.

It is concluded by Kloeber et al. and the US Department of Transport [6] that the temperatures cited above, and especially the rate of temperature increase, are extremely unlikely to be encountered under normal transport environments. Military explosives have in fact been subjected to temperatures as high as 46 °C, whilst undergoing truck shipment through Death Valley, California, and in excess of 65 °C during air travel [6]. However, explosives are characterised by poor heat dissipation. This can lead to thermal decomposition when exposed to prolonged "high" temperatures and may ultimately cause explosives to ignite.

In transport environments the main threat of explosives initiation from thermal stimuli is that of fire. This statement is supported by historical incidents, data collected by the US Material Command [25] and work carried out in the early 1980s at the Royal Armament Research and Development Establishment (RARDE). The results of this work illustrate that many explosives will initiate and burn to deflagration, and in some cases detonation, when subjected to engulfing or torch fires similar to those experienced in store and transport accidents. It has been shown by Dyer et al. [28] that the time required for the initiation of munitions in pallet fire tests and torch flame tests varies with respect to the type of fire and explosive used. For standard 155 mm military shells filled with 11.5 kg of explosive (RDX/TNT or CW3) typical initiation times for pallet fire tests range from 0.6 min to approximately 18 min. Dyer et al. note that military shell case temperatures vary from between 370 °C (or less) to over 590 °C, and that there appears to be no correlation between case temperature and detonation/deflagration. Only a minority of the tests actually result in detonation. It is thought that case failure, causing loss of confinement, inhibits transition from deflagration to detonation. From this it can be surmised that explosives subjected to vehicular fires are more likely to deflagrate than detonate (especially commercial explosives which are unlikely to be confined). The short duration times from fire inception to initiation recorded by Dyer et al. are thought to be a consequence of ignition at metal/explosive interfaces rather than any internal self-heating effect. This suggests that vehicular fires, which are usually of a short duration and similar intensity to that of pallet fire tests, have the potential to cause initiation of explosives leading to deflagration (and possibly detonation). In fact vehicular fires, especially HGV fires, may be fuelled by petroleum or diesel thereby increasing heat intensity and the likelihood of initiation. Physical orientation to heat and flame also has a notable effect on the length of exposure before initiation. For example, the average time for 155 mm military shells to initiate when subjected to pallet fires increases substantially from 3.5 min when laid horizontally to over 11 min when positioned vertically [28]. The reasons for this are thought to result from the greater uniformity and intensity of heat endured by explosives when shells are laid horizontally.

6. Chemical instability/reactivity

Both commercial and military explosives can under certain conditions or over long periods of time decompose to provide a risk of unintended initiation. For example, dynamites containing nitro-glycerine decompose during long storage periods and ultimately become liable to accidental initiation. Also, if such explosives are contaminated with other chemicals, such as, nitric acid, they decompose violently and become unstable.

Initiation of explosives by chemical reactivity during transport, either autogenously or by the introduction of external agents, can occur. Although commercial and military explosives are designed, manufactured and packaged so that they can be transported and handled without loss of integrity, thus avoiding possible decomposition, careless practices can arise. For example, the condition of boxes storing cerium fuseheads was identified as a contributory cause in the initiation of commercial explosives at Peterborough [29] in 1989. Subsequent investigation by the UK Health and Safety Executive [29] concluded that rust particles (within the storage boxes) sensitised the fuseheads to friction/impact stimuli. As the goods vehicle conveying the explosives (11.5 te) passed over a speed ramp, resulting in a minor jolt, a number of fuseheads ignited.

7. Electrical energy

Explosives can be initiated by electricity if sufficient energy is discharged. All explosives have a specific ignition energy level, above which initiation will occur. Most explosives have ignition energy levels below, for example, the energy released from arcing of electrical equipment. However, initiation is not only dependent upon the specific electrical properties of the explosive, but also environmental generation, storage and discharge mechanisms.

Electrical energy can take one of three forms: (a) current electricity; (b) electromagnetic radiation; and (c) static electricity.

Current electricity is a common means of initiating explosives, especially explosives linked to electric detonators and ignition systems. In transport environments current electricity is extremely unlikely to be encountered. However, potential current electricity sources along roadsides include transformer sheds, electricity sub-stations, street lighting and overhead electricity cables. Electricity sources along rail tracks include signal boxes, overhead lines and station lighting, etc.

Electromagnetic radiation poses a threat of accidental initiation only to those explosives forming electro-explosive devices. Stray radiation waves from transmitters may emit energy levels capable of initiating such devices. Sources of radiation waves stem from radio transmitters to citizen band (CB) frequency amplifiers. However, electro-explosive devices are packaged in anti-induction configurations and materials, thereby effectively eliminating initiation unless (intentionally or unintentionally) package integrity is breached.

The main electrical hazard is that of static electricity. Under certain conditions up to 0.02 J of electrostatic energy can accumulate on clothing (although this is extremely uncommon). Such energy is sufficient to initiate certain sensitive explosives. For example, some ether/oxygen and lead styphanate mixtures have ignition energy levels below 0.05×10^{-3} J and even common explosives such as PETN, nitro-cellulose and various cordites have ignition energy levels between 0.015 and 0.1 J. For transport purposes, with respect to static electricity, explosives can be chiefly divided into those explosives which are liable to initiate below 0.02 J and those which require greater energy input.

Electrostatic sensitivity testing of explosives essentially consists of a series of charged capacitors, which can be controlled to discharge electrical energy between 5×10^{-4} and 5 J. Initiation is either physically observed or verified with the aid of an infra-red analyser to detect decomposition gases, as previously mentioned. Tests performed by Hercules Inc. USA [21], with capacitors charged to 5000 volts, found that TNT and Gel Power A-2 slurry initiate at energy levels of 0.075 and 1.26 J respectively. However, the Allegancy Ballistics Laboratory [21] (ABL) indicate that possible electro-static discharge paths in normal transport environments are unlikely to discharge sufficient energy levels to cause explosives to initiate. For example, from an isolated conductor, having a surface area of approximately 400 cm^2, ABL found the discharge energy to be less than 0.02 J. Similarly, other tests conducted at the same time could find no sources of energy approaching a level required to cause TNT to initiate.

It should be noted that all the tests performed by ABL were on unpackaged explosives. Packaging would, it is suggested, often isolate explosives from electro-static discharge, reducing further the small possibility of initiation from such stimuli. In conclusion, under normal transport environments or even in the event of vehicular accidents, the possibility of explosives being initiated by electro-static discharge is small.

8. Conclusions

Accidental initiation of commercial/military explosives is possible in principle from a number of stimuli, namely (a) shock and vibration; (b) impact; (c) friction; (d) thermal energy (fire); (e) chemical instability/reactivity; and (f) electrical energy (static electricity).

However, as this paper illustrates by far the most likely stimuli to cause initiation in transport environments are impact and fire. Initiation by shock/vibration is thought to be unlikely except when accompanied by large impact forces, where it becomes difficult to distinguish between shock/vibration initiation and impact initiation. Similarly, initiation by friction is thought to be unlikely without the presence of (i) large impact forces capable of breaching packages and instigating sliding frictional forces; (ii) large impact forces capable of piercing packages and explosives thereby instigating friction/impact stimuli associated with stab-initiation/crushing effects; and (iii) sensitisation of explosives due to the presence of additional stimuli (chemicals, rust particles, etc.) as a result of carelessness/malpractice.

With regard to explosives initiation through electrical stimuli; transport environments tend to be characterised by stimuli which have energy levels below that necessary to cause initiation. Thus, initiation as a result of electrical energy is considered small.

Finally, it is concluded that at present explosives sensitivity cannot be quantified in exact units of measure. In fact collated data only provide a comparative means of assessing explosives sensitivity. More importantly, however, initiation of explosives is not so much dependent on the amount of energy delivered, but rather on its rate of delivery (i.e. energy density, expressed in w/kg). This latter point has been acknowledged and work begun to relate explosives sensitivity to energy density [30]. It is hoped that such an approach will provide an absolute measure of explosives sensitivity regardless of the way in which energy is delivered.

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