A COMPARISON OF THE EXPLOSION HAZARDS ASSOCIATED WITH THE TRANSPORT OF EXPLOSIVES AND INDUSTRIAL CHEMICALS WITH EXPLOSIVE PROPERTIES.

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In the United Kingdom, the transport of both explosives and highly energetic substances is controlled by legislation based on the United Nations Recommendations on the Transport of Dangerous Goods. Explosives and energetic substances which are not intended for explosive or pyrotechnic purposes are generally diluted or packaged such that they are not assigned to Class 1. Nevertheless, some of these substances present the danger of explosion in transport. This paper identifies some of the problems associated with the classification of energetic substances and considers the balance between the risk and hazard of explosion presented during transport.
Key words: transport, explosives, chemicals, energetic, risks, hazards.

INTRODUCTION

In the United Kingdom, the transport of packaged explosives and industrial chemicals is controlled via legislation based on the United Nations (UN) Recommendations on the Transport of Dangerous Goods (1). The UN Recommendations allow industrial chemicals which have some explosive properties and some explosives to be packaged or diluted in such a way that they are not assigned to Class 1. Although the UN Recommendations have no force of law, they form the basis for the international regulations concerning the carriage of dangerous goods. In a form modified for the particular mode of transport, they have been adopted into international agreements concerning transport by air, ICAO (2); sea, IMO (3); road, ADR(4); and rail, RID (5). Paragraph 4.1.6 of the UN Recommendations and UK regulations state that any substance having, or suspected of having explosive characteristics should first be considered for inclusion in Class 1 (explosives). The UK regulations which control the transport of explosives and dangerous substances are:

Explosives:

(i) The Classification and Labelling of Explosives Regulations 1983 (6).

(ii) The Road Traffic (Carriage of Explosives) Regulations 1989 (7).

Dangerous substances:

(iii) The Dangerous Substances (Conveyance by Road in Road Tankers and Tank Containers) Regulations 1981 (8).

The views expressed in this paper are the views of the authors and should not necessarily be taken to be those of the Health and Safety Executive.

(iv) The Road Traffic (Carriage of Dangerous Substances in Packages etc.) Regulations 1986 (9).

(v) The Classification, Packaging and Labelling of Dangerous Substances Regulations 1984 (10).

HAZARD AND RISK

The principle hazards from explosives and energetic substances with explosive properties are:-

- mass explosion and blast;
- projection of fragments and debris; and
- thermal radiation.

The risk of an event is a combination of the likelihood of the event taking place and the consequence of the event. The likelihood of an event occurring is related to the sensitivity of the substance to initiation and the frequency of exposure to initiation sources. The consequence of an event will depend on the amount of substance available, the packaging used and the mode of decomposition.

Explosion Hazards from Detonable Substances

Effect of detonation velocity. High explosives generally exhibit two distinct regimes (11) for detonation, i.e. high order and low order (see Figure 1). High order detonations usually proceed in the velocity range 4 to 9 km/s and low order detonations in the range 1.5 to 3 km/s. Most detonable energetic substances have detonation velocities in the lower range (see Table 1). Substances which detonate with a higher velocity have a higher shattering power and are thus more likely to form craters and to produce higher velocity fragments and debris, whereas energetic substances are more likely to form depressions. A crater is essentially a cavity which has been excavated by an explosion, but which will have been masked to some extent by fallback. A depression is also a cavity, but this time it has been formed by compaction, not excavation of the ground. The cavity produced from the 11 tonne stack of sodium chlorate in the B & R Hauliers explosion (12) was a depression, not a crater. No real crater was found in the 1988 ammonium perchlorate explosion (13).

TABLE 1. Detonation velocities

High explosive	Velocity (km/s)	Energetic substance	Velocity (km/s)
PETN	8.26	Nitromethane	6.29
Nitroglycerin	7.58	Dinitro benzenes/anilines	3.00
Picric acid	7.26	Ammonium nitrate	1-3.9
Lead styphnate	5.20	60% Methyl ethyl ketone peroxide	2.00
Mercury fulminate	5.40		
Lead azide	5.50		

Effect of blast waves. For high order detonations, the rate of energy release is extremely rapid. Lower order events, which are generally associated with energetic substances, release their energy over a longer, although still short, period of time. Despite differences in blast overpressure profiles from different types of explosions, it is usual to equate all of them to the waveform given by TNT and to express their ability to produce damage as a TNT equivalence (see Table 2). TNT equivalence can be estimated from results of tests of explosive power or by calculation from heats of formation or can be directly measured. Estimated values are frequently higher than measured values.

TABLE 2. TNT equivalences

High explosive	TNT Equivalence (%)	Energetic substance	TNT Equivalence (%)
PETN	128	Nitromethane	134
Nitroglycerin	148	Dinitro benzenes/anilines	80
Picric acid	93	Ammonium nitrate	56
Lead styphnate	42	60% Methyl ethyl ketone peroxide	19
Mercury fulminate	40	Sodium chlorate	15
Lead azide	34		

TABLE 3. Effect of explosives quantity on failure criteria

Structural Element	Failure mode	Approximate Peak Side-on Overpressure (kPa) at which failure occurs		
		1 tonne	10 tonne	100 tonne
Window pane	5% broken	1.0	0.7	0.7
	50% broken	2.5	1.7	1.5
	90% broken	6.2	4.1	3.7
House	Tiles displaced	4.4	2.9	2.6
	Doors and window frames broken in	9.0	5.9	5.3
	Minor structural damage	6.2	4.1	3.7
	Partial or total collapse of roof	27.6	16.5	15.9
	50-70% external brickwork destroyed or rendered unsafe	79.3	35.9	34.5
	Almost complete demolition	183	79.3	75.8
Telegraph poles	Snapped	358	179	165
Large trees	Destroyed	393	179	165

Predictions of damage at distance, using either peak overpressure or positive impulse criterion, are possible using the Hopkinson scaling rule (14):

$$\text{Scaled parameter} = [\text{parameter}] / [\text{TNT equivalent mass (kg)}]^{1/3} \quad (1)$$

where the parameter may be distance, impulse, arrival time or pulse duration.

An illustration of explosion damage versus overpressure (15) and charge size is given in Table 3. For low order explosive events where the rate of rise of pressure is slow and the duration of the explosion is relatively long, the TNT model grossly overestimates the close-in effects and underestimates the far-field effects. In the Henderson ammonium perchlorate explosion (see reference 13), the TNT equivalence was estimated to be approximately 33% close-in, and a half of this in the far field. Little information is available on blast effects from exploding energetic substances.

Effect of yield. The yield of an explosive event is governed both by the explosive power of the substance (c.f. TNT equivalence) and the efficiency of the process:

$$\text{Yield} = \text{Quantity} * \text{TNT equivalence} * \text{efficiency} \quad (2)$$

The efficiency is dependent upon factors including the quantity of material and amount of confinement, the type of substance and the mode of initiation. During transport of high explosives, probably the most likely cause of accidental initiation of the cargo is fire. In a fire, there could be some depletion of the substance before it burns to detonation and there may be some degradation of the packaging reducing the level of confinement. This reduction in explosion efficiency has a more pronounced effect with energetic substances. In general, for accidents involving substances such as ammonium nitrate, sodium chlorate and organic peroxides, about 10-15% of the available energy is released in the form of a blast wave with yields as high as 25% being occasionally achieved (16).

Explosion hazards from non-detonable substances

Effect of heating under confinement. Energetic substances decompose exothermically with the evolution of gas. If gas is generated faster than can be vented through the lid etc then the eventual failure of the packaging could be accompanied by an explosive event. Thermally stable energetic substances will only undergo a runaway reaction if involved in a fire. In soft packaging, such as fibreboard drums or plastics jerricans, it might be expected that the packaging would be degraded before significant quantities of substance reacted so that there would be little effective confinement. However, in steel drums, this may not be the case unless the lids are designed to relieve at low pressures. For thermally unstable substances, it is possible for them to self-heat under conditions where even soft packaging is not degraded and an explosive event can still occur. This is formally recognised in the UN organic peroxide scheme (reference(1), chapter 11) where a thermal explosion in the package test is performed rather than the fire engulfment test used for explosives to assess the effects of heating under confinement.

Effect of ignition under confinement. Substances which can deflagrate represent a particular problem if initiated when confined. The rate of deflagration normally increases with increasing pressure and hence, if the confinement is too great, can accelerate to explosive effect. Energetic substances such as industrial cellulose nitrate have to be transported in drums designed to relieve at a specific pressure to avoid violent acceleration of the reaction.

Explosion risks

Historically the importance of sensitivity, and therefore the likelihood of accidental initiation, has been recognised in the explosives industry where, at the simplest level, explosives have been subdivided into three types:

PRIMARY • explosives which are very sensitive to heat, impact or friction and which , even in very small quantities , either detonate or burn very rapidly. They are able to transmit detonation (in the case of initiating explosive) or deflagration to adjacent secondary explosives.

SECONDARY • conventional high explosives which are relatively insensitive (compared to primary explosives) and are initiated by primary explosives with or without the aid of boosters or supplementary charges.

TERTIARY • very insensitive explosives requiring initiation by booster charges.

Sensitivity to impact and friction. Nearly all primary explosives, but relatively few energetic substances, are sensitive to impact or friction. Some of the thermally unstable energetic substances e.g. certain organic peroxides and diazonium salts appear sensitive through heating effects between striking surfaces.

Sensitivity to heat. All primary explosives are very sensitive to initiation by localised heating but must be thermally stable at 75°C to be allowed for transport. However most secondary and tertiary explosives are thermally stable at temperatures up to 150°C. Many organic energetic substances such as organic peroxides and self-reactive substances are usually unstable at 150°C and some are unstable at ambient temperatures and require refrigeration during transport. However aromatic nitro compounds, e.g. musk xylene (UN no. 2956), have similar structures and stabilities to the related compounds used as explosives.

Sensitivity to shock. A few energetic substances may be initiated by a detonator (containing a primary explosive) alone but most require initiation with the aid of a booster charge (containing a secondary explosive). Propagation of detonation is effectively through hot spot generation by adiabatic compression of occluded air. The sensitivity to shock (ease of initiation by explosives) is dependent on:

Bulk density: as the bulk density of a powder increases, whilst the overall void space decreases, the number of discrete air spaces increases until a limiting value is reached. Further increases in bulk density achieved by pressing decreases the number of available initiation sites until there are an insufficient number for propagation i.e. the charge is non-detonable (known as "dead pressing"). Dinitrobenzene may be initiated by a detonator alone in fine crystalline form but in the very large crystalline/cast form normally transported, it cannot.

Charge diameter: the smaller the charge diameter the greater are the energy losses due to an increased surface area to mass ratio. There is a critical charge diameter below which detonation will not propagate. For energetic substances the critical diameters are normally much larger than those for explosives. Ammonium nitrate prills for example, at a density of 900 kg/m^3 or greater, are fairly insensitive to initiation and require a large charge diameter (1 metre) and large initiating

charges to achieve detonation (see Figure 2). This means that the standard detonation-tube-testing of these substances, will mainly be at diameters at which they cannot detonate unless the degree of confinement is effective in reducing energy losses.

Charge length: to attain stable detonation, charge lengths of 3 to 4 charge diameters are usually necessary.

These factors give rise to problems in assessing the sensitivity to shock (detonability) of energetic substances since the test sample has to be quite large or be heavily confined. Results from small scale detonability tests on energetic substances could indicate non-detonability when this is not the case.

CURRENT REQUIREMENTS FOR ENERGETIC SUBSTANCES

Currently UN listed energetic substances which are not transported under the provisions of Class 1 but which have shown either explosive behaviour in incidents or in laboratory testing are given in the Appendix. The UN classification schemes relating to energetic substances are discussed by Roberts and Royle (17). Specific examples of currently classified substances are discussed below.

CLASS 3 - Flammable liquids

Nitromethane, n-propyl and isopropyl nitrate all have explosive properties and are transported as flammable liquids. Only nitromethane is identified as having some explosive properties but all three are detonable. In the past there have been two rail tank car detonations with nitromethane (18). The first of these occurred in 1958 in a rail marshalling yard on the outskirts of New York. A rail tank car (35 tonne) of nitromethane detonated, forming a crater 50 by 85 feet and 16 feet deep. Damage extended out to 3 miles from the explosion centre. Later that year, an almost identical nitromethane detonation occurred at Mount Pulaski, Illinois, resulting in the death of two railmen and the critical injury of a third. Approximately 40 residents of the city some three quarters of a mile away were injured. The crater, from 43 tonne of nitromethane, was approximately100 feet diameter and 36 feet deep. Minutes before the detonation the tankcar had been involved in a shunting operation. Some decomposition of nitromethane, seen as white vapour, preceded the detonation. The cause of the tank car detonations has been attributed to cavitation and adiabatic compression effects, resulting in a localised decomposition which accelerated to detonation. Bulk rail and road transport of commercially pure nitromethane was banned in 1958 in the USA and is not recommended in the UN Recommendations. Tests show that commercially pure nitromethane is difficult to detonate. Certain contaminants however render the substance as shock sensitive as many liquid explosives. High velocity bullet impact tests on many 55 gallon drums of nitromethane resulted in two detonations.

DIVISION 4.1 - Flammable solids

Wetted Explosives. Wetted explosives of Division 4.1 (flammable solids) are substances of Class 1 (explosives) which are required to be wetted with sufficient water or alcohol, or plasticised, to suppress explosive properties. They are exempted from Class 1 on the basis of not being capable *of initiation by a detonator or capable of mass detonation through the action of a powerful* booster. There is no requirement that packages containing wetted explosives of Division 4.1 should be capable of withstanding fire engulfment. Currently this type of Division 4.1 substance

is assigned packing group I requiring the strongest packagings. It is recognised that increased confinement enhances the violence of any explosive event but, whilst volatile diluents are allowed to be used, strong packagings are required to prevent loss of diluent and subsequent increased sensitivity. Self-reactive substances and organic peroxides are all assigned to packing group II so that the confinement is kept to the minimum necessary to provide safe transport and only non-volatile diluents are allowed in most cases.

Self-reactive substances. Self-reactive substances are under active consideration by the UN Committee of Experts on the Transport of Dangerous Goods. Self-reactive substances have been provisionally defined as substances with an exothermic decomposition energy > 300 J/g and a *self-accelerating decomposition temperature* ≤ 75°C. *It is proposed that the principles for* classification of new self-reactive substances be based on those for organic peroxides (see reference (1), chapter 11). If accepted by the UN, self-reactive substances will be ranked according to their degree of hazard with the most hazardous being restricted to the smaller package sizes and to soft packaging.

Cellulose nitrate. At present industrial cellulose nitrate may be carried under the provisions of Division 4.1 if the packaging is such that explosion is not possible by reason of increased internal pressure. No tests are specified as a basis for giving approvals. No restriction is placed on the nitrogen content (degree of nitration) of the water-wetted material (UN no. 2555). Plasticised cellulose nitrate presents a higher thermal radiation hazard than solvent damp cellulose nitrate and, depending on the packaging, as great if not greater hazard than some Division 1.3 propellants. At present this is not recognised in package size and type restrictions.

Other energetic substances. There are other substances in Division 4.1 e.g. musk xylene, 40% isosorbide dinitrate and azodicarbonamide which have some explosive properties. It has recently been agreed by the UN Committee of Experts (December 1990 meeting), that musk xylene and azodicarbonamide should be regarded as substances "related" to self-reactive substances and 40% isosorbide dinitrate as a desensitised explosive. There are no principles for classification for either of these types of substance.

CLASS 5 - Oxidizing substances; organic peroxides

Oxidizing agents. Substances such as ammonium nitrate and ammonium perchlorate are detonable or can deflagrate to explosive effect but are carried under the provisions of Division 5.1. Explosive grade ammonium nitrate prills are far more sensitive to shock than fertiliser grade material but this is not formally recognised.

There have been numerous accidental explosions involving ammonium nitrate (19, 20). In the solid state and at ambient temperature, ammonium nitrate is fairly insensitive, requiring a strong shock and strong confinement to produce detonation. In the presence of more than 0.2% of carbonaceous substance, both sensitiveness and explosibility of ammonium nitrate increases dramatically which is reflected in the assignment of such formulations to Class 1. In a prolonged fire hot molten and decomposing ammonium nitrate could be formed which would be sensitive to impact, friction and shock. If contaminated or mixed with organic substances, the mixture will be very sensitive. Despite the serious hazard posed by ammonium nitrate in a fire, there is no recorded instance of fire induced explosion for pure ammonium nitrate. Large fire trials on multi-tonne quantities have produced the same result. During transport, it is likely that some if not all of

the forms of ammonium nitrate will be in a stowage arrangement of dimensions greater than the critical diameter, i.e. detonable. However, ammonium nitrate fertilisers (not necessarily explosive grade prills) will be very insensitive requiring a strong source of initiation (e.g. an adjacent condensed phase detonation) to pose a detonation threat.

Ammonium perchlorate is assigned either to Class 1 or to Division 5.1 depending on the particle size and packaging. On 4th May 1988 several hours of fire and numerous explosions destroyed the Pacific Engineering Company ammonium perchlorate manufacturing plant in Henderson, Nevada USA(13). The final and largest explosion is thought to have involved 1500 tonnes of coarse (nominal 200 micron) material. Up to this time, the coarse material has been classified by the UN as a Division 5.1 substance.

Over the years there have been many explosions involving sodium chlorate, the most recent significant one in this country being B & R Hauliers at Salford (12). In nearly all of these incidents, there was an intense fire just before the explosion(s). Mixtures of chlorates with organic material shave long been known to be sensitive and explosive. For a long time the predominant cause of chlorate explosions has been attributed to some possible admixture of chlorate and organic substance just prior to the event. In the B & R Hauliers explosion, an 11 tonne palletised stack of sodium chlorate (steel drums) exploded en masse. There was no evidence that the lids had been removed prior to the explosion and, say, an organic liquid poured in. In a more recent incident in Hamburg Harbour (21), two explosions occurred and involved potassium chlorate (16.2 tonne in 50 kg metal drums). Again the chemicals were involved in an intense fire (involving other flammable substances in the warehouse) prior to the explosions. Despite this very strong evidence that intense fire exposure of technically pure chlorates alone (in metal drums) can result in explosion, fire trials have failed to reproduce this effect. In the light of the experience with these materials the HSE has produced guidance (22) which essentially requires, amongst other things, that these substances be stored well away from combustibles.

Organic peroxides. Organic peroxides are considered to have a primary hazard because of their thermal instability. Some are detonable (23). A completely new system of classification has been introduced for organic peroxides in revision 6 of the UN Recommendations (1). This system is based on assigning all organic peroxides to one of twenty generic entries which indicate:

- the type (ranked according to hazard on the basis of test results);
- the physical state (solid/liquid); and
- temperature control (when required).

In the organic peroxide scheme, the ability to propagate detonation or deflagration and the effects of heating under confinement are specifically determined. Peroxides which are detonable are packaged in sufficiently small packages to be below the critical diameter for detonation. Those which can deflagrate violently or can give a violent effect on heating are normally restricted to less strong packagings which rupture before a violent reaction can occur.

Division 6.1 - Toxic substances

Dinitro compounds such as dinitrobenzenes and dinitroanilines are transported under the provisions of Division 6.1 (toxic). Many of these have explosive properties. For example, sodium dinitro-o-cresolate is carried under the provisions of Class 1 but the ammonium salt (UN no. 1843) is not recognised as having any explosive properties. m-Dinitrobenzene in fine crystalline form can be detonated by a detonator alone yet it is not identified as having explosive properties.

The Class 1 classification procedure may not have been applied to all of these substances. There appears little to distinguish these types of substance from wetted explosives in Division 4.1 with a "TOXIC" subsidiary risk but such substances in Division 6.1 are not required to be kept away from heat and sources of ignition.

MITIGATION OF RISKS

The fundamental requirement of any classification system, in terms of explosive properties, is to provide a means of delineating between explosive, energetic and other substances so that the necessary levels of control can be placed upon the transport and handling of the substances and the likelihood of explosion is minimised.

In practice, the main means of reducing sensitivity are:

- alteration of the physical form e.g. casting, pressing, particle size;
- phlegmatisation e.g. wetting, dilution;
- encapsulation e.g. detonators; and
- packaging e.g. cushioning material.

These methods are used to allow very sensitive explosives to be transported in Class 1 (i.e. so that they are not too dangerous for transport) or to allow explosives and energetic substances to be exempted from Class 1.

The hazard can be minimised by:

- reducing the package size to below the critical diameter;
- dilution to reduce the available energy to below that necessary to support detonation;
- reducing the level of confinement by selection of appropriate packaging; and
- separating packages so that if one package is initiated it cannot propagate throughout the load.

These methods allow energetic substances to be exempted from Class 1 and, in some cases, be considered non-dangerous.

In addition to reducing sensitivity and hazard, it is possible to reduce the overall risk by segregation. This is most important in regard to separating oxidizing substances from fuels. Fuel-oxidant mixtures are often very easily initiated and are very energetic. Segregation is usually performed on the basis of the class/division label. Other mitigatory measures for explosives are possible depending on the mode of transport. These measures include: fire protection, fuel cut off devices, specialised electrics, attended vehicles etc.

DISCUSSION

At present, there are well-defined UN classification schemes, with test methods and criteria, for explosives of Class 1 and organic peroxides of Division 5.2. These control both the quantity within a package and the type and strength of packaging. A scheme for self-reactive substances has recently been agreed by the UN. There is no scheme for flammable liquids of Class 3, wetted

explosives and other energetic substances of Division 4.1, oxidizing agents of Division 5.1 and toxic substances of Division 6.1 which have explosive properties.

The organic peroxide (and self-reactive) scheme bans detonable substances from transport unless it is shown that they cannot detonate as packaged for transport. However, other types of energetic substance may be detonable when packaged as for transport yet there are no similar requirements to reduce the risk. In view of this, the borderline between Class 1 and energetic substances in other classes/divisions seems to merit further examination. In practice, the level of control applied depends upon the classification. Within each class there is a ranking of degree of hazard and labelling requirements. Although the quantity in the package and the type of packaging has an important influence on explosive properties, only explosives of Class 1, self-reactive substances of Division 4.1 and organic peroxides of Division 5.2 have specific packaging requirements linked to the degree of explosion hazard. In cases where the packaging influences the degree of explosion hazard, there should be specific packaging requirements, both in size and type, irrespective of class/division. In addition, substances with some explosive properties, which have not been accepted into Class 1, are regarded by some as completely non-dangerous if they have no properties of any other class and have no restrictions at all placed upon them.

The main aims of the UN system of labelling are to indicate the nature of the risk by the symbol on the label (e.g. Bomb (explosion), Flame (fire)) and to give a first guide to handling and stowing by means of the colours on the labels. In the case of wetted explosives, most are not flammable yet are labelled as a flammable solid. No indication is given of explosive properties, although in some cases it has not been demonstrated that the packaged wetted explosive would not explode in a fire. Some packages containing organic peroxides and self-reactive substances with explosive properties are required to bear an "EXPLOSIVE" subsidiary risk label whereas packages containing other substances, which give the same violent effects in tests to assess the effects of heating under confinement, may not. Packages containing toxic energetic substances bear the "TOXIC" label which gives no warning against explosive properties.

In general the most effective way of suppressing explosive properties is dilution. Organic peroxides (and self-reactive substances) are ranked according to degree of explosion hazard with, in effect, those with the greatest dilution being transported with the largest packagings up to and including tanks. If such an approach was applied to other energetic substances manufacturers would be encouraged to transport safer formulations. As wetted explosives are normally desensitised with volatile diluents, they are required to be packaged in strong packagings to reduce the risk of loss of diluent. However, stronger packagings increases the violence of any event. In principle, a better approach would be to use less volatile diluents and less strong packagings.

For products which have been transported for some time there may be a history of non-explosive incidents which indicate that a substance does not explode under fairly severe conditions. In such cases, UN classifications take this into account. However, the fact that a substance has been transported for a long time with no incident does not mean that it is safe if during that time it has not been subjected to, for example, fire exposure. Many of the energetic substances currently listed in the UN Recommendations were classified before the current principles for classification were adopted. Whilst in general it will probably not be necessary to reclassify existing entries, there may be a need to reconsider some products.

CONCLUSIONS

In conclusion, the authors consider that:

(a) the interface between Class 1 and other classes/divisions containing energetic substances requires further development;

(b) it may be necessary to reclassify some energetic substances into Class 1 or to introduce additional requirements;

(c) the effect of fire engulfment on energetic substances, in particular some wetted explosives, requires further investigation; and

(d) the use of volatile diluents should be reviewed.

REFERENCES

1) United Nations, 1989, "Recommendations on The Transport of Dangerous Substances", Sixth revised edition, ISBN 92-1-139027-3.

2) International Civil Aviation Organisation, "Technical instructions for the safe transport of dangerous goods by air", 1989-90 edition.

3) International Maritime Organisation,1990,"International Maritime Dangerous Goods Code".

4) Department of Transport, 1990, "European Agreement concerning the International Carriage of Dangerous Goods by Road (ADR)", HMSO.

5) Department of Transport, 1990, "Regulations concerning the International Carriage of dangerous Goods by Rail (RID)", HMSO.

6) "The Classification and Labelling of Explosives Regulations 1983", SI 1983 No. 1140.

7) "The Road Traffic (Carriage of Explosives) Regulations 1989", SI 1989 No. 615.

8) "The Dangerous Substances (Conveyance by Road in Road Tankers and Tank Containers) Regulations 1981", SI 1981 No. 1059.

9) "The Road Traffic (Carriage of Dangerous Substances in Packages etc.) Regulations 1986", SI 1986 No. 1951.

10) "The Classification, Packaging and Labelling of Dangerous Substances Regulations 1984", SI 1984 No. 1244.

11) Stull, 1977, "Fundamentals of Fire and Explosion", AIChE Monograph Series No. 10, vol 73, 1977.

12) HSE, 1983, "The Fire and Explosions at B and R Hauliers, Salford, 25 September 1982", HMSO,ISBN 0 11 883702 8.

13) Seltzer, 1988, C and EN, 8, pp 7-15.

14) Hopkinson, 1915, British Ordnance Board Minutes 13565.

15) Scilly and High,1986, 5th Int. Symp. Loss Prev. Proc. Ind., 1, paper 39.

16) Overpressure Working Party,1989, "The Effects of Explosions in the Process Industries", I.Chem.E.

17) Roberts and Royle, 1991, I. Chem. E. Symposium Series No. 124

18) Lewis, 1983, Hazardous Cargo Bulletin, v, 36-38.

19) "The Explosion of the Nitrate Plant at Oppau", 1921, Chemical and Metallurgical Engineering, 25, No. 18, pp 818-822.

20) Bauer and King,1977, "A Review of Accidents With Ammonium Nitrate", Dept. Mining Eng., Queen's University, Kingston, Ontario, Canada.

21) Meyer, 1985, Gefahrliche Ladung., 30, No. 7, pp 301-303.

22) HSE, 1985, "Storage and use of sodium chlorate and other similar strong oxidants", HSE Guidance Note CS3; Chemical Safety ISBN 0 11 883523 8.

23) Fukyama, 1990, Safety Engineering (Japan), 17, pp. 17. (HSE translation no. 13926A)

APPENDIX. EXAMPLES OF CURRENTLY LISTED ENERGETIC SUBSTANCES

UN NO.	***EXPLOSIVE SUBSTANCES OF CLASS 1 WITH PROPERTIES SIMILAR TO THOSE OF NON-CLASS 1 ENERGETIC SUBSTANCES***
0407	TETRAZOL-1-ACETIC ACID
0448	5-MERCAPTOTETRAZOL-1-ACETIC ACID

UN NO.	***WETTED EXPLOSIVES OF CLASS 1 EXEMPTED BY SPECIAL PROVISION***
0401	DIPICRYL SULPHIDE
0234	SODIUM DINITRO-o-CRESOLATE
0214	TRINITROBENZENE
0215	TRINITROBENZOIC ACID
0155	TRINITROCHLOROBENZENE
0154	TRINITROPHENOL
0209	TRINITROTOLUENE
0220	UREA NITRATE

UN NO.	***ENERGETIC LIQUIDS OF CLASS 3***
2345	3-BROMOPROPYNE
2351	BUTYL NITRITES
1194	ETHYL NITRITE, SOLUTIONS
1222	ISOPROPYL NITRATE
2059	NITROCELLULOSE SOLUTION, FLAMMABLE
2060	NITROCELLULOSE SOLUTION, FLAMMABLE
2842	NITROETHANE
3064	NITROGLYCERIN, SOLUTION IN ALCOHOL
1261	NITROMETHANE
2608	NITROPROPANES
1865	n-PROPYL NITRATE

UN NO.	***WETTED EXPLOSIVES OF DIVISION 4.1***
1310	AMMONIUM PICRATE, WETTED
1571	BARIUM AZIDE, WETTED
1320	DINITROPHENOL, WETTED
1321	DINITROPHENOLATES, WETTED
1322	DINITRORESORCINOL, WETTED
2852	DIPICRYL SULPHIDE, WETTED
2555	NITROCELLULOSE WITH WATER
1336	NITROGUANIDINE, WETTED
1337	NITROSTARCH, WETTED
1347	SILVER PICRATE, WETTED
1348	SODIUM DINITRO-o-CRESOLATE, WETTED
1349	SODIUM PICRAMATE, WETTED
1354	TRINITROBENZENE, WETTED

1355	TRINITROBENZOIC ACID, WETTED
1344	TRINITROPHENOL, WETTED
1356	TRINITROTOLUENE, WETTED
1357	UREA NITRATE, WETTED
1517	ZIRCONIUM PICRAMATE, WETTED

UN NO.	***ENERGETIC ORGANIC NITRO AND NITRATE COMPOUNDS OF DIVISION 4.1***
2956	5-tert-BUTYL-2, 4, 6-TRINITRO-m-XYLENE
2907	ISOSORBIDE DINITRATE MIXTURE
2556	NITROCELLULOSE WITH ALCOHOL
2557	NITROCELLULOSE WITH PLASTICIZING SUBSTANCE
2555	NITROCELLULOSE WITH WATER

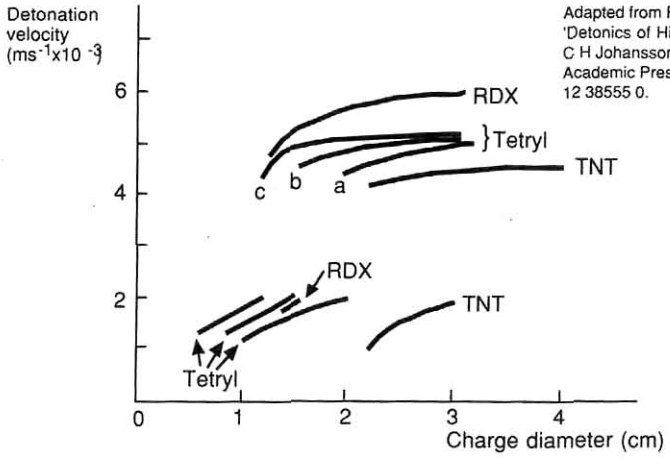
UN NO.	***SELF-REACTIVE SUBSTANCES OF DIVISION 4.1***
2952	AZODIISOBUTYRONITRILE
2955	2, 2'-AZODI-(2, 4-DIMETHYL-4-METHOXYVALERONITRILE)
2953	2, 2'-AZODI-(2, 4-DIMETHYLVALERONITRILE)
2954	1, 1'-AZODI-(HEXAHYDROBENZONITRILE)
3030	2, 2'-AZODI-(2-METHYLBUTYRONITRILE)
2971	BENZENE-1, 3-DISULPHOHYDRAZIDE
2970	BENZENE SULPHOHYDRAZIDE
3037	4-[BENZYL(ETHYL)AMINO]-3-ETHOXYBENZENEDIAZONIUM ZINC CHLORIDE
3038	4-[BENZYL(METHYL)AMINO]-3-ETHOXYBENZENEDIAZONIUM ZINC CHLORIDE
3033	3-CHLORO-4-DIETHYLAMINO-BENZENEDIAZONIUM ZINC CHLORIDE
3042	2-DIAZO-1-NAPHTHOL-4-SULPHO-CHLORIDE
3043	2-DIAZO-1-NAPHTHOL-5-SULPHO-CHLORIDE
3036	2, 5-DIETHOXY-4-MORPHOLINOBENZENEDIAZONIUM ZINC CHLORIDE
3039	4-DIMETHYLAMINO-6-(2-DIMETHYLAMINOETHOXY)TOLUENE-2-DIAZONIUM ZINC CHLORIDE
2973	N, N'-DINITROSO-N N'-DIMETHYL TEREPHTHALAMIDE
2972	N, N'-DINITROSOPENTAMETHYLENE TETRAMINE
2951	DIPHENYLOXIDE-4, 4'-DI-SULPHOHYDRAZIDE
3034	4-DIPROPYLAMINOBENZENEDIAZONIUM ZINC CHLORIDE
3035	3-(2-HYDROXYTHOXY)-4-PYRROLIDIN-1-YL BENZENEDIAZONIUM ZINC CHLORIDE
3040	SODIUM 2-DIAZO-1-NAPHTHOL-4-SULPHONATE
3041	SODIUM 2-DIAZO-1-NAPHTHOL-5-SULPHONATE

UN NO.	***ENERGETIC OXIDIZING AGENTS OF DIVISION 5.1***
1942	AMMONIUM NITRATE
2426	AMMONIUM NITRATE, LIQUID
1442	AMMONIUM PERCHLORATE
1467	GUANIDINE NITRATE
1510	TETRANITROMETHANE
1511	UREA HYDROGEN PEROXIDE

UN NO.	*TYPES B AND C ORGANIC PEROXIDES OF DIVISION 5.2**
3101	ORGANIC PEROXIDE TYPE B, LIQUID
3102	ORGANIC PEROXIDE TYPE B, SOLID
3103	ORGANIC PEROXIDE TYPE C, LIQUID
3104	ORGANIC PEROXIDE TYPE C, SOLID
3111	ORGANIC PEROXIDE TYPE B, LIQUID, TEMPERATURE CONTROLLED
3112	ORGANIC PEROXIDE TYPE B, SOLID, TEMPERATURE CONTROLLED
3113	ORGANIC PEROXIDE TYPE C, LIQUID, TEMPERATURE CONTROLLED
3114	ORGANIC PEROXIDE TYPE C, SOLID, TEMPERATURE CONTROLLED

* see reference (1), table 11.3, pp. 238 - 243.

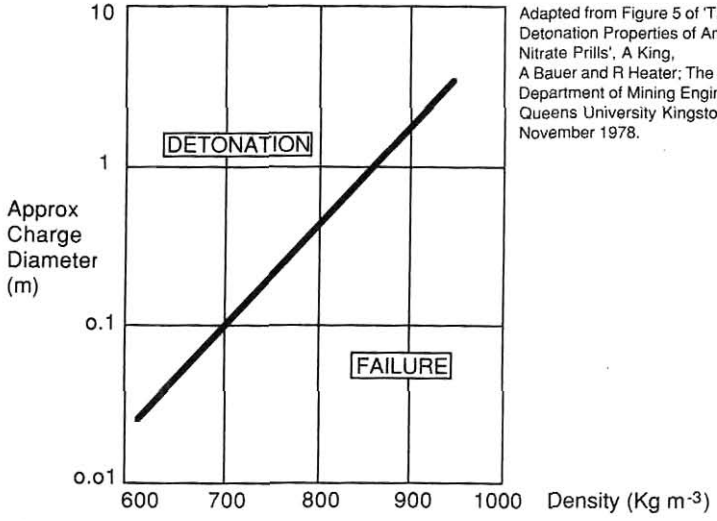
UN NO.	*ENERGETIC ORGANIC DINITRO COMPOUNDS OF DIVISION 6.1*
1843	AMMONIUM DINITRO-o-CRESOLATE
1577	CHLORODINITROBENZENE
1596	DINITROANILINES
1597	DINITROBENZENES
1598	DINITRO-o-CRESOL
1599	DINITROPHENOL SOLUTIONS
1600	DINITROTOLUENES, MOLTEN
2038	DINITROTOLUENES



Adapted from Figure 1.6 8 of 'Detonics of High Explosives', C H Johansson and P A Persson, Academic Press 1970, SBN No 12 38555 0.

Fig 1 High and Low Detonation Velocity in Powder Explosives.

Tetryl, 900 Kg m^{-3}, particle size in mm: a/1.0 - 1.6; b/0.63 - 1.0; c/0.4 - 0.63; RDX, 1000 Kg m^{-3} 1.0 - 1.6 mm; TNT 950 Kg m^{-3}, 1.0 - 1.6 mm.



Adapted from Figure 5 of 'The Detonation Properties of Ammonium Nitrate Prills', A King, A Bauer and R Heater; The Department of Mining Engineering, Queens University Kingston, Ontario, November 1978.

Fig 2 Critical Charge Diameter as a Function of Density for various Ammonium Nitrate Prills.