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EXPLOSIVES

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EXPLOSIVES

INTRODUCTION

An attempt has been made here to summarize some of the information on the properties and behavior of explosives as it is available from the open pre-war literature, Ordnance reports, reports from NDRC and British reports (AC Series).

To expedite the writing, the author has omitted references in all those instances where he believes that he remembers the contents of a report or an article but cannot remember what report it is. Thus, to some extent, the following pages are only "one man's opinion" and the readers are invited, if they distrust the author's memory or his interpretation, to look through the Library and the files to find the references in question. A particularly rich source of information and literature references is a compilation by Blatt, report No. OSRD 2014.

While the following pages contain comments on the hazards involved in the handling of explosives and describe those properties of explosives which cause the hazards, the reader must not expect to find detailed instructions for procedure in each individual operation. Writing such instructions would be a difficult task and the readers are urged instead to consult with those who have had longer experience in handling explosives before embarking on a new operation.

It should be emphasized that the materials with which this compilation deals, with the exception of primary explosives, are relatively safe military explosives, manufactured by the hundreds of tons and subjected to routine handling by rather unskilled labor in loading plants. Thus the maintenance of elementary precautions in the handling of these materials reduces the chances of an accident to a nominal value, not greater than those involved in handling other inflammable or toxic chemicals. In distinction to the other chemicals, however, one is not likely to commit more than one bad error in handling high explosives and therefore a careful consideration of the safety of a novel operation is strongly urged on all, before the operation is actually undertaken.

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BURNING

With very few exceptions (azides, acetylene) explosives contain loosely bound oxygen as well as elements which can form strong bonds with it; the chemical reaction which is responsible for their explosive properties is the transfer of oxygen atoms to the new partners, accompanied by a general rupture and rearrangement of molecules and a considerable heat evolution, which ranges from some 800 (TNT) to 1500 (PETN) cal/gr. The end products are mainly H_2O, CO, CO_2, N_2, H_2 and solids like C, Al_2O_3, BaO, etc.

One can visualize the over-all reaction as a sequence of two consecutive steps, the first being the decomposition of the original molecules into elements (i. e. C, H_2, O_2, N_2, etc.) and the second being the reaction of these elements with oxygen to form the end products. It is found that in most instances (exception being RDX) heat is absorbed in the first hypothetical step and is evolved in the second. Because of the preeminent role of oxygen in explosive reactions one commonly speaks of the burning or deflagration of explosives, even though the process is somewhat different from that of the burning of fuels.

In surveying the properties of explosives one notes readily a rather sharp difference between those materials which contain oxygen and its acceptors in the same molecule (e.g. organic nitrated materials) and those in which oxygen donor and oxygen acceptor are present as separate molecules aggregated into discrete (crystalline)particles (e.g. black powder). In gases and true solutions this distinction naturally is not observed, but in solid explosives one finds that even though materials containing oxygen and its acceptors in separate particles may be thermochemically much more "explosive", a high violence of explosions (so-called brizance) is obtained only when the contact of oxygen and its acceptors is much more intimate than can be realized in blended powders. Thus it has become an invariable

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rule to use those materials as "high explosives" which contain oxygen and acceptors in the same molecule; however, to improve the exothermicity of the overall reaction, one adds sometimes to the main explosive ingredient a separate oxygen acceptor (aluminum) and/or oxygen donor (inorganic nitrates or perchlorates). The result of this addition is usually a loss of local violence ("brizance") of action, due to the slower reaction, but a gain in long distance ("power") performance.

On raising sufficiently the temperature of every explosive (see below the section on thermal stability), the material begins to decompose violently or "burn" and the reaction, once started, continues spontanously even though the external source of heat and oxygen may be withdrawn. The process of burning can be made into a well controlled one by a suitable selection of the physical properties of the material and its environment. This has been made extensive use of in the so-called gun propellants. The modern propellants contain mainly the same materials which otherwise may act as high explosives, namely nitrocellulose and nitroglycerine. However, by the process of propellant manufacture the tendency to detonate is reduced and the stability of burning is enhanced. This is done by dissolving nitrocellulose (and nitroglycerine) and then eliminating the solvent 1) until the residue has become a hard horny non-porous gel possessing rather good mechanical properties (elasticity, non-brittleness, etc.). When converted into this state, the propellants are found to burn quite regularly from the surface inward, the reaction zone being limited to a very thin surface layer at any one instant.

If the coordinate normal to the surface of a propellant grain is denoted by L, then the law of burning can be quite accurately expressed by:

$$\frac{dL}{dt} = k\ p^n$$

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1) In the so-called dry-extrusion propellants nitroglycerine almost alone acts as the solvent of nitrocellulose, being present in such proportions that the resultant mass has the proper consistency.

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and hence the total rate of reaction is simply this expression times the total instantaneous surface area of all grains.

The constant k, for a given propellant, has been found to be a function of its initial temperature (rising with rising grain temperature). Also in general the "hotter" is the propellant (in the sense of evolving more heat in burning), the larger is the constant k. The exponent n has a value of about 0.8-0.9 for propellants made of nitrocellulose gel, without large amounts of oxygen donors present as discrete crystalline particles.

The mechanism responsible for this reaction law is now rather well understood 2). It consists in a partial decomposition of the solid constituents of the grain on the surface. This reaction is essentially endothermic but the escaping intermediate gaseous products undergo highly exothermic subsequent reactions in the gas phase, forming final products (H_2O, CO, CO_2, N_2, etc.). The "hot" molecules thus formed impinge on the relatively cool surface of the grain, transfer their energy to it and cause further endothermic decomposition; hence the dependence on the gas pressure surrounding the grain, since the higher the pressure the more molecules strike the grain surface. The dependance of the rate constant on the exothermicity of the reaction follows because the hotter the reacted gases the more heat is transferred to the grain surface. Dependance on the initial temperature of the propellant exists because the lower the temperature of the grains, the more heat energy must be supplied to them to heat them to the decomposition temperature.

It is very important to note that as the proportion of crystalline particles (each containing either oxygen donor or oxygen acceptor alone) in the propellant is increased, the law of burning changes. The exponent "n" starts to

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2) Most recent contributions have come from the Aberdeen Ballistic Research Laboratory in Ordnance Department reports.

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decrease, reaching values as low as 0.2 in materials of the type of black powder, while the constant "k" becomes less dependant on the initial temperature of the propellant 3) but still depends on the chemistry of it. The explanation has been advanced that basically the mechanism remains the same, but that now oxygen and its acceptor molecules are not molecularly mixed in the gas phase as they escape from the solid surfaces. Hence the diffusion in the gas phase of one to the other, to undergo the exothermic final reaction, becomes the rate determining process.

On application of heat, typical "non-colloided" high explosives in crystalline form, e.g. TNT, Tetryl, RDX, etc. are also found to ignite and burn non-explosively. Studies of the pressure dependance of the burning rate 4) have shown (up to 5,000 kg/cm^2) exactly the same behavior as that of nitrocellulose propellants. While it has not been possible to determine accurately the individual values of "k" and "n" for high explosives, qualitatively it has been found that the more sensitive (to initiation and mechanical impact) a material is, the higher is the constant "k".

Characteristically, the regular burning of these explosives in the closed vessel experiments does change occasionally and somewhat uncontrollably into a violent and almost instantaneous decomposition, usually harmful to the bomb. But this behavior is not altogether foreign to the gun propellants either. When the propellant has been made too brittle, or the temperature of the gun is very low (making the propellant brittle again), violent "detonations" in the gun have also been observed. It is thus reasonable to suppose that the cause is the same, namely that

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3) See for instance reports from Division 8 of NDRC in 1942-1944 on rocket propellants.

4) Division 8 NDRC reports from ERL, Bruceton, on H.E.

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rather rapid rise in pressure in the closed vessel or the gun brings the grains of the explosive into agitation. If it is violent enough, the grains break up, increasing the burning surface area. This increases the rate of pressure rise, brings with itself more breaking of the grains and soon the reaction is completely out of control.

However, with sufficiently finely divided (or larger but very fragile) grains, the burning may get out of control, even though the material is not confined, except by its own mass. This may occur even with such highly insensitive and slow burning materials as TNT. Piles of it in the open will burn quietly for many minutes but if the quantity is large enough (several tons), burning not only accelerates but ends in a violent explosion.

A very severe explosion destroyed a gun propellant plant in 1941 when a newly designed powder drier, containing much more material (about 10,000 lbs) than was common before, caught on fire and the plant personnel, accustomed to relatively harmless fires in such equipment, grabbed fire hoses and started to advance towards the building instead of running away. At this instant the burning changed to detonation and more than 100 persons were killed by the blast and fragments.

In a project of Division 8 of NDRC mixtures of inorganic nitrates had to be milled with ammonium picrate in edge-runner mills. Occasionally the mixture caught on fire. With about 50 lbs. in the mill the burning was quite gentle and no harm resulted to the equipment. When, however, larger mills were tried, containing about 400 lbs. of the same mixture, no fires but three very violent explosions occurred, each throwing the cast-iron runners weighing about a ton each high into the air, but fortunately, due to good barricade construction, not injuring anybody.

To understand these phenomena one may note that the burning advances quite

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rapidly along the surface of the grains or from one grain to the other (in a gun, for instance, a rather small black powder igniter sets fire to all grains in a small fraction of a millisecond). Given a sufficiently large quantity of the explosive material, a time comes when the burning reaches deep into the heap. Here the gases formed escape but slowly because of long and narrow channels between the particles surrounding them. Thus pressure rises above atmospheric, rate of burning goes up, hence gas is formed more rapidly, raising the pressure further and so, in a very short while, the reaction gets out of control.

With some exceptionally rapidly burning materials (i.e. probably materials having very large k's) it does not require a large quantity to change burning to detonation. Thus mercury fulminate will detonate very rapidly after ignition (i.e. in a millisecond or less) even when the quantity present is but a small fraction of a gram, unless it has been compressed so highly ("dead-pressed") that the flame cannot penetrate below the surface. Only in fairly high vacuum is it possible to decompose mercury fulminate fast but without violence.5) Lead azide, apparently, has an even higher burning rate constant, since it is virtually impossible to dead-press it and it does detonate on ignition even in high vacuum.

Quite generally, those materials which spontaneously change from burning to detonation at atmospheric pressure when present in small quantities are called PRIMARY (or initiating) EXPLOSIVES. Materials which do not do so unless present in very large quantities, and then only after long delays, are called HIGH EXPLOSIVES, while materials which are difficult or impossible to detonate even under confinement are called PROPELLANTS. To this latter class belong par excellence those materials

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5) Ignition and detonation of mercury fulminate and lead azide have been studied by Garner and co-workers and descri[redacted] in Proc. Roy. Soc.

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in which oxygen donors and oxygen acceptors are present as separate microscopic particles. In view of what has been said before on the dependance of their burning rate on pressure this is not difficult to understand.

SHOCKS AND DETONATION WAVES

On the basis of the preceding discussion it might seem that there is no natural limit to the rate of explosive reactions, but actually such a limit does exist. It is determined by the hydrodynamic laws of propagation of shock and detonation waves.

In order to understand what follows it is necessary to present here at least a highly simplified discussion of such waves. The literature on the subject is quite large and must be consulted for a more rigorous and detailed treatment.6)

Suppose we have a cylinder filled with a gas or liquid and behind it a piston. The piston is given a slight forward motion and then rapidly reversed and brough to its original position. The result is an acoustic wave, consisting of the compression and rarefaction zones, traveling through the medium with acoustic velocity. At the crest of the wave, due to compression, the medium is slightly warmer than originally, but it is cooled by the adiabatic expansion behind the crest and finally reaches the same state it originally possessed.

Now let the piston move always forward, being accelerated in small jerks. The first wave will not be followed by a rarefaction because the piston keeps pushing the medium, hence the second wave will travel in a somewhat hotter and denser medium and consequently, in all known substances, it will travel faster. The same is true

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6) A book, Flame and Explosions in Gases, by B. Lewis and G. von Elbe gives a fairly elementary but not always correct treatment. A somewhat more exact presentation will be found in NDRC report (Nos. OSRD 69, 70, 114) by Kistiakowsky and Wilson. There also will be found references to the earlier literature. A complete and original treatment of detonation waves is presented in Division 8 NDRC reports of J. von Neumann (Nos. OSRD 549, 1140), but is is hard going.

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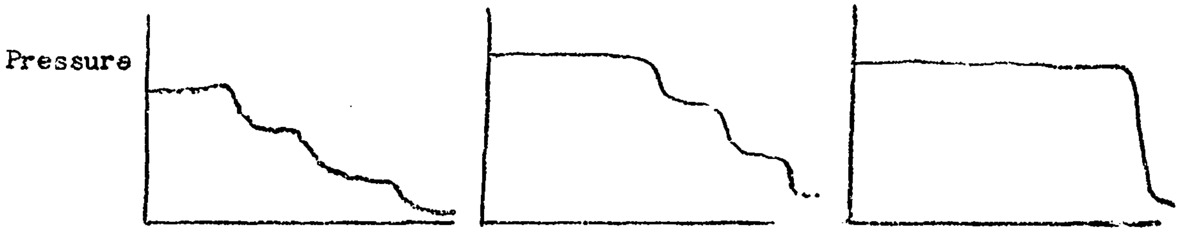
of the third wave relative to the second, etc. Thus the waves will tend to catch up with those in front, as is indicated on the schematic drawings below.



Early Position   Later   Still Later

The last phase shown here is that of a shock wave. Mathematical analysis shows that it will be formed even if the piston (or any other suitable source of pressure) is accelerated steadily rather than in jerks. If it were not for processes of heat conduction and molecular diffusion, the front of the shock wave would be infinitely steep; actually a finite slope does exist. The velocity of the shock wave is greater than that of acoustic waves; according to calculations of Hugoniot, it is only slightly less than the acoustic velocity in the medium raised to the temperature and pressure of the crest of the wave plus the velocity of the medium itself in the crest. The latter velocity is by no means negligible and in gases may account for much of the shock velocity. In condensed media, however, except with shocks of extraordinary strength, most of the shock velocity is due to acoustic velocity whereas the matter moves much slower. Because of the (theoretically) infinite rapidity of compression in the shock front, the heating of the medium is not carried out reversibly as in an acoustic wave; thus, even after the passage of the rarefaction wave and the return of the medium to its original pressure, it is found to be hotter than originally. This means, of course, that in a shock the mechanical energy of motion is being dissipated and converted into heat energy. Thus any shock, aside from the purely geometric weakening of spherical or cylindrical expanding waves, must gradually die out.

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The interpretation of detonations by Chapman and Juguet, put on a solid theoretical foundation by v. Neumann, regards them as shock waves, self supported by the energy released in the burning of the explosive. The establishment of detonations out of the burning process can be visualized qualitatively as follows. From a burning volume element in the mass of the explosive the reaction is spread by the effluent hot product gases. Behind the spreading reaction front the temperature and pressure of the gases are higher, hence conditions exist for the formation of a shock wave (see drawings above). As this developing shock passes around new grains of the material, they begin to decompose and react faster than the grains ignited earlier, because of higher pressure surrounding them. After a while the shock becomes so strong that it is not limited to a flow of gases around the grains, but involves compression and physical displacement of the grains themselves; thus a well defined shock front becomes established. Its velocity and the pressure in the crest would keep on rising indefinitely, were it not that energy is required to compress the material 7), but the energy available from the burning of the explosive is finite. Eventually a balance must be established between the energy released by the explosive and that used up in compressing the material to the conditions existing in the shock; then the shock becomes stabilized as a true detonation wave.

The theories referred to above show that the knowledge of the chemical composition of the reactants, together with that of their density, of the equations of state of the substances involved, and some other thermodynamic functions, is sufficient to predict all the hydrodynamic properties of ideal detonation waves.

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7) In strong shocks this energy is large and very much greater than in reversible compressions.

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The velocity of these waves is found to be equal to the acoustic velocity in the reacted medium at the pressure and temperature of the crest of the wave plus the material velocity of the medium in the crest. In solid organic nitrated explosives at the densities commonly used (0.7 to 1.7 g/cc) the density of the medium at the crest of the wave is some 30 to 50 percent higher than that of the unreacted material; the material moves with velocities of the order of 1,000 m/sec. and its temperature is perhaps 30 percent higher than would exist in products of controlled adiabatic burning while pressure reaches 200,000 kg/cm^2. Acoustic velocities in such media are of the order of several thousand m/sec.

According to v. Neumann the detonation wave consists of a thin mechanical shock wave followed by a chemical reaction zone of lower pressure; the energy released in the latter zone supports the shock in front and this, in turn, serves to start the chemical reaction (by a mechanism which will become clear later). The initial mechanical shock is supposed to acquire a definite profile (i.e., pressure-distance relation) which it retains regardless of the shape of the charge, etc. The same should be true of the reaction zone if this were infinitely thin. In any case, however, they are followed by a zone in which the phenomena are best described by saying that a rarefaction wave follows the detonation wave, a rarefaction due to the flow of gases from the crest of the wave into the space behind which was originally occupied by the charge, and further beyond. Thus the complete wave profile depends on the shape of the charge, on the confinement around it, on the distance the wave has travelled through the explosive and, finally, on whether the wave is a divergent, plane or a convergent one 8). In general one can say that the longer has the wave traveled through the explosive the thicker it becomes (i.e., the high

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8) This subject has been treated in British reports, mainly by Taylor, Penney, Jones.

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pressure lasts longer); due to this circumstance larger charges have greater destructive effect. Naturally, when the charge is in the form of a thin rod, sideways flow of gases controls the shape of the detonation wave and the latter acquires a constant shape regardless of the length of the charge.

The detailed mechanism and the rate of chemical processes occurring in the wave are of no importance for the propagation of a detonation wave through an infinite amount of explosive, hydrodynamic and thermodynamic laws controlling all the properties of the wave. However, as will be seen below, deviations from ideal behavior are frequently observed in charges of finite size. They consist in a slowing or a complete failure of detonation and can be traced to the finite rate of the chemical processes responsible for the detonation; thus the mechanism of these is of some interest.

Precise theory of these processes does not exist; however, the writer believes that in the detonation wave, as in controlled burning, individual particles of the explosive burn from the surface inward, the rate being probably controlled by the law given earlier.

This idea is reasonably consistent with the absolute rates of reaction observed in the detonation zones, which are of such magnitude that finely divided loose explosives complete the burning of 0.1 to 1 microsecond. On the other hand the burning rate of typical propellants and H.E. in closed vessels in such that decomposition progresses through the grains about 0.2 mm per millisecond at 1,000 kg/cm^2 pressure. Taking the 0.8 pressure exponent of the burning law, particle size of loose explosives as 0.1 mm and 150,000 kg/cm^2 pressure in the wave, one gets complete conversion in about 5 microseconds. The remaining discrepancy, if any, may be qualitatively accounted for by the crushing of particles in the shock and by the higher temperature of the product gases in the detonation wave as compared to their temperature in the adiabatic burning experiments.

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SENSITIVITY AND INITIATION

An explosion may be caused not only by heating but also by a mechanical blow on the explosive; in fact, even materials which are difficult to bring to detonation by heat, can be set off readily by a mechanical shock under proper conditions. This mechanical sensitivity has naturally received a great deal of attentio from many investigators, but its controlling factors are not fully understood. The following review is based mainly on recent data contained in Div. 8, NDRC reports from the Hercules Powder Co. and from ERL, Bruceton (Nos. OSRD: 803, 1288, 1706, 2014, 3149, 3185, 4099). The studies have been generally divided into those of sensitivity to friction, to mechanical impact, and to gun projectiles, although from a strictly scientific point of view such a division may not be justifiable.

The main fact emerging from these studies is that pressure *per se* does not cause explosions. Thus Bridgman (NDRC report No. OSRD 64) slowly applied pressures in excess of 50,000 kg/cm^2 to various explosives and then subjected the materials to shear without getting any explosions unless the rate of shear was *fast*. Other tests show that even fast application of pressure does not cause explosion without some shear of particles or without friction between particles. Thus lead azide was suspended in a liquid (under conditions readily giving explosions after a suitable impact) contained in a small cylinder with a piston. The liquid was compressed very suddenly by dropping a large weight on the piston, but no explosions resulted.

Frictional sensitivity has been studied by letting a "shoe" attached to the arm of a pendulum scrape along a surface (usually roughened) covered with the explosive. Studies at ERL have shown that even using shoes weighing several Kg and heights of drop up to a meter, no explosives less sensitive than RDX could be made to explode consistently. Various materials have been used in these tests for the shoe and the anvil, but the most effective way to increase sensitivity of an explosive was to mix it with a small proportion of a hard gritty powder. The kinetic

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energy of the shoe used up in these friction experiments was at least equal to that which in the so-called drop test machines causes regular explosions. An attempt to find the reasons for this behavior leads to the conclusion that in the "pendulum" tests the material, while subjected to a fast blow and shear, due to the nature of the impacting surfaces, was not as well confined between the shoe and the anvil as it was in the drop-test machines.

The drop test machines usually consist of an anvil mounted on a heavy base and a striker, with a few milligrams of explosive between them. A suitable weight is dropped on the striker and aural observation tells whether explosion occurred or not. When flat polished surfaces of hard tool steel are used to contain the material, a sensitive primary explosive like mercury fulminate explodes fairly consistently after a drop of a 2 kg weight from a height of a couple cm.[9] In the same arrangement, but with a 5 kg. weight, PETN gives a 50 percent explosions height at about 15 cm, while for RDX (Cyclonite) this height is about 25 cm. Going to still more insensitive materials one runs into difficulties. Tetryl, for instance, gives occasional explosions at 25 cm, but their probability never rises with height of fall to anything like 100 percent. In fact, above 1 meter height of fall, Tetryl almost ceases to explode, while TNT and ammonium picrate just can't be made to explode with this arrangement, regardless of height and weight, until the striker and the anvil are badly damaged. It takes, however, only a thin sheet of tin foil covering the explosive under the striker to cause Tetryl to explode regularly and at a height as low as that of RDX; even TNT will explode now at an only slightly greater height, but RDX and PETN explosion heights are little changed by the new arrangement. A coating of wax on the striker surface is almost as effective as tin foil, but the same amount of wax intimately mixed with the explosives reduces their

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[9] Plotting percentage explosions against height of fall one gets typical S-shaped probability curves; by controlling experimental conditions more and more closely one can somewhat narrow the curves but no one has succeeded as yet in producing a device giving a sharp boundary between "no-explosion" and "explosion" height of fall.

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sensitivity well below what it is with the bare steel surfaces.

Generally speaking, one finds that the more insensitive a material is under "normal" condition of the test, the more its apparent sensitivity can be increased by confining it to a tightly closed space in the instant of impact, if this does not prevent shear and crushing of the particles.

Using a typical set-up (like the flat surfaces) it is found that the required energy of impact increases linearly with the quantity of the explosive on the anvil. The dependance is different for different explosives, however, so that even the order of sensitivities may be changed when tests are made with altered standard quantities.

Further observations of significance are that anvil and striker made of hard steel are by no means more effective than those of softer metals; in fact one must go to metals as soft as lead before the sensitivity of materials like RDX is materially reduced on the drop test machine. Of course, when thin layers of soft metals are backed by hard steel then one gets, as mentioned above, the most effective initiation of insensitive materials, probably because of the confining action of the soft layer, combined with the fast concentration of energy made possible by the hard material behind it. Foreign materials reduce sensitivity when mixed with explosives, except when they are of the type of hard gritty powders. These latter increase sensitivity quite materially in the drop test; curiously enough, their effectiveness as a function of hardness seems to go through a maximum.

The sensitivity to projectile (rifle bullet) impact, while quantitatively quite different, can be shown to be not inconsistent with the observations just cited.

Compared to the drop test machine conditions. the impacts by bullets bring into the explosive incomparably more kinetic energy. (.30 and .50 caliber, ball and AP, show little difference in effect, provided they all penetrate the confining

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Nonetheless sensitivity to bullet impact is not extraordinarily high and this must be accounted for by the relatively low confinement unavoidable in bullet impact tests. In the laboratory the tests have been acrried out on small (some 100 g) samples placed in containers of varying degree of strength, from cardboard tubes to heavy steel pipes with screwed-on caps. Under these conditions the sensitivity to bullet impact is found to depend very much on the strength of the container and on the physical state of the explosive. Pure RDX, pure PETN, 50/50 Pentolite, Tetryl, Comp. B, when present as loose powders at about 1 g/cc density detonate invariably even in paper containers. Only materials like TNT must be confined in a steel tube before explosions are observed. TNT pressed to high density has not been exploded even in steel containers, while cast TNT must be placed into an extra strong steel bomb to obtain occasional explosions. Cast Comp. B does not detonate, even in steel every time, and completely fails to explode in light containers. The change of sensitivity with physical state is observed with other explosives, low density loose explosives being most sensitive, then the cast materials, while the highly pressed powders are least responsive to bullet impact. The effects of physical state and of the degree of confinement are so pronounced that by a suitable choice of conditions it is possible to make TNT, for instance, appear to be more sensitive than even the 50/50 Pentolite. However, when the tests are arranged under "standard" conditions, the explosives can be arranged into a series of rising sensitivity: Ammonium Picrate < TNT < Comp. B (waxed) < Comp. B (unwaxed) < Tetryl < Pentolite < RDX < PETN . It is, incidentally, about the same order as that into which the explosives can be arranged when tested on a "reasonable" arrangement of a drop test machine.

The apparent sensitivity to bullet impact increases with increase of the size of the charge, so that, for instance, large bombs loaded with cast TNT almost invariably give a (low order) explosion when penetrated by a bullet.

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The effect of the size of the charge is particularly pronounced with aluminized explosives. With small laboratory samples one usually gets mild fires, but large charges give violent detonations. There is very little doubt that these effects of size must be attributed to the confining effect of the mass of the charge on the region directly acted upon by the bullet.

If one counts the fires in laboratory tests as explosions, then the addition of aluminum powder can be said invariably to sensitize explosives to bullet impact. The meaning of the drop test machine trials of aluminized explosives is open to even greater doubts than that of non-aluminized materials. However, if one again takes them at their face value, aluminum should be considered definitely as a sensitizer. In this sense Torpex (not the desensitized kind, with 5 percent wax) should be placed near Pentolite on the scale of sensitivities, while HBX (desensitized and degassed Torpex) will fit into the series between TNT and waxed Comp. B.

Materials like Baratol (Barium nitrate and TNT) are difficult to fit into this series because they show high sensitivity to bullet impact but are quite insensitive (like TNT) on the drop-test machine.

Summing up various practical findings about mechanical sensitivity of explosives, the following regularities may be formulated:

(a) Slow application of pressure with or without shear is quite safe, except with extremely sensitive materials like lead azide.

(b) The hazards in the above operation increase as the confinement of the charge increases. To give an example: rubbing two flat plates against each other, with the material in between, is more hazardous than rubbing a point on a spherical surface against a flat plate covered by the explosive.

(c) Hazards of this operation are further increased when grit is mixed

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with the explosive. For example the writer does not think that Tetryl mixed with grit would be safe to rub between two steel plates with a vigor greater than that of a southern belle.

(d) In view of the above it is evidently safe to operate slowly a metallic tool against a chunk of explosive not more sensitive than Pentolite, but if the latter contains a concealed piece of metal or of rock, trouble may arise.

(e) There is no gain in safety from the use of softer metals for tools, except possibly with the most insensitive materials like cast TNT; steel is to be avoided (if at all) only because of its sparking tendency, with the accompanying dangers of ignition (small with all non-aluminized high explosives; somewhat greater with aluminized explosives). However very soft materials like wood increase safety greatly.

(f) Rubbing of two pieces of explosive against each other or stirring loose explosive is quite safe, provided it is done not so violently as to cause obvious heat evolution and provided that the materials are less sensitive than, say, pure RDX.

(g All sharp blows on explosive must be avoided as definitely hazardous. The hazards increase greatly when the explosive is present in a small quantity between fairly hard materials providing good confinement and some grit is mixed with it. The following hypothetical impacts have been arranged in the order of rapidly decreasing hazards:

1. A hard object hitting a thin layer of explosive on a dusty hard surface.
2. Same, but explosive on a clean hard surface.
3. Hard object hitting a large volume of explosive (or explosive on a very soft support).
4. Soft object hitting a large volume of explosive.

To make things even more precise, the writer will venture to guess that a metal

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object weighing one kilogram falling from 1 meter height, particularly if not in the shape of a smooth surfaced ball, is quite likely to set off all common military explosives in the first case, except ammonium picrate and probably TNT. In the second case only materials more sensitive than waxed Comp. B will be likely to go off, whereas in the third case it will take something at least as sensitive as PETN to produce explosions. With lead azide the writer would not try even the fourth test without a barricade protecting him but suspects nonetheless that even this material would take such a blow without explosion.

(h) Very hard metals are not more hazardous in impacts than those of medium hardness. Shape of impacting surfaces is probably more important than hardness.

(i) All explosives may be made extremely safe even against impact by addition of desensitizers. Thus, when mixed with large excess of water, only materials like lead azide are still capable of detonation. When mixed with about 30 percent by weight of water, pure RDX powder is just capable of detonation when tested with a strong booster charge. Of course, to be effective, mixing with desensitizer must be intimate; it does no good to pour water between large blocks of cast HE for they will, of course, go off when properly initiated. Liquid desensitizers are more effective than equal weights of powdery diluents. The latter, if present in small quantities (e.g., not more than a few percent) and of sufficient hardness (e.g., harder than the crystals of the explosive itself) may even act as sensitizers.

From those comments it follows that in order to make the machining and cutting of HE castings safe, the following rules should be followed:

(a) Tools must not produce gritty powder; hence grinding wheels, sand or emery cloth should be avoided.

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(b) The pressure (not the total force but force per unit area of contact) should be kept low and all fast impacts (i.e., fast-moving tools) should be avoided.

(c) The shape of the tools should be such that there is little confinement; i.e., small area of contact is better. This means that sharp tools are better probably than dull ones.

(d) Pouring water on the tool and the casting will increase safety but only if water penetrates to the point where cutting is being done.

After these practical pointers, let us return to fundamentals and consider what deductions one can draw from the described tests about the mechanism of initiation of detonation by impact.

To the writer, at least, they suggest that in the explosion on impact two distinct phases can be discerned. The first consists in a very local heating of the surfaces (the original surfaces or the new ones if particles are ruptured by impact) as the material is pressed between the impacting surfaces. When the temperatures, very locally reach high values (calculated to be 1000 to 1500°K in drop test machine impacts), ignition occurs with sufficiently short delays (see below) to spread with an accelerating rate. This requires the instantaneous confinement to be so tight that the product gases can not escape in the early microscopic stages of the burning, but build up local pressure and thus speed up the deflagration process. Otherwise either nothing observable happens or, at most, one hears and sees a barely noticeable local decomposition. This, for instance, is what happens with tetryl and less sensitive explosives on the drop test machine when flat steel surfaces are used. An explosion here is always a partial one and most of the material is found unchanged, just scattered around the anvil.

According to this view the first phase of the detonation by impact is controlled by such factors as (a) thermal sensitivity of explosives (see below), (b) their friction coefficient, (c) heat conductivity through their crystals. When the conditions are made such that the original microscopic ignition is certain to

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develop into detonation, these factors become the sole ones to control mechanical sensitivity of explosives. This theory of detonation by impact has been worked out semi-quantitatively 10) and found to describe drop test results quite well.

When the confining conditions are not quite so favorable (confinement either not present at all or lifted very rapidly after ignition) sensitivity to impact becomes more dependant on the subsequent fate of the initial burning, that is, the burning law of the explosive in question becomes of importance. This is probably the case in most bullet impact tests, since it has been shown that explosions do not necessarily originate at the point where the bullet strikes the walls of the confining vessel 11). The evidence further suggests that quite some time passes between the initial ignition and the large scale explosion.

With these facts in mind and allowing for a purely practical safety requirement that the more sensitive an explosive is, the less of it should be used in planning a charge, one may justify the normal practice of a step-wise transition from a detonator through a booster to the high explosive charge.

In the detonator (except the super-fast ones) the primary explosive is only ignited by the impact of a striker pin or the fusion of the bridge wire but its burning rapidly changes into detonation 12). If the very small quantity of the primary explosive used were placed directly against the insensitive mass of the cast high explosive, the impact of its detonation wave might ignite locally the main charge;

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10) G. Gamow, BuOrd Report of about 1943

11) A block of explosive directly behind or in front of a metal plate is less sensitive to impact than one completely confined in a metal box.

12) Were one to use a less sensitive material here, the confinement needed to convert burning to detonation would have to be heavy and anyway the delay would be long. This, incidentally, is made use of in a very elegant delayed action fuze for AP projectiles, in which a thin column of tetryl in a very heavy metal tube is ignited at one end on impact of the projectile on the armor, burns along the column to detonation and thus detonates the main charge at the other end with a delay of a few hundredths of a second.

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however, the pressure would drop so fast, because of the small exploding mass, that the ignition would either peter out or would only slowly build up into detonation. It is therefore desirable to place next to the primary explosive a material of fairly high sensitivity and choose the amount of the former so that the pressure from its detonation is maintained until the adjoining material develops fully its own detonation wave. Roughly speaking, this means a longer time than the reaction time of the next explosive. Studies of the propagation of detonation through explosives (see later section) show that small particle sizes give shorter reaction times. Detonation is better propagated in explosives of lower density, while cast materials with their large crystals are worse from this point of view. Thus it follows that next to the small amount of the primary explosive one should place a sensitive high explosive in the form of low density finely-divided powder, next should come a layer of pressed powder and finally, when the detonating charge has been built up to a respectable size (and the detonation wave to a respectable duration), may come the main cast explosive charge.

Experimental data are in general agreement with these deductions. Thus investigations of the minimum quantity of a primary explosive required to detonate a given high explosive have indicated that the quantity increases with the density of the latter and becomes particularly large for cast materials. Under comparable physical conditions various high explosives require different quantities of primary explosives for their initiation and the quantity required seems to vary about inversely to their mechanical sensitivity, as will be seen by inspecting the Interim Report PT-28 of Div. 8, NDRC.

It is not quite clear to the writer why the increasing powder density of the high explosive charge requires more of the initiating material, unless the shock

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wave coming from the latter expends more and more of its energy in a (more or less) adiabatic compression of the particles of the former and less in "rubbing" them against each other. Straight compression of the particles, as remarked before, does not seem to be a good method of ignition.

From the practical point of view it is very important to note that judging from the bullet impact and other tests, it is possible to detonate a high explosive, even though it is initially only burning. Thus a weak booster charge may cause seemingly reproducible detonations, but there may exist considerable time delays, while the initial burning changes over into full grown detonation of the main charge. The laws of this effect are not known and should be investigated in each individual case. Not only from the point of view of the uncertainty of the delays but also from that of reliability, the delayed initiation is decidedly undesirable.

In evaluating the probable performance of an initiating system it is well to bear in mind that the detonation wave starting from a detonator or the tip of a primacord through the booster and then through the main charge is not a truly spherical wave. Thus in the development of instantaneous explosive flash light sources at ERL (Division 8 of NDRC Report No. OSRD 1488) it was found that better approximation to reality was obtained by assuming that the center of a spherical wave originated by primacord is located some 3 to 5 mm. beyond the tip of the primacord, than by assuming that the wave originates at the end of the primacord. This observation can be expressed, of course, also by saying that there is a directional effect of initiation along the axis of the initiator. The well known observation that detonators initiate much more effectively from their end rather than from the sides belongs in this class also. Finally it may be mentioned that a

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booster in the form of a narrow column reaching through the entire charge (a form favored by Ordnance in some types of bombs) seems to be the least effective booster design, judging from experiments of UERL at Woods Hole (UE Interim Reports of Division 8 of NDRC)

THERMAL STABILITY

From the practical point of view one may describe the response of explosives to heating by saying that there is a region of temperatures where a given explosive is completely stable, a region of higher temperatures in which it undergoes a slow decomposition, while at still higher temperatures the material ignites or explodes. This division is, of course, not justified from the point of view of the theory of chemical reaction kinetics, but practically it is a useful one, as the following will show.

At ordinary temperatures all military explosives can be considered as completely stable, i.e. they can be stored for many years without any detectable decomposition or change in physical properties due to chemical reaction. Least stable are nitrocellulose of high degree of nitration and mercury fulminate. Both may show noticeable decomposition after a storage of several months at 60°C, unless the former has been stabilized by addition of materials which react readily with oxides of nitrogen and the latter is scrupulously dry; even these materials may be left in cool magazines for years at a time without any worry about measurable changes taking place.

With increasing temperature all explosives show decomposition into partially gaseous products, a process which does not give the same chemical individua as the high-temperature explosion but usually results in considerable quantities of oxides of nitrogen and products of only partial rupture of the molecules.

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The rate of these reactions changes with temperature in about the same manner as does the rate of most other chemical reactions, i.e. exponentially, with a two-to three-fold rise in rate for every 10°C rise in temperature.

With some materials the rate, at a given temperature, is strongly autocatalytic; the oxides of nitrogen have been found to act as the catalyst. This is particularly characteristic of the decomposition of nitrocellulose. Therefore all modern propellants contain small quantities of such materials as diphenylamine to react with nitrogen oxides formed from nitrocellulose and thus to prevent autocatalysis of the latter's decomposition. Many other explosives do not show to the same degree the catalysis by oxides of nitrogen (e.g. TNT, RDX, PETN). Some materials show occasional lack of stability at low temperatures which is due to the presence of small quantities of unstable by-products (e.g. TNT and Tetryl). Modern methods of manufacture insure that such impurities are completely eliminated.

Most materials (e.g. PETN, Tetryl, RDX) show a very marked increase in their decomposition rate on melting or in solution, as compared with the crystalline state at the same temperature. This is not a special characteristic of explosives but is a rather common observation in the field of chemical kinetics and has been adequately explained by the modern theory of reaction rates.

A necessary requirement to make an explosive acceptable for military purposes is that at 100°C the material be still quite stable. Ammonium Picrate, TNT, Tetryl, Comp. B, RDX (Cyclonite), Torpex, Baronal, PETN, PbN_6 , can all be stored at 100° for 24 hours without detectable decomposition. Pentolite, in which at 100°C PETN is partially dissolved in liquid TNT, shows traces of decomposition (0.1 percent with bad specimens) in this test, while materials containing highly nitrated cellulose may decompose seriously under such conditions.

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At 120°C, Tetryl and pure PETN, (of course Pentolite also) undergo slight decomposition in 24 hours, while Amm. Picrate, TNT, RDX, PbN_6 , Comp. B, are still too stable for their decomposition to be measured in this time. At about 150°C, Amm. Picrate, Comp. B and Torpex decompose measurably, while at 200°C only Amm. Picrate, TNT and RDX react rather slowly, the rest of the materials mentioned undergoing fairly fast or explosive decomposition.

If instead of being kept constant the temperature of an explosive is being steadily increased, one of two things may happen. If the explosive is stable and the rate of temperature rise is slow, all the material of the (small) sample decomposes gradually; however, if the rate of temperature rise is fast enough (say, 20° C/min), the material (after partial decomposition) suddenly catches on fire, or explodes. The temperature at which this occurs is called the explosion temperature (not to be confused with the temperature of the products formed in an explosion). It ranges from some 180°C for nitrocellulose, to over 360°C for RDX and TNT. This temperature is dependant on the rate of heating and on the size of the sample, because variable delays precede explosion. Detailed investigation shows that these delays or induction periods are quite reproducible and are exponential functions of the temperature. If one dares to extrapolate that far, one finds that with reasonably stable materials one must go to temperatures of the order of 1500°K and higher before the calculated delays decrease to the order of a few microseconds. With small samples of explosive one is usually not able to follow the induction periods to low temperatures and long times as then the material decomposes quietly. With larger samples, however, one occasionally observes very long induction periods, running into days and more. It seems that reaction foci are gradually established in large samples, which grow at an accelerated rate and finally set the entire material on fire. With nitrocellulose propellants, for instance, it is a common

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practice to determine explosion times at 150°C (which may take as much as 100 minutes with 5 gram samples). With this material, of course, the autocatalytic nature of the reaction is particularly pronounced. However, the writer recalls an incident when a 2-lb. batch of a mixture of TNT and lead dioxide suddenly caught fire after heating to 100°C for about 30 minutes, while small samples passed heating tests at 120° for longer times, and without measurable decomposition.

Because of the more-or-less autocatalytic nature of thermal decomposition and explosion reactions, an important practical point in handling explosives is that no samples of explosives should be allowed to stay at high temperatures indefinitely. Therefore, for instance, it is most essential that melting kettles be emptied and cleaned after use; otherwise it may happen that some of the old material gradually reaches an unstable (partially decomposed) state and acts as the nucleus for a destructive reaction of the entire freshly added batch. Another important point to note is that, because of the explosive violence of the reactions when initiated by sudden heating to high temperatures, it is very essential to avoid contact with explosives of really hot objects, e.g. glowing wires from electric heaters, etc.

The writer's knowledge of the effects of electrostatic sparks on explosives is extremely limited and therefore very few remarks will have to suffice here.

Materials with low ignition temperatures, such as nitrocellulose, black powder, mercury fulminate, are very sensitive to sparks and extreme precautions must be taken to insure safe operations. However, the high explosives discussed here are probably only slightly more sensitive to sparks than other ignitable materials, e.g. coal dust, etc. ; the additional danger comes about mainly because the deflagration once started, cannot be put out. There is no evidence known to the writer that such materials as TNT, Tetryl and RDX can be detonated by a weak

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spark such as caused by a charged human body; they are ignited instead. The ignition is much more likely to occur when the materials are present as fine powder than as pressed or cast blocks. Experimental efforts to cause by sparks explosion of TNT and Amm. Picrate dust suspended in air have proved completely unsuccessful; these powders must be settled on conducting surfaces to produce deflagration by sparks; Tetryl dust, however, can be detonated when suspended in air.

PROPERTIES OF REAL DETONATION WAVES

Detonation rates have been repeatedly measured under conditions intended to approximate the ideal ones. The normal method is to take cylindrical charges of increasing diameter and to determine the highest, "limiting", rate. Where this has not been done (and that is frequently the case), the observed rates should be considered only as the lower limits of the "hydrodynamic" rates. Numerical values of the rates of various explosives will be found later in this text with other data on individual explosives. For interpolation of these data it is useful to remember that where one deals with organic nitrated materials without additions such as aluminum, inorganic nitrates, etc., the following interpolation formula holds quite well:

$$D = D_0 + 3770 \, (d - d_0) \text{ met/sec}$$

Here D and D_0 denote detonation rates and d and d_0 are the corresponding densities of the explosive in g/cc.

Explosives mixtures containing other ingredients than organic nitrated materials do not follow this interpolation formula. However, it seems that in most cases (Amatols, i.e. TNT - ammonium nitrate mixtures, are a striking exception) one can use a linear relation between density and rate, with the proportionality coefficient varying from one mixture to another.

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Three major factors are known to influence the detonation rate of a charge, in addition to the thermodynamic variables mentioned in the discussion of the hydrodynamic theory of detonation rates. They are:

I. Initiation

II. Size and confinement of charge

III. Physical state of the explosive

The effect of initiation on an apparent steady rate of propagation of detonation has been studied mainly with liquid explosives (nitroglycerine and related materials). In addition to a well defined high rate of detonation, which seems to check the predictions of the hydrodynamic theory (and which is obtained with strong initiation), these materials possess also a slow (not very reproducible) rate. Nitroglycerine initiated by immersing into it a weak initiator like Primacord propagates the detonation with a rate of something like 1,800 met/sec (instead of the full rate of about 8,000 met/sec) for rather considerable distances. The same result may be achieved by butting a narrow tube filled with nitroglycerine into a charge of wide diameter and detonating the former with full velocity. The phenomenon is not observed when the transition between the two tubes is made gradual 13). The theory of this phenomenon has not been worked out, but indications point to a surface reaction of nitroglycerine in the slow detonation, the material in the interior of the charge remaining unreacted and being only scattered about.

No reliable published data on similar effects in solid explosives are known to the writer, although he believes to recall some pre-war articles dealing with commercial dynamites and describing effects of weak initiation.

The effect of the diameter of a cylindrical charge on the rate of detonation has been repeatedly studied14) and is rather well understood. Starting with

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13) Most of these data are quoted from a confidential report of the Hercules Powder Co. which is not generally available; ERL gives some data on the subject in their Interim NDRC reports.

14) Fairly extensive recent data will be found in Interim and Progress Reports of Div. 8 of NDRC from ERL, Bruceton.

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large diameter charges filled with a reasonably good (not less sensitive than, say, cast TNT) explosive, one finds constant rates independent of the charge diameter. With charges of this size, confinement appears to have no effect on the rate.

With a reduction in the charge diameter one eventually observes slowing down of the detonation wave and this becomes more pronounced as the diameter is further decreased. Finally, very thin charges simply fail to propagate detonation. Optical studies of the shape of the detonation waves in cylindrical charges show a lagging of the wave near the surface, i.e. a shape reminiscent of the meniscus of a liquid in a tube. This shows that the detonation propagates slower near the surface of the charge. When the charge diameter is so far reduced that only these slower propagating portions remain, then the detonation wave as a whole is slowed down. The explanation usually advanced attributes this effect to the finite time of the chemical processes in the detonation wave. Near the surface the product gases expand so rapidly that the chemical reaction is unable to maintain the normal detonation pressure; hence the mechanical shock preceding the reaction zone does not receive the energy it receives in the interior of the charge; therefore its pressure and hence its rate of propagation is reduced. The correctness of this interpretation is further confirmed by the observation that confinement of thin charges increases the rate, but not to the full rate of thick charges.

The magnitude of the charge diameter effects depends strongly on the character of the explosive tested. Extremely thin charges of primary explosives, like lead azide and mercury fulminate, are able to propagate detonation. With PETN the diameter effects are noted only with charges a few mm. thick. In Primacord, for instance, the charge is only 1.5 mm. thick but propagation is very reliable; however the rate (6400 m/sec) is about 1000 m/sec. lower than in a large charge of the same density (7400 m/sec. at 1.48 g/cc). Slightly larger diameter effects are

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noted with RDX and Tetryl, but with TNT even charges 2-3 cm. in diameter do not have quite the full velocity, while charges only a few mm. in diameter fail to propagate altogether (unless heavily confined, as in the Bickford fuse). With cast charges (i.e. TNT, Comp. B) the failure to propagate occurs relatively more readily and one cannot follow the dependence of the rate on diameter as far as one can with pressed or low density powder charges. Thus 2-3 cm. diameter charges of cast TNT fail rather rapidly[15]. However, even 1 cm. diameter charges of cast Comp. B and Pentolite still propagate and at rates which, at least in the case of Pentolite, are near the hydrodynamic values.

In mixed explosives (except Comp. B, Pentolite, Tetrytol, in which both components are true high explosives) the effects of charge diameter are generally large. They have been properly investigated only in Amatols (TNT and Amm. Nitrate), where they reach extreme values. Actually in Amatols containing as little as 50-60 percent Amm. Nitrate the measured rates fall far below the predictions of the hydrodynamic theory regardless of charge diameter (c.f. Div. 8 of NDRC Report No OSRD 3411).

The theory predicts for Amatols higher raters than those of TNT of equal density but all observed rates are definitely lower and unconfined charges of even moderate size are very apt to fail. The writer has been told, however, that in the detonation of 10,000 lbs. bombs, provided with Comp. B boosters weighing several hundred pounds, higher rates have been observed at Aberdeen with 50/50 Amatol than with TNT. Thus, possibly, with charges of this enormous size even Amatols reach their full rate.

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[15] The ability of cast TNT at such small diameters to propagate detonation is quite sensitive to the method of casting. If the completely molten material is allowed to cool and solidify slowly (large crystals), 2.5 cm. diameter charges will almost certainly fail. If the TNT is cooled and stirred in the pot until a mush of fine crystals is obtained, this material cast into 2.5 cm diameter charges will almost certainly propagate [redacted]

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Du Pont also report Dautriche[16] rates on 60/40 cast Amatol of 5" diameter which approach TNT rate.

Probably the most extreme effects are observed with commercial dynamites made of ammonium nitrate and organic non-explosive ground materials soaked with 10-20 percent nitroglycerine. These explosives will not detonate at all when compressed to high densities but in the loose form they propagate at rates as low as 1800-2000 met/sec in charges of a few cm. diameter and under moderate confinement. However, the rates can be raised to values as high as 4,000-5,000 met/sec under extreme conditions, so that it looks as if nitroglycerine alone was responsible for the detonation wave in smaller unconfined charges, the rest of the matter reacting so much later that it does not help the detonation wave, while still contributing its share to the "gentle" push which these explosives are expected to give in boreholes in order not to crush coal or rock too much.

British observations on the air blast derived from 2000 and 4000 lbs. thin cased bombs led them to the conclusion that the 60/40 Amatol charge detonates more or less completely in the smaller bombs but partially fails in the larger ones. Both types have the same long tetryl booster and the difference is in the diameter of the Amatol charge. It has been concluded therefore that a conical expanding detonation wave travels through Amatol for some 20 to 30 cm but then dies out.

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[16] The Dautriche method of measuring detonation velocities is based on a comparison of the velocity of the material to be tested with that of Primacord, which is assumed to be known. In actual execution the ends of a loop of Primacord are attached to two points along the charge of the material, made into a cylinder and fired from one end. A lead plate is laid under the Primacord. As the detonation wave is propagated along the charge to be tested, it sets off first the one and later the other end of Primacord. The two waves in the Primacord eventually meet and at this point the lead plate is found to be more damaged by the Primacord than elsewhere. Knowledge of the distances involved, through the charge between the ends of the Primacord and through the Primacord to the point of meeting of the waves as well as of the velocity through Primacord is then sufficient to calculate the velocity through the charge.

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To the writer the observation is very puzzling. The supporting effect of the detonation wave from a 5 cm. thick central charge of tetryl should have vanished long before the end of the 20 or 30 cm path in the Amatol charge. As the wave travels towards the outside of the bomb, the radius of its curvature increases and hence, according to all the other information, the chance of its dying out should decrease, instead of rather suddenly becoming large. However, the experimental data obtained in these investigations are difficult to reconcile with anything but a partial failure of the 4000 lbs. bombs and a satisfactory performance of the smaller ones.

A preliminary and unconfirmed but interesting observation has been made at the UERL, Woods Hole (see Interim Reports of Div. 8, NDRC, UE Series). Fairly small cast Minol charges (Minol is a mixture of ammonium nitrate, TNT and aluminum) were found to give higher performance when the outside of the charge was coated with a thin layer of Comp. B than when the same quantity of Comp. B was used as the central "boostering" charge next to the usual tetryl booster. It was suggested that Minol, being a slowly reacting explosive, does not complete its reaction near the surface of the charge, but that the outer layer of the faster reacting Comp. B insures all of the Minol participating in the detonation process.

The effects of the charge diameter are mixed up with the effects of the physical state of the explosive and their exploration has only been started as yet. The remarks made in the preceding paragraphs refer, by and large, to charges made of "commercial" loose powder explosives, in which the particle sizes are mixed and only roughly controlled. In fact, the writer knows of no investigations in which particle size was controlled and charge diameters and charge densities were varied in a systematic and comprehensive manner. Studies made at ERL, Bruceton, come

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nearest to this requirement, but they also provide only partial data. Most of these will be found in the monthly Interim Reports (DF and earlier series covering the same topics) of Div. 8 of NDRC.

With low density charges particle size is found to have very important effect on the rate of detonation (with pressed charges such study is difficult because of the uncertain crushing of the particles by the compression). Thus TNT in charges of even 4 to 5 cm diameter and density of 0.8 to .9 g/cc has a detonation rate faster by 150-200 m/sec when the particle size is reduced to about 10 microns than when the common "grained" material is used. This effect of the particle size, observed in other materials also, is readily fitted into the theory of detonation reactions discussed above. However, the real phenomena are probably more complex, judging by the observations made on low density ammonium picrate charges (Report OSRD 1755 from ERL, Bruceton). Charges of this material of about 0.9 to 1.0 g/cc density and 2.5 cm diameter show a detonation rate near the hydrodynamic value when the particle size is about 10 microns. Charges of the same density and diameter made of particles of about 100 microns size have a rate slower by a couple hundred meters per second. When the two particle sizes are mixed in various proportions, one does not find, as expected, a linear relation between the rate and the composition of the mixture. Instead the rate is relatively too slow in mixed powders and passes through a minimum at about 70 percent by weight of coarse particles (actually 2.5 cm diameter charges even do not propagate detonation when made up in these proportions of particles). Quite obviously the dependance of the chemical rate on particle size does not explain these effects. It has been pointed out, however, that the natural packing density of mixed powders depends on the proportions of the coarse and fine particles and happens to reach a maximum for the 70/30 proportions

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of the particles used in these experiments, if the particles are assumed to be spheres. Thus the experiments made at the same bulk density were made at densities different relative to the close packing of the particles. The average character of the contacts between the particles differed therefore in the various mixtures tested and this must have affected somehow the processes that occur when the mechanical shock preceding chemical reaction in the detonation wave passes through the powder. The experiments show that the details of the mechanical action of the initial shock are of great importance for the velocity and even for the maintenance itself of the detonation wave. Whether the different consistency of the powder causes more of less intense attenuation of the shock, whether the ignition of particles depends on how the powder reacts to the passage of the shock, or whether still other phenomena are of prime importance cannot be decided at present.

Unfortunately no analogous studies have been made with other explosives and ammonium picrate is so insensitive that it could be looked upon as an exception rather than the rule. The writer, however, believes that they are descriptive of the general behavior of explosives, at least in the low density charges. Naturally with individual explosives the effects will be found in charges of different diameters and in sufficiently large charges they all must disappear.

To the writer are known no really systematic investigations of the charge diameter effect as a function of the density of the charge, although it has been shown that high density charges do show it. In fact, the more difficult initiation of high density charges suggests that in them the diameter effects should be more pronounced. The same deduction is supported by observations on pressed charges of 50/50 Amatol (Report No. OSRD 3411 from ERL, Bruceton). In charges of 2.5 to 5 cm diameter, instead of finding a linear dependence of the rate of density, one actually

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observes that the rate almost ceases to increase with increasing density (in commercial dynamites actual maxima of rates have been reported) when the latter reaches values of the order of 1.5 g/cc. Thus one must conclude that for a given charge diameter the deviations of the actual rate from the hydrodynamic value increase with density, at least in case of Amatols.

With cast charges, as already mentioned, propagation of detonation becomes particularly difficult, but little quantitative data are available. It has already been mentioned that "creamed" TNT, i.e. TNT which has been allowed to crystallize partially in a kettle with stirring, gives castings which propagate detonation much better, because of relatively fine crystal size, than does TNT poured completely as a liquid into the molds and allowed to solidify there into large oriented crystals. Cast Amatols made with fine grained ammonium nitrate are also said to propagate the detonation better, etc.

EFFECTS OF EXPLOSIVES ON THE SURROUNDINGS

This is a very extended topic and is somewhat outside the main subject of this review. Therefore a few brief remarks and a table of comparative performance of various explosives will have to suffice.

In laboratory practice two terms have been universally in use, the power and the brizance of explosives. The definition of both terms, particularly of the latter, is somewhat loose and tests proposed to measure them are varied and not always to the point. Following custom, the power is defined as the ability to do work at a distance, which is little dependent on the speed of the explosive, while brizance refers to the destructive effects in the immediate vicinity of the explosive and is undoubtedly related to the speed of establishment and the magnitude of the pressure in the detonation wave.

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Of all the laboratory methods of determining the power of an explosive[17], ballistic mortar appears to be most satisfactory. In this test a sample of explosive weighing some 10 g is detonated in the center of the chamber (of some 300 cc volume) of a short mortar with a close fitting heavy projectile. Recoil energy is measured and the results are expressed as grams of TNT to give the same effect as 10 grams of the explosive tested. Calculations (Div. 8 of NDRC Interim Reports from ERL) show that the work done in the mortar is very close to the thermodynamic maximum, so that the speed of the explosive is obviously of little importance.

In the Trauzl lead block test a quantity (10 g) of explosive is detonated on the bottom of a cylindrical hole in a large lead block, the hole being tamped with clay or such, and the volume increase is measured. Experimental data exist to show that the results are a rather complex function of the conditions so that the test is less readily interpretable than the mortar data.

For the determination of the brizance the sand crushing test and the plate denting test have been used among others. In the former a known quantity of the explosive is detonated while surrounded with carefully graded sand and the quantity of sand crushed is measured. In the latter a charge is placed in direct contact with a steel plate and the depth of indentation in the latter is measured. The writer favors the second test because in the former the data vary in a complex manner with the density of the charge used, while in the latter a simple linear relation is observed. Furthermore the second test is the nearest laboratory approximation to the field use of the brizance of explosives, namely in demolition work. Finally, a

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17) With gun propellants a closely related term, potential, which is obtained by multiplying the heat evolved by the volume of gases formed, can be calculated from the more fundamental thermodynamic data. In case of explosives the speed of expansion of the products may be so rapid, however, that chemical equilibrium is not established and hence the potential is variable and not calculable.

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study of the numerical data of the sand crushing test suggest that it measures power more nearly than brizance.

Aside from demolitions the explosives in military practice are used to fragment casings, or to produce air blast and shock in water.

For fragmentation two matters are of importance: size of fragments and their velocity. As regards the former, the results depend so much on the physical properties and geometry of the case, on the shape of the detonation wave in the charge, and on the charge to case mass ratio, that it is impossible to discuss them here. It will not be too wrong however to state that, other things being equal and the mass ratio being not too far from unity, the size of fragments decreases as the speed or brizance of explosives increases. There is no complete parallel between the size of fragments and their velocity. For instance Torpex gives higher velocity to shell fragments than Comp. B, but produces on the average larger fragments (BuOrd reports from the Dahlgren Proving Grounds and also Div. 8 of NDRC Interim Reports from ERL) suggesting that it is more powerful but less brizant than the latter.

With moderately or very heavy casings the velocity of fragments appears to be a function primarily of the power of explosives, varying by about 20-25 percent between the extremes of TNT and Torpex. In shells, in which the charge-mass ratio is of the order of 0.1 the velocity of fragments is in the neighborhood of 1000 m/sec. In very large bombs, with charge mass ratios of 2/3, velocities of almost 4000 m/sec. have been observed. Even higher velocities can be attained with very thin casings.

Air blast is usually measured several tens of charge diameters away from the charge, where the magnitude of the pressure peak is of the order of tens of pounds per square inch. Measured is usually the peak pressure, the impulse (time integral of positive excess pressure) and the energy (time integral of the square of pressure excess). It is important to note that the following

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scaling law has been well confirmed by experiments: the impulse does not depend on the size of the charge, provided the measurements are made at such distances that the ratio of distance to the cube root of charge weight is a constant. Of course, distance from the ground, character of the topography, etc. must be appropriately scaled, too.

What has been just said about air blast, applies also to the shock in water, except that due to lower compressibility of water the magnitude of pressure rise is much greater. The measurements (and damage to typical marine structures) are usually carried out at distances of twenty to fifty charge diameters and give pressures of a few tons per square inch.

Following is a table giving performance of various explosives in the tests and under conditions discussed above. The data (which are unfortunately not complete) are given relative to TNT which has been taken as standard. Most of this information has been taken from a compilation issued by the Naval Bureau of Ordnance (Res. Memorandum No. 10, August 1944), supplemented by data taken directly from ERL reports.

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EFFECTIVENESS OF SOME EXPLOSIVES

Explosive	Ballistic Mortar	Trauzl Block	Sand Crushing	Plate Dent	Energy Air Blast	Energy Water Shock	Fragment Velocity
Amatol (50/50)	118	130	86		84	94	
Comp. B (60/40/1)	134	132	118	131	116	123	106
Comp. C-2	126		110				
Amm. Picrate	99		88	91			
Lead Azide		45	42				
Mercury Fulminate		50	52				
Minol	143	168	96	72	133	138	100
Pentolite (50/50)	129	124	131				
PETN	145	178	150	129			
Picric Acid	111	109	109	107			
RDX	151	180	136	135			
Tetryl	129	130	118	116			
TNT	100	100	100	100	100	100	100
Torpex	134	166	160	119	146	141	120

PROPERTIES OF INDIVIDUAL EXPLOSIVES

The numerical data given below for individual explosives have been taken from the excellent compilation by A. H. Blatt (Report from Div. 8 of NDRC, No. OSRD 2014). Literature references and complete data should be consulted in that publication; here an attempt has been made to select or average the data critically, insofar as possible. In appreciating the information given below it should be remembered that all mechanical sensitivity tests suffer from the impossibility of selecting a truly absolute method of testing; hence only comparative data can be given and even these scatter considerably, depending on the precise conditions of test.

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The same criticism applies also to the data on initiation, as will be observed clearly after the study of the numerical data presented by Blatt. Heat and stability tests, the data on which also suffer from lack of uniformity, are carried out at selected temperatures until reaction of a convenient indicator is observed; employed usually are the Methyl Violet impregnated paper and a paper impregnated with starch and potassium iodide, both of which react with nitrogen oxides. In the vacuum stability tests the volume of gases evolved in vacuum by a 5 g sample of material is measured. Explosion temperature is frequently determined by dropping a small sample on the surface of Woods metal.

TNT $C_7H_5N_3O_6$; 2,4,6,-Trinitrotoluene

Description: M.p. 80.5° ; d(liquid at 80.5°) 1.465; crystal density 1.654; pressed density at 4125 kg/cm^2 1.61. Hardness about 1.2 on Mohs scale. Vapor pressure immeasurably small at room temperature but at the m.p. is sufficient to produce noticeable vaporisation from the liquid surface and condensation on cold surfaces over long periods of time; vapor somewhat toxic.

Sensitivity: Determinations at various laboratories relative to Picric Acid (PA) give values ranging from equality with PA to a sensitivity of 62 percent of PA. Relative to Tetryl a value of 50 percent sensitivity has been determined. Here sensitivity is expressed as inversely proportional to the height of fall of a certain weight needed to give a certain effect. Sensitivity has been observed to decrease with increasing temperature, between 30 and 90°C.

Initiation: When a small quantity (1.0 to 0.4 g.) of TNT and of an initiating explosive are pressed together into a detonator cap and the latter is ignited, the following typical minimum quantities are found to initiate TNT: Mercury fulminate 0.25 g; Lead azide 0.16 g; Diazodinitrophenol (DDNP) 0.16 g. Available data do not

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show any obvious dependance of these amounts on the compression.

Power and Brizance: Determinations at some 10 different laboratories of the Trauzl lead block expansion give values ranging from 83 to 103 percent of Picric Acid, with an average of 93 percent. On the ballistic mortar the figure is 90 percent of PA. Sand crushing gives 94 percent of PA.

Detonation Rate: 4870 m/sec at d = 1.0 g/cc; 6700 m/sec at d = 1.6 g/cc.

Stability: Decomposes without explosion on Woods metal surface up to 360°, but explodes at 420° to 470° . At 135° there is no explosion and no acidity in 300 minutes. At 120° in the vacuum stability test 0.2 cc are evolved in 48 hours (small quantities such as this may easily be due to occluded gases or to traces of impurities and should not be considered significant).

Reactivity: With alkalies and ammonia TNT furnished products which are dangerously sensitive to heat and are probably more sensitive to impact. TNT is not hygroscopic. It does not react with metals except in the presence of dilute nitric acid; then the products are hazardous.

Comments: Because of its low melting temperature and great insensitivity, combined with high performance, TNT occupies a unique position among explosives. It is used alone for filling a great variety of munitions and is also used as the liquid component of a variety of explosive mixtures which are poured as slurries. Tetryl and PETN are quite soluble in TNT and form eutectics melting at 62° and 75°C respectively. Even RDX is soluble in TNT to the extent of about 4 percent at the m.p. and about 10 percent at 100°C.

Available now is the so-called Grade I, TNT, with a settling point above 80.2° ; it is furnished in two forms, flake TNT and granular TNT; the latter is a powder of essentially single crystals of TNT; the former is obtained by rapidly freezing a thin layer of TNT on a cold drum and scraping the flakes off.

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TETRYL (CE) $C_7H_5N_5O_8$ 2,4,6-trinitrophenylmethylnitramine

Description: M.p. 130°; crystal density 1.73; hardness about 0.8 on Mohs scale.

Sensitivity: Various comparisons with PA give a sensitivity of from 160 to 125 percent. Comparison with TNT gives a sensitivity of about 200 percent. Comparison with RDX gives about the same sensitivity in one type of test, lower sensitivity in the other. Sensitivity decreases with increasing temperature between 30 and 90°C.

Initiation: Under the same test conditions as described for TNT, the minimum initiating amounts are: Mercuric fulminate 0.16 g. ; lead azide 0.03 g ; DDNP 0.075 g ; there are again no clear cut data to show that higher density requires more of the initiating material.

Power and Brizance: Determinations by a large number of investigators with the Lead block test give values of about 120 percent of PA. Ballistic mortar data are from 121 to 132 percent of TNT. Sand crushing test gives from 113 to 124 percent of TNT.

Detonation Rate: 5420 m/sec at d = 1.0 g/cc ; 7510 m/sec at d = 1.6 g/cc.

Stability: Explodes at 196° when heated at the rate of 20° / min ; ignites but does not explode even at 360° when dropped on Woods metal surface. Not acid and no explosion in 300 min. at 100° , but acid in 100 min at 120° . Vacuum stability: 4 cc in 48 hours at 120° .

Reactivity: Tetryl is not affected by boiling water or dilute acids but is hydrolyzed by boiling sodium carbonate; it is not hygroscopic. Contact of skin with Tetryl may cause dermatitis.

Comments: Tetryl is the material most commonly used for booster pellets in pressed form at a density of about 1.5 g/cc. It is usually available in bulk form as "spherical grained" tetryl, individual particles being of fairly uniform size and of approximately spherical shape; they are of microcrystalline structure. It has been reported that finely divided tetryl dust suspended in air at a concentration of

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70 mg/liter can be ignited by an elecrostatic spark of 0.015 joule energy.

RDX (Cyclonite) $C_3H_6N_6O_6$ Cyclomethylene trinitramine

Description: M.p. 202°(decomp.) Crystal density 1.816. Hardness between 2 and 3 on Mohs scale.

Sensitivity: Sensitivity 150 percent of that of PA ; sensitivity 250 to 160 percent of that of TNT, sensitivity 140 to 100 percent of that of tetryl and about 70 percent of that of PETN have been reported. In a friction test RDX appears to be more sensitive than PETN.

Initiation: Determined as described before, it takes 0.15 g of an 80/20 fulminate-chlorate mixture to initiate RDX.

Power and Brizance: With lead block a figure of 167 percent of PA has been given. Ballistic mortar data range from 150 to 161 percent of TNT. Sand crushing test gives 145 percent of TNT.

Detonation Rate: 5830 m/sec at d = 1.0 g/cc; 8000 m/sec at d = 1.60.

Stability: Does not explode on Woods metal surface up to 360°C. At 135° no acid and no explosion in 300 minutes. Vacuum stability: 0.9 cc (?) in 48 hours at 120°.

Reactivity: RDX is rapidly hydrolyzed by hot sodium hydroxide solutions. Mixtures of RDX with iron (and copper) oxide have much lower thermal stability and may ignite but little above 100°C. RDX is not hygroscopic. RDX does not cause dermatitis but taken orally acts as poison, causing convulsions.

Comments: Most of RDX manufactured at present is not a pure compound but a mixture with about 10 percent of a homologue (HMX). The latter is explosively indistinguishable from RDX, except that it may be converted by precipitation from solution at temperatures around 100° into a more sensitive crystal modification.

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PETN $C_5H_8N_4O_{12}$ Pentaerythritol tetranitrate

Description: M.p. 139° ; crystal density 1.77 ; pressed density about 1.54 at 30,000 lbs/sq. inch ; hardness about 1.8 on Mohs scale.

Sensitivity: Sensitivity 250 percent of tetryl and 160 to 110 percent of that of RDX have been reported. Friction test sensitivity is less than that of RDX however.

Initiation: Very sensitive to initiation; only 1/20 the amount of lead azide is required to initiate PETN than tetryl.

Power and Brizance: With lead block test values of from 147 to 168 percent of PA and from 173 to 179 percent of TNT have been recorded. Balistic mortar gives 146 percent of TNT.

Rate of Detonation: 5550 m/sec at d = 1.0 g/cc ; 7920 m/sec at d = 1.6 g/cc.

Stability: Explodes in 1 second at 255°. No explosion in 300 minutes at 135° . Acid in 90 minutes at 100° . Vacuum stability: 6.5 cc in 48 hours at 120° .

Reactivity: Hydrolyzed only slowly by alkalies; very slightly hygroscopic.

Comments: PETN does not press nearly as well as tetryl, probably because of greater hardness of crystals. The two major uses of PETN at present are in mixtures with TNT (Pentolites) for the bursting charges and as the charge in Primacord. The latter is made by extruding wet paste of PETN, wrapping it in cloth, drying, wrapping again with waterproofing plastic impregnated covering. Primacord contains about 3 g of PETN per foot of length. Its detonation can be initiated by a No. 8 or a No. 6 cap and it is propagated at rates varying from about 5900 to 6500 m/sec. However variations in rate within one spool are usually very much smaller than the above indicated limits. Because of the small quantity of PETN in it, Primacord is a very weak initiator. In demolition work it is common to push the end of a strand of Primacord into a detonator; another expedient is to make a knot of Primacord and insert this into the main charge. [illegible] sensitive than cast Pentolite

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EXPLOSIVE D $C_6H_6N_4O_7$ Ammonium Picrate

Description: M.p. 265° (with decomp.); crystal density 1.717; pressed density at 12,000 lbs/sq.in. 1.48.

Sensitivity: Sensitivity 83 to 77 percent of TNT.

Initiation: Under identical conditions it takes 0.85 g of mercuric fulminate to initiate AP as against 0.26 for TNT.

Power and Brizance: On the ballistic mortar the value given is 99 percent of TNT. Sand crushing - 73 percent of TNT.

Detonation rate: 4750 m/sec at d = 1.0 g/cc ; 7040 m/sec at d = 1.6 .

Stability: Explodes in 5 seconds at 320° . At 130° no acid and no explosion in 300 minutes.

Reactivity: Being a salt (moderately soluble in water) this material will readily exchange ammonium ion for metal ions. Salts of heavy metals with Picric acid are known for their sensitivity, particularly the lead and the silver salts. Amm. picrate is not hygroscopic and is not toxic, except possibly when taken orally.

Comments: Ammonium picrate is usually supplied as a coarse crystalline powder. It is considered to be the most insensitive military explosive. While, as remarked above, it does undergo "double decomposition" with salts of heavy metals in solution, it does not attack metals, in which respect it is very different from the free picric acid.

MERCURIC FULMINATE $Hg(ONC)_2$

Description: Crystal density 4.4 ; pressed density 3.55 at 5,000 lbs/sq.in.

Sensitivity: Explosions in the drop test have been obtained by the different investigators with weights of 0.5 to 1.0 kg at heights ranging from 0.25 to 20 cm. Evidently the results depend too much on the specific conditions chosen to have much

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meaning, except to indicate high sensitivity of M.F. to impact. Mercuric Fulminate is detonated by an electric spark from a person charged to 5000 volts.

Power and Brizance: Lead block tests give values of from 36 to 50 percent of PA.

Initiation: The following table shows the initiating action of M.F. on several explosives. The last column shows the pressure at which loading has been done; other columns show the amounts of mercuric fulminate necessary to initiate explosives indicated. Unfortunately the data at various pressures have been reported by different investigators and hence are not fully comparable; however some trends with increasing density to greater required quantities may be recognized.

Picric Acid	TNT	Tetryl	Amm. Picrate	PETN	Tetranitroaniline	Pressure lbs/sq.in.
0.21	0.26	0.24	0.85		0.20	1000
0.225	0.24	0.165			0.175	3400
0.25	0.26				0.20	3000
0.21	0.26	0.24	0.85		0.20	3000
0.30	0.36	0.29				17000
				0.33		30000

Rate of Detonation: 2700 to 3300 m/sec at $d = 1.67$; 4500 to 4700 m/sec at $d = 3.6$ g/cc.

Stability: Explodes in one second at 240° ; explodes at 170° when heated at the rate of 20°/min.

Comments: Mercuric fulminate is used exclusively as an initiating material, most frequently in a mixture with potassium chlorate (to which crushed glass is added when the mixture is used as an impact detonator or igniter). When detonation is to be caused by heat (electric detonators, etc.) it is important not to "dead-press" mercuric fulminate. Pressed at pressures in excess of ca. 7000 lbs/sq.in. mercuric fulminate will not change burning into detonation and hence will not act as a primary explosive; however, when initiated by lower density mercuric fulminate it will

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propagate detonation even in a dense state. Sensitivity of mercuric fulminate to flame and spark is so great that extreme precautions must be used in its handling.

LEAD AZIDE $Pb(N_6)_2$

Description: Crystal density 4.68 to 4.72. Two crystalline modifications have been reported, orthorhombic, stable, and monoclinic, unstable and extremely sensitive.

Sensitivity: Sensitivity about 200 percent of PETN has been reported; also 500 percent of PA. Sensitivity about 50 percent of Mercuric fulminate can be estimated from available scattered data.

Initiation: Minimum initiating charges of lead azide, pressed with the high explosive to 3400 lbs/sq.in. in detonator caps are, for: TNT, 0.16 g; PA, 0.12g; tetryl, 0.03g ; tetranitroaniline 0.05g ; hexanitrodiphenylamine ("Hexanite"), 0.05 g. The minimum initiating charges for PETN, when loaded at indicated pressures are:

Pressure on PETN, kg/cm^2	0	2000	2000
Pressure on lead azide, kg/cm^2	0	0	2000
Dextrinated lead azide	0.04g	0.17g	0.04g
Pure lead azide	0.015g	0.10g	0.01g

Power and Brizance: Lead block expansion, 40 percent of PA or 70 percent of mercuric fulminate. Sand crushing test--75 percent of mercuric fulminate.

Rate of Detonation: 4500 m/sec at 3.4 to 3.8 g/cc density.

Stability: Explodes at 300 to 340° when heated at the rate of 20°/min. At 80° no change is observed after 15 months.

Reactivity: Attacks copper and brass in presence of moisture to form extremely sensitive copper azide.

Comments: Improperly precipitated, lead azide forms polycrystalline (twinned) aggregates which are extremely sensitive; large crystals in general are more sensitive

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than the fine powder. The process of crystal growth may continue even when lead azide is kept as an aqueous slurry. Consequently it is common in USA not to use pure lead azide but the so-called dextrinated lead azide, i.e. material precipitated out of solution in presence of dextrin. This material does not show twinned crystals and does not undergo the process of crystal growth in presence of water; it can therefore be transported wet. The British use microcrystalline pure lead azide.

AMATOLS Ammonium Nitrate and TNT

Description: Commonly used are slurries containing 50 (50/50), 40 (60/40) and 20 (80/20) parts of TNT; only the former is now used in USA. The last slurry is so thick that it cannot be poured but must be "screw-loaded", i.e. extruded hot, into shells.

Sensitivity: All Amatols appear to be less sensitive to impact than TNT.

Initiation: With increasing proportion of ammonium nitrate, the materials become more difficult to initiate.

Power and Brizance: On the ballistic mortar the Amatols give higher values than TNT, 80/20 mixture being the most powerful; however in actual use the performance decreases as the proportion of ammonium nitrate is increased, partly because of lower casting density obtainable in practice, partly because of decreasing brizance.

Detonation Rate: Cast 80/20 Amatol is reported to have a detonation rate of about 5500 m/sec; cast 60/40 material a rate of about 5600 m/sec., cast 40/60 mixture a rate of 6500 m/sec.

Stability: Materials ignite at 250-300^0, hence are less stable than TNT; they also show significant gas evolution in the vacuum stability test at 120° in 48 hours. All Amatols are highly hygroscopic and in presence of moisture attack many metals.

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COMP. B RDX and TNT (and Wax)

Description: Now in use is a mixture of 60 parts of RDX and 40 parts of TNT with (Comp. B) or without (Comp. B-2) 1 part of a special wax. The setting point of these slurries is about 79° , since TNT forms an eutectic with about 4 percent of RDX.

Sensitivity: Between that of tetryl and TNT; wax has a small but distinct desensitizing action.

Power and Brizance: About 130 percent of TNT

Detonation Rate: Can be computed by the additivity rule from those of TNT and RDX and the density. Normal cast rate is about 7800 m/sec.

Stability: RDX and TNT do not appear to react with each other and therefore the stability of Comp. B is comparable to those of its ingredients.

Comments: In the preparation of Comp. B wet RDX is added to molten TNT and the slurry is heated at 100 to 110°C. until most of the water has evaporated; consequently Comp. B contains a small percentage of water. The heating of the slurry is accompanied by a significant (factor of two) rise in viscosity, probably because of a deflocculation of RDX crystals.

PENTOLITES PETN and TNT

Description: Most commonly in use now is the 50/50 mixture, which is quite fluid because a considerable part of PETN is in solution. Setting point about 75°.

Sensitivity: Greater than that of Comp. B(-2), but very much less than of pure PETN, both with respect to mechanical impact and initiation.

Power and Brizance: Slightly less than those of Comp. B. They and the detonation rate can be computed by the additivity rule from those of the ingredients.

Stability: Less than that of pure PETN, because of the labilizing effect of the liquid phase; however at 100° the stability is quite satisfactory, except in impure specimens.

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Comments: In distinction to Comp. B, the proportions of the liquid and solid phases in Pentolites change rapidly with temperature because of large and temperature dependent solubility of PETN. Hence the viscosity of Pentolites rapidly decreases with rising temperature.

TORPEX TNT, RDX and Aluminum

Description: In common use is a mixture containing 18 percent aluminum powder (mostly through 325 mesh sieve), 42 percent RDX and 40 percent TNT. Water originally present in Comp. B from which Torpex is made reacts with aluminum powder and causes gases (containing hydrogen) to be formed. This "gassing" occurs particularly fast in the molten state but does not cease in finished castings and is there very troublesome. Thus a 300 lbs. charge of Torpex may produce as much as 100 cc/day for periods of months. Addition of .5 percent of anhydrous calcium chloride stops gassing altogether. Sensitivity of Torpex is rather high, particularly to bullet impact and therefore an addition of 5 percent of a special desensitizing material is recommended, which makes the resulting material less sensitive than Comp. B. De-gassed and desensitized Torpex is now known as HBX.

Detonation Velocity: 7200 m/sec at 1.70 g/cc density (cast)

MINOL TNT, Ammonium Nitrate and Aluminum

Description: Commonly used is a mixture approximating Torpex but with ammonium nitrate replacing RDX. Both these materials have very high performance, for air blast and water shock, but Minol is much less brizant and therefore does not give as high fragment velocity as Torpex in cased charges. Minol gasses also and the addition of calcium chloride does not solve the difficulty, since reaction appears to occur between ammonium nitrate and aluminum powder.

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Minol is a special case of a class of explosives which are called Ammonal and which, in general, contain less aluminum than Minol.

Detonation Velocity: 5900 m/sec at 1.65 g/cc density.

BARONAL TNT, Barium Nitrate and Aluminum

Description: A slow detonating but powerful mixture which may contain 35 percent by weight of TNT, 50 percent barium nitrate and 15 percent aluminum powder. Cast density up to 2.3 can be obtained.

Detonation Velocity: 5100 m/sec at 2.3 g/cc density.

BARATOL TNT, and Barium Nitrate

Description: A slow detonating and insensitive mixture of TNT and Barium nitrate, containing up to 73 percent of the latter. Cast density of 2.5 can be obtained.

PICATINNY ARSENAL DATA

A Technical Report (Serial No. 1372, Nov. 1943, written by W. R. Tomlinson) from Picatinny Arsenal summarizes a great many numerical data on military explosives as determined in the course of time at Picatinny Arsenal. In some instances those data differ numerically from values quoted on the preceding pages, which is understandable because the conditions of tests, as remarked before, are not generally standardized and the values quoted earlier were obtained from many sources. No attempt will be made to interpret these discrepancies and the P.A. data are reproduced below without further comments. The original report should be consulted for the details of the test procedures which led to the data.

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Table I

Sensitivity to Impact and Friction.

Explosive	Drop Test-2Kg. Wt. Picatinny Machine-inches	Drop Test-2Kg. Wt. Bureau of Mines Machine-cm.	Friction Pendulum Test Steel Shoe	Friction Pendulum Test Fibre Shoe	Rifle Bullet Impact Test-Number of Trials	High Order Detonations	Partial Explosions	Burned	Unaffected
80/20 Amatol	15	89	Unaffected	-	5	0	0	0	5
50/50 Amatol	12	95	-	-	5	0	0	0	5
Ammonal	11	-	-	-	-	-	-	-	-
Cyclonite (RDX)	7	23	Detonates	Unaffected	5a	5	0	0	0
Explosive "D"	17	100	-	-	10a	0	0	3	7
Lead Azide	6	10	-	Detonates	-	-	-	-	-
Mercury Fulminate	2	5	-	-	-	-	-	-	-
PETN	6	17	-	-	5d	5	0	0	0
75/25 Pentolite	-	26	-	-	5	4	0	0	1
50/50 Pentolite	-	34	Unaffected	-	24	18	5	0	2
40/60 Pentolite	-	-	-	-	5	0	2	0	3
30/70 Pentolite	-	40	-	-	5	0	0	0	5
Picric Acid	13	80-85	-	-	5a	0			
RDX Composition B	-	75	Unaffected	-	40	0	7	1	32
RDX Composition C2	-	90	-	-	5b	0	1	0	4
Tetryl	8	26	Unaffected	-	10a	8	1	0	1
80/20 Tetrytol	-	28	-	-	5	0	1	0	4
75/25 Tetrytol	-	28	-	-	5	0	1	0	4
65/35 Tetrytol	-	28	-	-	5	0	0	0	5
Torpex	8	38	-	-	5	1	4	0	0
TNT	14	95-100	Unaffected	-	25	1	0	0	24

a. Pressed at 10,000 psi.

b. Hand pressed, those not labelled a, or b were cast.

c. When packed in paper 7 out of 8 were unaffected and 1 partial explosion was obtained in the Rifle Bullet Impact Test.

d. In the Rifle Bullet Impact Test this sample contained 4.86 percent water.

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Table II

Explosive	Ignition Temperature- 5 Secs., °C.	Stability at Elevated Temperature. 75°C. International Heat Test % Loss in 48 hr.	100°C. Heat Test % Loss 1st 48 hr.	% Loss 2nd 48 hr.	Explosion in 100 hr.	120°C. Heat Test Salmon Pink - min.	Red Fumes - min.	Explosion min.	Vacuum Stability Test cc. of gas evolved in 40 hrs. at 100°C.	120°C.
80/20 Amatol	280	0.06	0.03	0.05	None	-	-	-	-	2.5
50/50 Amatol	265	-	-	-	-	-	-	-	0.2	1.0
Ammonal	265	-	None	0.1	None	-	-	-	-	4.4
Cyclonite(RDX)	260	0.03	0.04	None	None	-	-	-	-	0.5
Explosive "D"	320	-	0.1	0.1	None	-	-	-	0.2	0.4
Lead Azide	330	-	-	-	-	-	-	-	-	0.7
Mercury Fulminate	210	0.18	Explodes in about 40 hr.			-	-	-	-	-
PETN	210	0.02	0.1	None	None	-	-	-	0.5	11 +
75/25 Pentolite	-	-	0.01	0.2	None	-	-	-	-	11 +
50/50 Pentolite	220	-	-	-	-	-	-	-	3.0	11 +
40/60 Pentolite	-	-	-	-	-	-	-	-	-	11 +
30/70 Pentolite	-	-	-	-	-	-	-	-	-	11 +
Picric Acid	320	-	-	-	-	-	-	-	-	0.5
RDX Composition B	270	-	0.2	0.1	None	-	-	-	-	0.7
RDX Composition C2	285	-	1.8	1.4	None	-	-	-	2.0	9.0
Tetryl	260	-	-	-	-	-	-	-	-	3.0
80/20 Tetrytol	-	-	0.1	0.5	None	-	-	-	3.0	11 +
75/25 Tetrytol	-	-	-	-	-	-	-	-	-	11 +
65/35 Tetrytol	-	-	-	-	-	-	-	-	2.8	11 +
Torpex	280	-	None	0.1	None	-	-	-	-	1.0
Trimonite	315	-	-	-	-	-	-	-	-	0.9
TNT	450	0.04	0.2	0.2	None	-	-	-	-	0.4

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Table III

Sand Test, Ballistic Mortar Test, Fragmentation Test.

	200 Gram Bomb Sand Test			Ballistic Mortar Test	Fragmentation Test			
		Sensitivity to Initiation			3" AA, M42, Shell		37 mm., M63, Shell	
Explosive	Brisance-gm. sand	Gm. Mercury Fulminate	Gm. Tetryl	TNT equivalent-percent	Charge Density gm./cc.	Total No. Fragments	Charge Density gm./cc.	Total No. Fragments
80/20 Amatol	32.0	0.24	0.07	117	1.46	460	-	-
60/40 Amatol	37.6	0.24	0.06	-	-	-	-	-
50/50 Amatol	39.0	0.24	0.05	122	-	-	-	-
Ammonal	45.9	0.20	None	122	1.65	550	-	-
Cyclonite(RDX)	58.7	0.19	None	150	-	-	-	-
Explosive "D"	37.5	0.24	0.06	97	1.45	468	-	-
Lead Azide	18.0	-	-	-	-	-	-	-
Mercury Fulminate	22.4	-	-	-	-	-	-	-
PETN	61.9	0.17	None	145	-	-	-	-
75/25 Pentolite	56.5	0.18	None	-	-	-	-	-
50/50 Pentolite	53.0	0.19	None	120	1.70	747	-	-
40/60 Pentolite	51.7	-	-	-	-	-	-	-
30/70 Pentolite	49.2	-	-	-	-	-	-	-
Picric Acid	46.8	0.27	None	108	-	-	-	-
RDX Composition B	51.8	0.22	None	-	1.70	750	-	-
RDX Composition C2	47.5	0.25	0.10	127	-	-	-	-
Tetryl	52.8	0.20	-	121	-	-	1.60	202
65/35 Tetrytol	51.5	0.22	None	-	1.66	765	-	-
Torpex	57.9	0.18	None	132	1.76	534	-	-
TNT	53.0	0.25	None	100	1.59	655	1.44	148

a. Contained 5 percent Wax.

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Table IV

Detonation Rate

	Detonation Rate - meters/sec.						
	Pressed charge density - gm/cc.						
Explosive	0.80	1.20	1.50	1.60	1.65		Cast
80/20 Amatol	-	-	-	-	-	Approx.	4500
60/40 Amatol	-	-	-	-	-	"	5500
50/50 Amatol	-	-	-	-	-	"	5600
Cyclonite(RDX)	5110	6550	7650	8000	8180		-
Explosive "D"	4000	5520	6660	7040	-		-
Lead Azide	-	3620	-	3840	-		-
Mercury Fulminate	-	2910	-	3220	-		-
PETN	4760	6340	7520	7920	-		-
50/50 Pentolite	-	5410	7020	7360	-		7510
Picric Acid	-	5840	6800	-	-		7350
RDX Composition B	-	6360	7200	7480	-		7800
RDX Composition C2	-	-	-	-	-		7660
Tetryl	4730	6110	7160	7510	-		-
TNT	4170	5560	6620	6970	-		6790

	Pressed Charge Density - gm./cc.		
	2.0	3.0	4.0
Lead Azide	4070	4630	5180
Mercury Fulminate	3500	4250	5000

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Charge Density

	Charge Density - gm./cc.							
	Pressure in - 1000 psi.							
Explosive	0	3	5	10	12	15	20	Cast
80/20 Amatol	-	-	-	-	-	-	-	1.46
60/40 Amatol	-	-	-	-	-	-	-	1.61
50/50 Amatol	-	-	-	-	-	-	-	1.59
Cyclonite(RDX)	-	1.455	1.52	1.60	1.63	1.65	1.675	-
Explosive "D"	-	1.33	1.41	1.47	1.485	1.505	1.53	-
Lead Azide	-	2.62	2.71	2.96	-	3.07	-	-
Mercury Fulminate	-	3.00	3.20	3.60	3.67	3.82	3.99	-
75/25 Pentolite	-	-	-	-	-	-	-	1.57
50/50 Pentolite	-	-	-	-	-	-	-	1.59
40/60 Pentolite	-	-	-	-	-	-	-	1.65
30/70 Pentolite	-	-	-	-	-	-	-	1.63
Picric Acid	-	1.40	1.49	1.57	1.59	1.61	1.64	1.71
RDX Composition B	-	-	-	-	-	-	-	1.67
RDX Composition C2	1.57	-	-	-	-	-	-	-
Tetryl	-	1.40	1.47	1.57	1.60	1.63	1.67	-
80/20 Tetrytol	-	-	-	-	-	-	-	1.51
75/25 Tetrytol	-	-	-	-	-	-	-	1.50
65/35 Tetrytol	-	-	-	-	-	-	-	1.60
Torpex	-	-	-	-	-	-	-	1.76
TNT	-	1.34	1.40	1.47	1.49	1.515	1.55	1.58-1.59

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Table VI

Hygroscopicity - Volatility.

Explosive	Hygroscopicity at 30°C., 90 percent Relative Humidity		Volatility		
	Percent Gain in Weight	Time - Days	Percent Loss in Wght.	Temp. - °C.	Time- Days
80/20 Amatol	61.1	2	-	-	-
Cyclonite(RDX)	None	15	-	-	-
Lead Azide	0.3	-	-	-	-
PETN	None	15	-	-	-
RDX Composition B	None	15	-	-	-
RDX Composition C2	0.55	4	1.2	25	5
Tetryl	0.04	-	None	25	-
TNT	None	15	-	-	-

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TABLE VII

Solubility

Solubility - gm. Explosive/100 Gm. Solvent

Solvent	°C.	Cyclonite	Explosive "D"	Lead Azide	Mercury Fulminate	PETN	Picric Acid	Tetryl	TNT	Ammonium Nitrate
Water	0	Insol.	-	Insol.	Insol.	Insol.	0.85	0.0050	0.0100	118
"	20	-	1.1	0.05	-	-	1.17	0.0075	0.0130	192
"	40	-	-	-	-	-	1.88	0.0110	0.0285	297
"	60	-	-	-	-	-	2.98	0.0350	0.0675	421
"	80	Insol.	-	Slightly Sol	-	Insol.	4.53	0.0810	-	580
"	100	-	75.0	-	-	-	7.1	0.1842	-	871
Ethyl alcohol	0	0.040	-	-	-	0.070	4.5	-	-	-
"	20	0.105	Slightly Sol.	-	-	0.195	6.9	-	-	2.5
"	40	0.240	-	-	-	0.415	12.0	-	-	5
"	60	0.579	-	-	-	1.205	-	-	-	7.5
"	78	1.195	-	-	-	-	-	-	-	10.5
95% ethyl	0	-	-	-	-	-	-	-	-	-
alcohol	20	-	-	-	-	-	-	-	-	-
" "	40	-	-	-	-	-	-	-	-	-
" "	60	-	-	-	-	-	-	-	-	-
Acetone	0	4.37	-	-	-	14.37	-	-	57	-
"	20	7.31	-	-	-	24.95	About 130	-	109	-
"	40	11.52	-	-	-	30.56	-	-	228	-
"	60	18.00	-	-	-	42.68	-	-	600	-
Benzene	0	-	-	-	-	0.150	About 2	-	13	-
"	20	0.045	-	-	-	0.450	9.56	-	67	-
"	40	0.085	-	-	-	1.160	27.5	-	180	-
"	60	0.197	-	-	-	3.350	59.0	-	478	-
"	80	0.405	-	-	-	7.900	-	-	Over 2000	-
Toluene	0	0.016	-	-	-	0.150	-	-	28	-
"	20	0.020	-	-	-	0.430	About 13	-	55	-
"	40	0.050	-	-	-	0.620	-	-	130	-
"	60	0.127	-	-	-	2.490	About 30	-	367	-
"	80	0.298	-	-	-	5.850	-	-	Over 1700	-
"	100	0.646	-	-	-	15.920	-	-	-	-
"	112	0.990	-	-	-	30.900	-	-	-	-
Carbon	0	-	-	-	-	-	-	0.007	0.20	-
tetra-	20	-	-	-	-	-	About 0.07	0.015	0.65	-
chloride	40	-	-	-	-	-	-	0.058	1.75	-
" "	60	0.007	-	-	-	-	About 0.4	0.154	6.90	-
" "	70	-	-	-	-	-	-	-	17.34	
" "	75	-	-	-	-	-	-	-	24.35	

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Table VII (Cont'd)

Solubility

Solubility - gm. Explosive/100 Gm. Solvent

Solvent	°C.	Cyclonite	Explosive "D"	Lead Azide	Mercury Fulminate	PETN	Picric Acid	Tetryl	TNT	Ammonium Nitrate
Ether	0	-	-	-	-	0.200	-	0.188	1.73	-
"	20	-	-	-	-	0.340	About 3	0.330	3.29	-
"	34.7	-	-	-	-	0.450	3.96	-	-	-
Ethyl-	0	-	-	-	-	-	-	-	-	-
acetate	20	0.055	-	-	-	-	-	About 40	-	-
"	40	0.090	-	-	-	-	-	-	-	-
Chloroform	0	-	-	-	-	-	-	0.28	6	-
"	20	-	-	-	-	-	About 2	0.39	19	-
"	40	-	-	-	-	-	-	1.20	66	-
"	60	-	-	-	-	-	About 6	2.65	302	-
Ethylene-	25	-	-	-	-	-	-	4.5	-	-
dichloride	75	-	-	-	-	-	-	45.0	-	-
Trichloro-	25	-	-	-	-	-	-	0.15	3.5	-
ethylene	55	-	-	-	-	-	-	0.52	60.0	-

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