

METAFEX COMPOSITES: SAFE, ENERGETIC, ECONOMICAL REPLACEMENTS FOR EXPLOSIVES

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ABSTRACT

Metal-oxidant blends are ordinarily unsuitable as direct replacements for explosives, because the reaction occurs too slowly. Oxide coatings protect metals, preventing or delaying reaction. By contrast, the electrically-activated reactive composites described below are configured as metal fibers or foils in close proximity to oxidants, with continuous electrical paths from one end to the other. By quickly vaporizing the metal component with an electrical pulse, a reactive composite will be activated, and the reaction will occur rapidly.

Called Metafex™ (for metal-fueled explosive replacements), electrically-activated reactive composites are safer, can be environmentally benign, and are lower in cost in materials, manufacturing, and handling than conventional explosives.

Before activation, Metafex composites are inert and non-hazardous. Afterwards, they behave as explosives with approximately three times the energy density as TNT. For a given application, the shape of the pressure pulse can be controlled by the shape of the electrical pulse.

INTRODUCTION

Certain metal-oxidant reactions are much more energetic than explosives, for example, a 50/50 blend of aluminum and water produces 7.9 kJ/gm from the reaction of the two components whereas, for example, TNT has an inherent chemical energy of 4.3 kJ/gm and Composition A-3 has an inherent chemical energy of 5.4 kJ/gm. Metal-oxidant blends such as aluminum and water (not activated by electrical pulses) have been considered unsuitable as direct replacements for explosives, because the reaction occurs too slowly under ordinary conditions.

If the metal component is finely divided and vaporized, the reaction can occur very rapidly, and the blend can be considered as a replacement for conventional explosives. By electrically heating the metal component, uniform heating can be achieved, and the reaction energy can be made significantly greater. For example, with the 50/50 aluminum/water blend mentioned above, the energy will be at least 12.9 kJ/gm (the sum of 7.9 kJ/gm from the chemical reaction and 5.0 kJ/gm, the electrical energy required to vaporize the aluminum).

The term "reactive blend", used above, signifies any reactive mixture of liquid and/or powdered materials. By contrast, the term "reactive composite" signifies a reactive mixture in which the metal component is configured to conduct an electrical current for activation of the mixture.

If a reactive composite is to replace a conventional explosive in an explosive device, the reaction energy must be high, the peak pressure must be greater than approximately 80 kbar, and the work potential must be comparable to or greater than that of the conventional explosive. Analysis with the TIGER and CHEETAH computer programs [Cowperthwaite & Zwisler, 1973] shows that this is indeed the case for typical reactive composites (see Figure 1).

Systems containing reactive composites will be safer, less costly, more environmentally acceptable, and more efficient than conventional systems containing high explosives. Reactive composites will be inert under all environments, and they will not require the special handling that explosives require. Cost savings will also be found in manufacturing devices containing reactive composites in place of explosives.

A system using reactive composites will require pulsed power to activate the reactions. The prime power for such a system can be extracted from the power grid, from an autonomous motor/ generator set on the back of a medium-sized truck, or from the electrical system on a ship. The high power pulses could be created by a pulse forming network (PFN) and/or some form of rotating machinery/flywheel system configured as a trailer or as a palletized device. Capacitive systems could be configured, for example, in sections of drill pipe to operate downhole in oil wells. Small throw-away capacitive PFN's could be designed to initiate conventional explosives for operations where safety is a primary concern.

BACKGROUND

Shidlovskij of the Soviet Union reported tests of aluminum and magnesium powders mixed with water and methyl alcohol initiated with detonators and tetryl boosters [Shidlovskij, 1946]. The samples were large (40 to 100 gm) and heavily confined. The author observed strong reactions in some cases that destroyed his apparatus. He concluded that the mixtures reacted explosively. He made no measurement of pressure. One pair of magnesium/water tests suggested that size could be a factor: a 50 gm sample exploded but a 10 gm sample did not.

Friedman and Ury, 1977, described tests of aluminum and other foils exploded under water used as high-voltage switches. After the aluminum reacted, the reactants no longer conducted current. The authors noted that hydrogen peroxide improved switch performance.

Lee and Ford, April 1988, reported levels of energy deposition of about 2 kJ/gm required to start a reaction with both a 97.5/2.5 aluminum/lithium alloy and a pure aluminum wire exploded under water. As depositions increased, the alloy was more reactive than the unalloyed wire. Reaction for the alloy was 90 percent complete at a deposition level of 4 kJ/gm, but the pure aluminum required about 8 kJ/gm to reach this level of completion.

Lee electrically exploded aluminum wires inside columns of aluminum powder with particles less than 40 microns in size [Lee, 1991; Lee et al., 1993]. He measured pressures as great as 2.5 kbar. Depositions occurred over an interval of 50 μ s or more. In Lee et al., 1993, the authors reported that reactions were less complete when confined. In Lee & Ford, October 1988, the authors preheated aluminum wires alone under water and observed that explosion did not occur until after about 80 μ s of electrical heating. They concluded that a significant level of reaction occurs when the deposition is greater than 3 kJ/gm in the aluminum.

Workers at Eglin AFB exploded one to three aluminum wires embedded in aluminum/ water slurries to stimulate the reaction between the aluminum and the water [Matyac, 1997]. They were unable to heat the 40-micron aluminum particles enough by this process to cause detonation.

In a survey paper, Cho et al., 1994, reported the outcomes of several studies of metal/ water reactions. They noted that a small detonator could trigger a metal/water explosion that would not occur otherwise. A 95/5 aluminum/lithium alloy was found to react at about 660 °C, but reactions with pure aluminum did not occur until the metal temperature was between 930 and 1565 °C.

Tao et al., 1989, reported tests of 38, 51, and 76 micron diameter aluminum wires electrically heated (quickly) under water and observed with a streak camera. The wires developed a vapor sheath around themselves at early time that expanded, then collapsed, stimulating a reaction in some cases. Deposition levels ranged from 0.2 to 9.4 kJ/gm. At the higher levels, violent reactions occurred, but they could not be characterized as explosions. The reactions occurred after the wires had expanded; the geometric symmetry of the tests precluded immediate reactions. The authors did not obtain reliable measurements of pressure.

Theofanous et al., 1994, described tests of aluminum droplets in water that showed reactions above 1400 °C but none below. They noted other work that cited a threshold of 1150 °K for large scale tests.

In summary, other workers have been unable to cause an immediate explosion or detonation of an aluminum/water reaction. Some have observed reactions that have gone to near-completion, but the times to completion have been at least a few tens of microseconds, much longer than the reaction times for the devices we propose (below). In the prior work cited above, which focused on other goals, no one demonstrated pressures in excess of a few kilobars. The pressures will be almost two orders of magnitude higher if the reaction time is reduced to a few microseconds.

Torreyson et al., 1994, reported detonation of mixtures containing mainly aluminum particles and hydroxyl ammonium nitrate (HAN). The aluminum content was between 20 and 28% by weight, and the particle size averaged approximately 8 microns. The HAN was stabilized with 10% ethyl ammonium nitrate. Each mixture contained 16% polyvinyl alcohol, added at the last moment to cause solidification. The critical diameter for

detonation was approximately two inches (5 cm), a large value, suggesting that the mixtures were difficult to initiate and relatively safe. Similar formulations without aluminum particles did not detonate.

ANALYSIS WITH THERMOCHEMICAL EQUILIBRIUM CODES

If a reactive composite is to replace a conventional explosive, (1) the reaction energy must be high, (2) the peak pressure must be greater than approximately 80 kbar, and (3) the work potential at a relative volume of 10 to 40 must be comparable to or greater than that of the conventional explosive. Analysis with the TIGER and CHEETAH thermochemical equilibrium computer programs shows that this is the case for typical reactive composites (see Figure 1 and Table 1). Figure 1 also illustrates the capability of reactive composites to continue accelerating surrounding media at large expansions.

Peroxide (H_2O_2) improves the performance, but it may not be a good choice because it will be unstable in long-term storage. The methanol (CH_3OH) composite was included because of its ability to retard freezing at low temperature and because of its ability to increase gas volumes with methane and carbon oxides. The aluminum/HAN values show that inorganic oxidants may have good potential. Many more metal/oxidant combinations should be examined to determine which ones best suit the environmental and performance requirements.

The fourth entry in Table 1 is the case of aluminum and water heated to approximately 1100 °K, just below the reaction temperature, then shock-initiated to create a detonation front. The ratio (work at $V/V_0 = 10$ or $V/V_0 = 40$)/(energy deposition), a measure of system efficiency, is about twice as great for this process as it is for a simple explosion.

CONCEPT

Rapid activation can be achieved by exploding fine aluminum wires embedded in an oxidant (Figure 2). The diameters of wires expand very rapidly as a result of an electrical energy deposition sufficient to vaporize them. Rapid mixing of the metal and the oxidant will occur as a result. The theoretical pressure will be reached if the reaction occurs quickly enough, i.e., before rarefaction waves arrive from the surface. We estimate that a mixing time of 2 μs or less will be required for a 30 gm sample. Pulsed power devices are able to explode the metal component of our devices and to activate them in such short intervals.

To confirm that aluminum heated with an electrical pulse would expand and rapidly mix with the surrounding water, we made an AUTODYN 2D [Birnbaum et al., 1987] calculation simulating an array of 14-micron diameter (conservatively large) wires under water representing an aluminum/water composite, electrically heated to 5 kJ/gm at a constant rate over a 0.1 μs interval. The calculation included no effects of chemical reactions between the constituents.

The aluminum moved a significant distance (about one-tenth the wire diameter) in a very short time (100 ns or 0.1 μs). Although this analysis does not prove that mixing will occur in a short time, it does suggest near-

optimum conditions for the process. Magnetohydrodynamic instabilities are expected to enhance the mixing of the aluminum vapor with the water.

The pressure reached 6 kbar in the aluminum as a result of the electrical heating alone (no reactions). In this analysis the pressure reached equilibrium very quickly, so the values are typical of an entire test sample. The pressure was a linear function of the energy deposition. Note that this analysis typifies material inside a sample. At the edges, the reactants will expand to regions with lower pressures.

Practical configurations with liquid oxidants (such as water) are possible if wires are wrapped with threads or foils stacked alternatively with fabrics to keep the windings or layers separated. The fluid oxidant is then introduced by capillary action. Solid oxidants can be sprayed onto the wires or foils prior to assembly or embedded in polymer films.

Lee et al. activated part of a surrounding slurry of aluminum particles, but they were unable to cause a detonation. They did not attempt to pass the electrical pulse through the reactants. Their particles were somewhat larger than the filaments or foils that we propose to test. The authors speculated that aluminum/water reactions were suppressed by pressurization when confined. We believe, to the contrary, that the reactions were more complete in the tests that were less confined because venting mixed the constituents better in these tests.

Some workers, such as Tao et al., have observed water or hydrogen vapor layers around exploded wires that isolated the reactants from one another. Such layers are victims of symmetry and would not be present for the practical devices that we contemplate.

The Tao et al. paper included a graph of resistivity in aluminum as a function of energy deposition. At 10 kJ/gm the resistivity was more than a hundred times greater than it was under ambient conditions. This data suggests that the electrically-activated reactive composites will be heated uniformly: as parts heat up they become more resistive, thereby shunting the current into cooler, less resistive regions.

VALIDATION

Figure 3 illustrates a test setup for evaluating electrically-activated reactive composites. Samples will be placed in cavities drilled in polymethylmethacrylate (PMMA) blocks and will be activated with electrodes placed on both ends. PMMA is well-characterized at high pressures. The time-of-arrival at the composite/PMMA interface will be obtained by extrapolation from the data. Figure 4 is a drawing of a typical test sample.

COMPUTER STUDIES OF EFFECTS AND PROTOTYPES

Prototypes for devices used for blasting, tunneling, or initiation could be built and tested without additional studies, but more data will be needed for computer studies of effects or for the design of shaped charges. In particular, the equation of state (relationship between volume and energy), estimated with chemical equilibrium codes such as TIGER or CHEETAH, should be derived from experiments similar to the cylinder tests used for conventional explosives.

Figure 5 is a diagram of a prototype tunneling charge. Note that the tunneling charge is activated from one end whereas the test sample of Figure 4 is activated from both ends. Demolition charges could also be configured with spiral-wrapped foils, similar to the tunneling charge.

The capacitive discharge unit (power unit) that activates a reactive composite stores electrical energy in capacitors. The volume of the power unit must be about a thousand times the volume of the electrically-activated reactive composite. This makes the reactive composite technology impractical for replacement of large bulk charges such as those used in bench mining. Operations can be made safer, however, by replacing the sensitive-explosive-filled initiator with one using a reactive-composite initiator activated by a small power unit. A power unit with dimensions ten times the dimensions of the initiator will have a thousand times its volume. The power unit will be small because the initiator is very small.

Figure 6 shows a conventional and an electrically-activated shaped charge. The liner for the electrically-activated device must be able to properly form a jet under conditions that are somewhat different than for shaped charges containing conventional explosives. The reactive composite in this case is configured as a ropelike bundle of coated fibers wound around the liner. Current flows between the cable's central conductor and the casing, initially through the reactive composite and later through the liner. The insert carries electrical current between the liner and the casing for added effect after activation of the composite.

CONCLUSIONS

Electrically-activated reactive composites are potentially a safe, energetic, environmentally-benign alternatives to conventional explosives. Tests of activation on short intervals ($t \approx 2 \mu\text{s}$) will confirm the high pressures ($P \geq 80 \text{ kbar}$) predicted by the analysis. Reactive composites for shaped charge applications will require additional tests for characterization of the equation of state to be used in design studies.

Practical devices will contain filaments, foils, or sintered particles with dimensions of approximately 10 microns. They will be activated by electrical pulses produced by capacitors or by generators driven by rapidly rotating devices.

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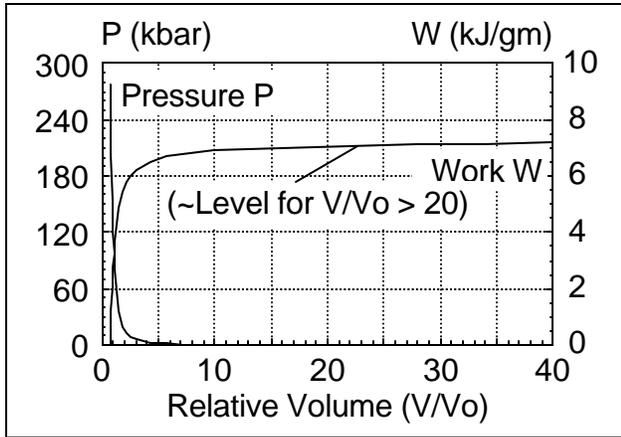
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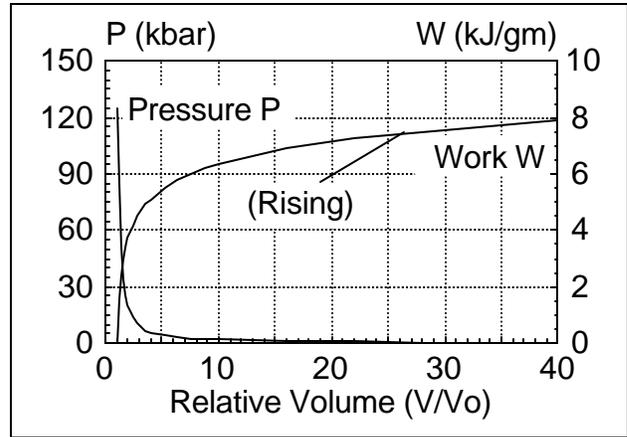
Table 1. TIGER and CHEETAH calculations. Composites included aluminum/water (Al/H₂O), magnesium/water (Mg/H₂O), aluminum/water/peroxide (Al/H₂O/H₂O₂), zirconium/water (Zr/ H₂O), aluminum/water/ methanol (Al/H₂O/CH₃OH), and aluminum/hydroxyl ammonium nitrate (Al/HAN). The work for an expansion of ten times the initial volume (V/V₀ = 10) is a measure of the potential of shaped charges containing Composition A-3 (and similar explosives) or reactive composites. The work for an expansion of forty times the initial volume (V/V₀ = 40) is a measure of the potential of bulk charges.

Composites (Percentages Are by Weight)	Reactant Density (gm/cm ³)	Energy Deposition (kJ/gm)	Net Energy/Mass (kJ/gm)	Net Energy/Volume (kJ/cm ³)	Type of Reaction	Peak Pressure (kbar)	Temperature at Peak (°K)	Work (kJ/gm) at V/V ₀ = 10	Work (kJ/gm) at V/V ₀ = 40
Composition A-3	1.65	-	5.4	8.9	Det.	278	2730	6.8	7.2
50/50 Al/H ₂ O	1.46	5.0*	12.9	18.8	Expl.	113	5200	5.0	6.1
50/50 Al/H ₂ O	1.46	10.0	17.9	26.1	Expl.	143	6640	6.4	7.9
50/50 Al/H ₂ O	1.46	2.5	10.4	15.2	Det.	134	5050	5.3	6.2
57/43 Mg/H ₂ O	1.32	5.7	12.5	16.5	Expl.	61	6250	4.7	5.7
34/23/43 Al/H ₂ O/H ₂ O ₂	1.51	3.4*	9.4	14.2	Expl.	137	6290	5.7	6.8
72/28 Zr/H ₂ O	2.54	7.2	11.7	29.7	Expl.	85	8280	3.7	4.8
35/23/42 Al/H ₂ O/CH ₃ OH	1.28	3.5*	10.3	13.2	Expl.	81	4110	4.7	5.7
43/57 Al/HAN	2.13	4.3*	11.0	23.4	Expl.	172	6400	6.0	7.0

*10 kJ/gm in the aluminum, close to its burst energy.



Composition A-3



Typical Reactive Composite

Figure 1. Pressures and work potentials for an explosive and a typical reactive composite. The work curve for the conventional explosive leveled off for $V/V_0 \geq 20$, and the surrounding material is "coasting." For the reactive composite, the work curve is still rising with $V/V_0 = 40$, and the surrounding material is still being accelerated.

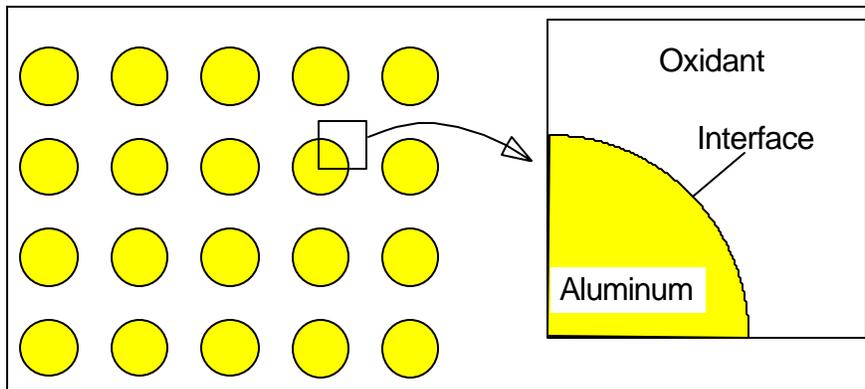


Figure 2. Parallel-wire analogy. Activation will occur rapidly with such a configuration or one with parallel foils in place of the wires. To facilitate the mixing and the transfer of heat from the metal to the oxidant, diameters of wires or thicknesses of foils will be approximately 10μ .

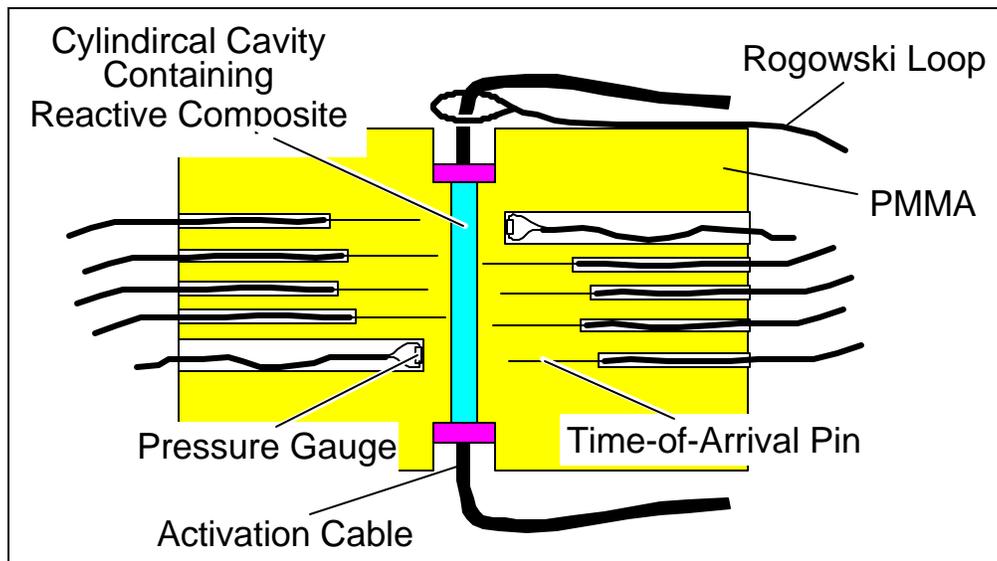


Figure 3. Test setup. The reactive composites will be placed in cavities drilled in PMMA blocks. PMMA is a clear, well-characterized plastic. The tests will measure shock motion with time-of-arrival pins and will measure pressures with carbon resistor gauges. The tests will also measure electrical pulse voltages and currents. The Rogowski loop measures electrical currents.

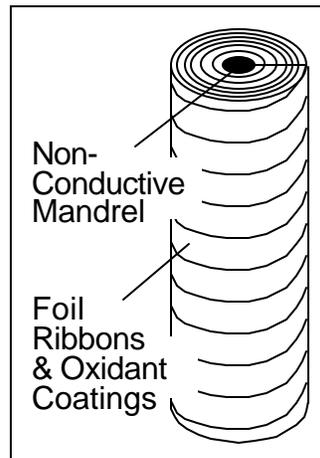


Figure 4. Typical test sample with a continuous electrical path from end to end, and. To meet an expected requirement for reduced effective cross-sectional area, foils will be folded or wound around a mandrel. This example shows many layers of thin foil ribbons, separated by layers of oxidant, wrapped helically around a non-conductive mandrel. The oxidant could be sprayed on the ribbons before winding; layers could also be separated by fabric impregnated with oxidants or by polymer films encapsulating oxidants. Rope-like bundles of metal fibers could replace the foil ribbons. Individual turns of the helical windings will be insulated from one another to avoid arcing.

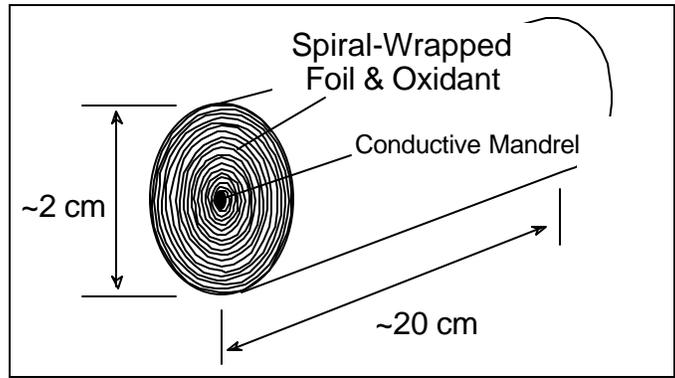


Figure 5. Tunneling charge. Electrical leads will be attached to the conductive mandrel and to the outer surface. Electrically-activated bulk charges can be placed in cavities with tamping to spall material from rock surfaces. They will be safer and much more energetic than conventional bulk charges.

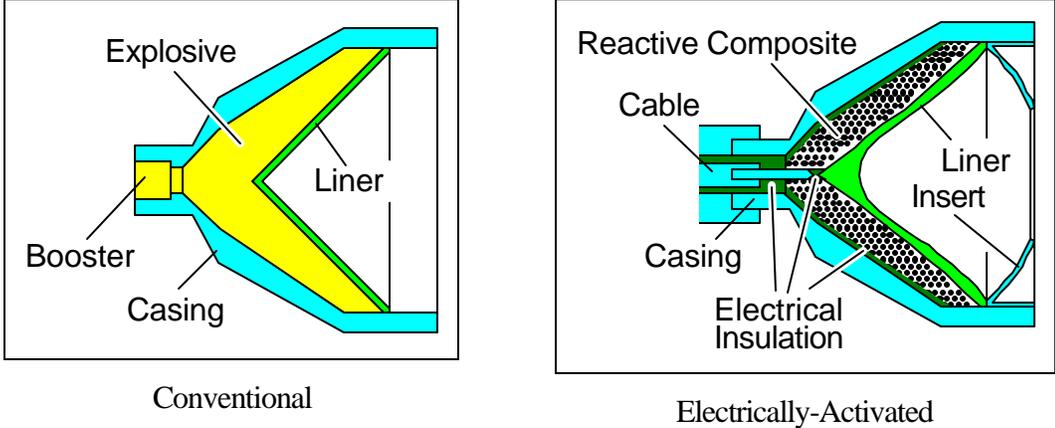


Figure 6. Conventional and electrically-activated shaped charges.