Energetic Materials;

What are they?

Bruce Cranford, P.E., F. AIChE

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Abstract:
The formation of the Energetic Materials Group focused on many issues involving the science and engineering of energetic materials. One unresolved issue was the meaning of "energetic materials." This paper attempts to identify a rational for defining the category of Energetic Materials. The paper first reviews the categories of energetic materials identified in the literature, addressing the advantages and disadvantages of each. Based upon the results of the analysis, a concise definition of Energetic Materials is be proposed.

1 Introduction

What is an energetic material? If you ask 10 professionals, you will get 12 opinions with an exothermic discussion. Depending on your definition of energetic materials, the history can go back to China 1000 years ago (e.g. black power) or early Greek Civilization (Greek Fire), over 2500 years ago.

The formation of the Energetic Materials Group within the Particle Technology Forum of the American Institute of Chemical Engineers focused on many issues involving the science and engineering of energetic materials. One unresolved issue was the meaning of “energetic materials.”

This paper attempts to identify a rational for defining the category of Energetic Materials. This paper draws attention to the characteristics of materials qualifying them to be considered Energetic Materials. A review of the literature and the internet reveals the following definitions of energetic materials, see Figure 1, Definition of Energetic Materials.

The most common energetic materials are listed in the Appendix 1, Table 1: Energetic Materials. A comprehensive list of all energetic materials, however is beyond the scope of this paper.

The paper first reviews the categories of energetic materials identified in the literature, and then addresses the advantages and disadvantages of each.

2 Categories

Many categorization methodologies were identified in the literature. They included categorization based upon function, composition, class of chemicals, physical properties, and forces.

2.1 Function

Attempts to date have used the definition of materials by function, e.g., explosives, propellants, pyrotechnics, batteries, bio processes, high energy mixtures. The drawback with these terms is they are vaguely defined and may vary from one author to the next. Official definitions gleaned from several sources are shown in Figure 2, Definitions, explosive, propellant, propellent, pyrotechnics, etc.

Many energetic materials can be considered

- Energetic materials are a class of materials with high amount of stored chemical energy that can be released.(Wikipedia)
- The term energetic material is used to describe any material which can react to release energy. The category of energetic material is extremely broad and includes everything from common fuels used to power automobiles such as gasoline, and diesel, all the way up to high explosives such as gun-powder, dynamite, and TNT.(University of Missouri)
- Energetic materials include but are not limited too energetic reactions, explosives, propellants, and pyrotechnics.(Energetic Materials)

Figure 1 Definition of Energetic Materials

Burn - Subsonic oxidation, thermal transfer. (Cooper)

Deflagration - Subsonic oxidation, thermal transfer. (Cooper)

Detonation - Supersonic chemical reaction, shock wave. (Cooper)

Explosive - Tending to explode. (Neufeld, Stein) (NB Not much help).
- A violent expansion or bursting with noise. (Stein)
- A release of mechanical, chemical, or nuclear energy in a sudden and often violent manner with the generation of high temperature and usually with the release of gases.(Answer.com)
- “...wide range of energetic materials that can react chemically to produce heat, light, and gas.(Cooper)
  - High explosives: Chemicals that detonate.
    - Primary, can detonate easily.
    - secondary, more difficult to detonate, do not easily fo from burning (deflagration) to detonation.
    - tertiary, most difficult to detonate, insensitive high explosive.
  - Low explosives, pyrotechnics, propellants, blasting agents, cannot be caused to detonate by meas of a common blasting cap.
- Achieved by:(Cooper)
  - bursting a vessel containing a pressurized fluid.
  - rapid heating of air and plasma by an electric arc.
  - Very fast burning reaction.
  - detonating an explosive.
- Derived from the Latin word *explōdere*, “to drive out by clapping”.(Answer.com)

Fireworks - Pyrotechnics intended for amusement, public entertainment or artistic purposes(Conkling)

Propellant - A propelling agent (Stein). (NB Not much help).
- The explosive charge that propels a projectile from a gun.(Neufeld)
- Produces gases used to perform mechanical work.(Cooper)
- from “L. propellere "push forward," from pro- "forward" + pellere "to push, drive." Meaning "to drive onward."(Etymology on line)
- Mixtures of chemicals that produce large volumes of high temperature gas at controlled, predetermined rates.(Kirk-Othmer)
- Categories include:
  - Mono propellant, single compound (internal oxidation)
  - Heterogeneous mixtures
    - double base
    - elastomer-modified composite double base
    - composites
    - composite-modified double base
  - Solid
  - Liquid

Propellent - Propelling or tending to propel.(Stein, Neufeld)

Pyrotechnics - The art of making and using fireworks.(Neufeld)
- Dazzling display, as of eloquence, wit, virtuosity.(Newfeld)
- The area of technology that deals with the application of self-contained and self-sustained exothermic chemical reactions of solids to produce heat, sound, smoke, motion, combinations of these, and/or useful reaction products.(Conkling)
- Derived from the french *pyrotechnique*, which is derived from the Greek word *pyr* for fire, and *technē* for art.(Newfeld)

Figure 2 Definitions, explosive, propellant, propellent, pyrotechnics, etc.

an explosive and a propellant and a pyrotechnic. An example is black powder which is used for all three purposes. Black powders used in pyrotechnics, are also used as a propellant to propel the pyrotechnic charge into the air, where additional black powder explodes providing, sound, light, and smell. Numerous examples exist of black powders intended use being that of a propellant, malfunctions, and acts as an explosive!

2.2 Composition

The literature provides examples of energetic materials defined by composition. Energetic materials are composed of the same star dust as the human body, and Mount Everest! The historical classification of materials falls into two groupings, the Greek Elements (or variations thereof) and the Periodic Table.

2.2.1 Greek Elements

Energetic material composition can be based upon the four Greek elements, earth, wind, fire, and water. The Japanese, Chinese, Hindus and Buddhist all have similar elements. All the energetic materials can be considered fire which produces wind and comes from the earth. Not much help.

2.2.2 Periodic Table

Modern science uses the periodic table to identify and classify all the elements. All energetic and non energetic materials are composed of the same elements. Not much help in defining energetic materials.

2.3 Class of Chemicals

Chemists, chemical engineers, and other scientists have spent years developing names and naming metrologies for various class of chemicals based upon the chemical structure or function. Examples include Inorganic oxidizers, cyclic aliphatic, and azides. The chemical structure of energetic materials is not unique to any one class.

Consequently, class of chemicals is not useful in segregating energetic materials from non energetic materials.

2.4 Physical Property

Categorization by physical properties does not help either. A given chemical may be a solid, a liquid, or a gas[1], depending on the manufacturing processes, additives, or temperature. All matter falls into one of these categories. Many other physical properties are used to identify and classify materials, including the size of the solids, (e.g., nano particles), flow properties of the liquids and gases (rheology), physical tests (United Nations System, 27 CFR 55, numerous federal regulations, and tests to determine sensitivity and performance).

2.5 Forces

In reviewing the literature, it becomes evident that categorization by forces may add some insight and provide some assistance in defining energetic materials. The four forces found in nature are gravity, electromagnetic, strong interaction and weak interaction.[2] See Figure 3, Energetic Materials Flow Chart. The approach discussed in this paper defines energetic material through the four known forces.

Energetic Materials

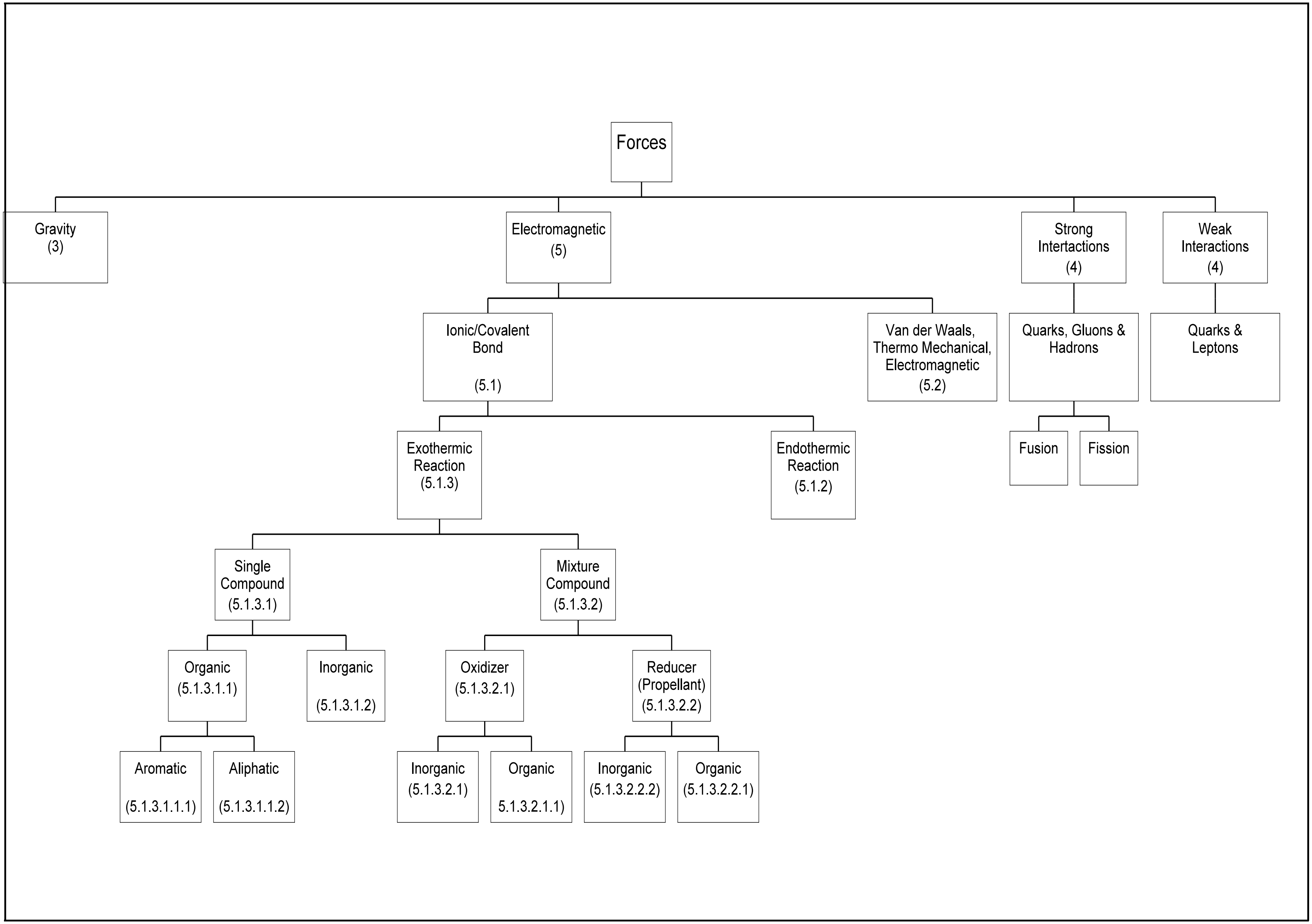

Figure 3 Energetic Materials Flow Chart

3 Gravity:

Gravity acts on all matter. Gravity acts equally on non-energetic materials as well as energetic materials. A pound of lead weights as much as a pound of HMX. The force of gravity does not help in defining energetic materials.

4 Strong and Weak interactions:

The strong and weak interaction forces act on the atomic nucleus and sub atomic particles of energetic and non energetic materials, alike. The unleashing of these forces produces very large amounts of energy, e.g., nuclear fusion, fission. Conventional chemical reactions are capable of releasing up to 10^3 J/g where nuclear fission can release up to 10^{11} J/g, eight orders of magnitude greater than chemicals. However, all atoms contain a nucleus and sub atomic particles. If the strong and weak interactions are included, than all matter can be considered energetic materials. The Strong and Weak interactions are not much help in defining energetic materials vs. non energetic materials.

5 Electromagnetic:

The electromagnetic force also acts on all the elements of the periodic table and all chemicals, but not equally. Individual atoms are attracted to other atoms by the electromagnetic forces. This is described through the concept of Ionic, Covalent, and Van Der Waals[3] bonds. Ionic and Covalent bonds are involved in chemical reactions. Chemical reactions can involve the combining and/or disassociation of chemicals. The covalent bond is typically stronger than the ionic bond which is stronger than Van der Waals forces. Van der Waals bonds are so weak, they are not typically involved in chemical reactions. The following discussion is keyed to Figure 3, Energetic Materials Flow Chart.

5.1 Electromagnetic, Ionic and covalent bond:

The ionic and covalent bond is examined first. The ionic and covalent bonds determine how atoms bond to each other, forming chemicals. The Ionic and covalent bonds are also known as electronic transfer, oxidation/reduction reaction, see Figure 4 Chemical Bonds.

Covalent bond;	Valence electrons are shared by atoms in a molecule. This is also known as electron pair bonding. The greater the attraction between atoms in a molecule, the closer the atoms are to each other and the greater the energy required to break the bond and the greater the energy release when the bonds are broken. Also, the number of electron pairs involved in a bond influence the bond energy. A single pair (single bond) contains less energy that a double bond which contains less energy then a triple bond. E.g. A single bond between two carbon atoms, represented by C-C is 80.5 kcal/mole, where the triple bond $C \equiv C$ is 195 kcal/mole. Covalent bonds are typically stronger than ionic bonds but the bonds between molecules are typically weaker than ionic bonds.
Ionic bond;	Valence electrons are transferred by one atom to another atom. Now the atoms have an unbalanced charge and are attracted to each other by electromagnetic forces. The first step of the reaction, removing an electron from an atom, creates a positively charged ion and requires energy. The second step is when that electron is attracted to the other atom forming a negatively charged ion, releasing energy. The third step is when the negatively charged ion is attracted to the positively charged ion, releasing additional energy, and forming a molecule. The energy needed for step one is less that the energy released by steps tow and three. The energy in step one is known as ionization potential. Ionic bonds are typically weaker than covalent bonds, by the bonds between molecules are typically stronger than covalent.
Van der Walls bonds:	Attraction between molecules, which do not play a significant role in the formation of molecules.

Figure 4, Chemical Bonds

5.1.A Electromagnetic, Ionic and covalent bond, Energy Release

In order to understand energy release, one should understand the laws of thermodynamics. See Figure 5, Laws of Thermodynamics.

Zeroth Law ≡ Two systems in thermal equilibrium with a third are in thermal equilibrium with each other.

First Law ≡ Internal Energy of systems (ΔU) is the heat absorbed by the system (q) minus the work done by the system (w) on its surroundings,
$\Delta U \equiv q - w$

Second Law ≡ Entropy (S) of the Universe increases or in isolated systems processes for which the entropy change is negative are not spontaneous.

Third Law ≡ Entropy of a perfectly ordered system is zero.

Figure 5 Laws of Thermodynamics

From these laws we get the following relations applicable to chemical thermodynamics and Energetic Materials.

- Enthalpy (H), Figure 6
- Entropy (S), Figure 7
- State Variables, Figure 8
- Ideal Gas Law, Figure 9
- Gibbs Energy (G), Figure 10
- Helmholtz (A), Figure 11.

The word Enthalpy is derived from the Greek *Enthálpein*, to heat[Stein]. It is also known as the heat of reaction, heat of formation. Enthalpy can be expressed as joules per mole or kilo joules per mole (kJ/mole), kilo calories per gram (kcal/g) or kilo joules/kilogram (kJ/kg).

Figure **6** Enthalpy (H)

Entropy is from the German *Tropē*, turning toward.[Neufeld] The greater the disorder, the greater the Entropy Term. In general the Entropy of a solid is less than a liquid which is less than a gas.

Figure **8** Entropy (S)

<u>State Variables</u>

Density (ρ)
Energy (E)
Enthalpy (H)
Entropy (S)
Gibbs (G)
Helmholtz (A)
Internal energy (U)
Mass (m)
Pressure (p)
Temperature (T)
Volume (V)

Figure **7**, State Variables

Ideal Gas Law

$$pV = nRT$$

n = number of moles
R = Universal gas constant = 8.3145 J/mol K

Figure 9 Ideal Gas Law

Gibbs Energy:- Maximum useful work (excluding PV work associated with volume changes of the system) that a system can do on the surroundings when the process occurs reversibly at constant temperature and pressure(Thermodynamics of Chemical Equilibrium)

- Energy of a system that is free to do work at constant T, and p.(Chemical Thermodynamics)

$$G \equiv H - TS = U + pV - TS$$

$G \equiv$ Gibbs Energy (T & p = constant)
$H \equiv$ Enthalpy
$p \equiv$ pressure
$S \equiv$ Entropy
$T \equiv$ Temperature (absolute ˚K or ˚R).
$U \equiv$ Internal Energy
$V \equiv$ Volume

Figure **10** Gibbs Energy (G) Equation

Helmholtz Energy:- Maximum amount of work a system can do a constant T and V.(MIT)

$$A \equiv U - TS$$

$A \equiv$ Helmholtz Energy (T, V = constant)

Figure 11 Helmholtz (A) Energy Equation

From the analysis of these relations we get the following that apply to Energetic Materials:
- Spontaneous Reaction Definition, Figure 12
- Spontaneous Reactions, Figure 13, which represent the direction a reaction will precede to equilibrium.
- Spontaneous Reactions table, Figure 14.

Spontaneous Reactions: - Process will precede to equilibrium once it has started.(Journal of Pyrotechnics)

Figure **12** Definition of Spontaneous Reaction

Enthalpy Change (dH or ΔH)	**Entorpy Change (dS or ΔS)**	**Spontaneous Reaction (dG or ΔG)**
Exothermic ($dH < 0$)	Increase ($dS > 0$)	Yes $dG < 0$
Exothermic ($dH < 0$)	Decrease ($dS < 0$)	Only at low temperatures if $\lvert TdS \rvert < \lvert dH \rvert$
Endothermic ($dH > 0$)	Increase ($dS > 0$)	Only at high temperatures if $\lvert TdS \rvert > \lvert dH \rvert$
Endothermic ($dH > 0$)	Decrease ($dS < 0$)	No $dG > 0$

Figure **14** Spontaneous reaction table(Chemical Thermodynamics)

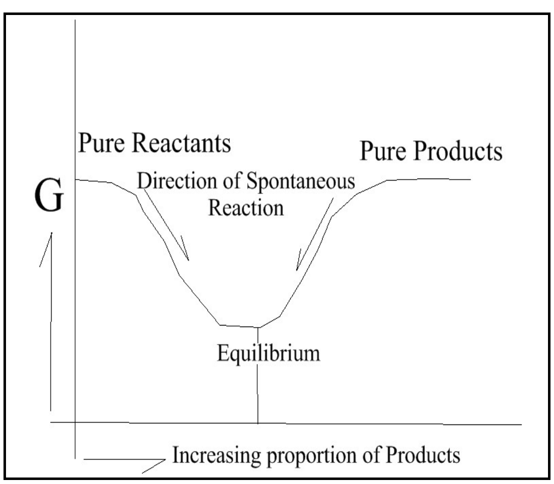

Figure 13 Spontaneous reactions (Chemical Thermodynamics)

When atoms form bonds, becoming molecules, the bonds either absorb energy or release energy in the process, E.g., endothermic or exothermic.

G is composed of two types of energy, Enthalpy and Entropy. Enthalpy (H) is the heat content, Figure 6 Enthalpy. If the Enthalpy is negative, then the reaction is exothermic. If the Enthalpy is positive, then the reaction is endothermic. Chemical reactions can be complex processes. In a chemical reaction where two or more chemicals react, part of the reaction may be endothermic, part may be exothermic.

The reaction must be started using an additional energy source, some type of initiation. This is defined as the “activation energy”, Figure 15, Definition Activation Energy. The chemical bonds of the original compound(s) must be broken before they are free to react with other compounds to form new chemicals. See Figure 16, Activation Energy. Some compounds have low activation energies at ambient conditions and decomposes or age at these conditions.

Typical energy generation per gram of an energetic material compound is about 2 to 9 kJ/g (.... kcal/g)

Definition of Activation Energy:- Energy applied to initiate the reaction.[Journal of Pyrotechnics]

Figure **15** Definition Activation Energy

5.1.B Electromagnetic, Ionic and covalent bond, Reaction Rate

A physical property of the exothermic compound that is important is the reaction rate. The faster the reaction rate, the more energy and gases are liberated per unit of time, see Figure 17 Thermodynamic Mechanisms.

Of interest is the bulk reaction rate of large quantities of the compound(s). The reaction rates vary greatly in absolute value as well as different terminology. Slow reaction rates are fractions of a mm (or inch) per second. Fast reaction rates can be more than 10 km/sec (21,000 miles/h), about nine orders of magnitude. E.g., (Potassium Dichromate, Boron & Silicon mixture) reaction rates are as slow as 1.7 mm/sec [Journal of Pyrotechnics] (0.06 in/sec)(1.7×10^{-6} km/sec) where CL-20 is more than 10 km/sec[Teipel] (21,000 miles/h). Terms like aging, rotting and fermentation are used to describe very slow reaction rates. As the reaction rates increase, terms used to describe them include burning, sub sonic[4] combustion and deflagration. As reaction rates increase into the supersonic region, terms like detonation and explosion, and supersonic combustion are used to describe them. Additional descriptions are used in very narrow fields of specializations. No hard rules determine the burn rate with descriptive terms. Of course, terms like “Oh s..t” can describe many types of reaction rates.

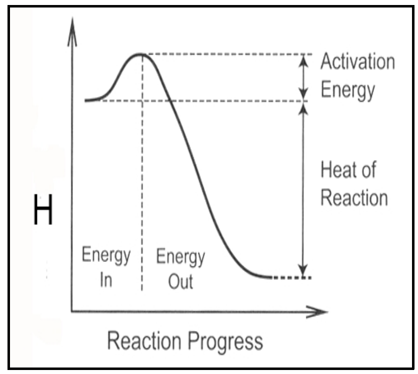

Figure 16 Activation Energy[Journal of Pyrotechnics]

Thermodynamic Mechanisms that affect reaction rates:
- Conduction
- Convection
- Radiation

Figure **17** Thermodynamic Mechanisms

Typically the reaction rate of a gas is faster than the reaction rate of a liquid which is faster than the reaction rate of a solid. As an example, in the space shuttle, there is no reaction of a solid propellant in its solid form. However, when the solid propellant is heated to a liquid/gas state, the reaction rate is very fast and is called combustion. During combustion, the components actually disassociate and recombine. Further discussion is provided in the discussion of specific categories of energy materials below.

Many properties affect the reaction/burning/decomposition rates, including chemical composition/formulation, pressure, density, diameters, particle size, mixing, additives, bulk temperature, grain geometry, ignition technique and physical state of the chemical/mixture to name a few.

In mixture compounds, one or more of the chemicals may be endothermic, but the bulk reaction must be exothermic. Also, the chemical/mixture must sustain itself until completion.

Typical operating pressures vary but rage between 500 psi (3 MPa) to about 100,000 psi (689 MPa). Gas volume generation varies from 13 cm^3/g to over 1,000 cm^3/g.

5.1.C Electromagnetic, Ionic and covalent bond, Combustion temperature:

Combustion temperatures vary from ambient temperatures to approaching 4000˚K (6800˚F, 3763˚C, 7264 ˚R) for some NC/NG formulations(Teipel). HMX flame temperature is 3255 ˚K (3018˚C, 5464˚F). Fluorine and Hydrogen combustion temperatures may reach 4700˚K (4463˚C, 8065˚F). When temperatures reach more than 3550˚K (3313˚C, 6000˚F), combustion product disassociation may play a significant role.

5.1.2 Electromagnetic, Ionic and covalent bond, Endothermic:

Endothermic reactions require energy to form chemical bonds, or require energy to break the chemical bonds. See figure 18, Endothermic Reaction, decomposition of Potassium perchlorate

$$KClO_4 + energy_1 \downarrow \rightarrow K + Cl + 2 \bullet O_2$$
$$energy_1 \text{ (change in Enthalpy)} = 430 \text{ kJ/mole}$$

Figure **18** Endothermic Reaction, decomposition of Potassium perchlorate

Potassium perchlorate requires 430 kJ/mole of energy in order for it to dissociate. This energy must come from another source[5].

5.1.3 Electromagnetic, Ionic and covalent bond, Exothermic:

Some chemicals combine or disassociate exothermically, producing heat and simpler compounds, e.g., CO_2, H_2O, N_2, C. The combustion of aluminum with potassium perchlorate liberates 6725 kJ/mole in the form of heat, increased pressure and/or increased volume of gases of potassium chloride and aluminum oxide, and any other material in contact with these reaction products, e.g., air is a good example. See Figure 19, Exothermic Reaction, potassium perchlorate plus aluminum.

$$3 \bullet KClO_4 + energy_1 \downarrow + 8 \bullet Al \rightarrow 3\ KCL + 4 \bullet Al_2O_3 + energy_2 \uparrow$$
$$3 \times energy_1 \text{ (430 kJ/mole)} + energy_2 \text{ (} 3 \times (-437 \text{ kJ/mole}) + 4 \times (-1676 \text{ kJ/mole})) = -6725 \text{ kJ/mole}$$

Figure **19** Exothermic Reaction, potassium perchlorate plus aluminum (Journal of Pyrotechnics)

Four types of reactions are possible:
1) disassociation (endothermic) →recombination (exothermic)
2) disassociation (exothermic) →recombination (exothermic)
3) disassociation (endothermic) →recombination (endothermic)
4) disassociation (exothermic) →recombination (endothermic)

Two types of reactions occur, those involving a single molecule (single compounds) and those involving the interaction of different molecules (mixture compounds).

5.1.3.1 Electromagnetic, Ionic and covalent bond, Exothermic, Single Compound:

In the single compound category, all the components are contained within one molecule for a chemical reaction. Typically, a small amount of energy (known as activation energy) shown as $energy_1$ is applied to the molecule which starts the disassociation. The intra molecular chemical bonds are broken, releasing large amounts of energy. The reaction products now recombine to form simpler molecules, releasing more energy. Often, the product molecules are small enough and the temperatures high enough, that the products gasify, creating high pressures. The molecule disassociates exothermically. The individual atoms or small groups of atoms then recombine into very simple molecules, e.g., CO_2, H_2O, and release additional energy. Ideally, all the resulting products should be gases. E.g., See figure 20, (2, 4, 6-Trinitrotoluene). The molecule disassociates releasing more $energy_2$, then recombines releasing additional $energy_3$. In the lexicon of energetic materials, $energy_1$ is often referred to as the activation energy.

$$C_7H_5N_3O_6 + energy_1\downarrow = 7\bullet C + 5\bullet H + 3\bullet N + 6\bullet O + energy_2\uparrow = 1.5\bullet N_2 + 2.5\bullet H_2O + 3.5\bullet CO + 3.5\bullet C + energy_3\uparrow$$

Figure **20** (2, 4, 6-Trinitrotoluene)

Single Compound can be composed of organic and/or inorganic compounds.

5.1.3.1.1 Electromagnetic, Ionic and covalent bond, Exothermic, Single Compound, Organic compounds:

Organic compounds are composed of hydrogen and carbon atoms. Most energetic materials of interest are either aromatic or aliphatic compounds. The difference is the shape of the molecules

5.1.3.1.1.1 Electromagnetic, Ionic and covalent bond, Exothermic, Single Compound , Organic compounds, Aromatic

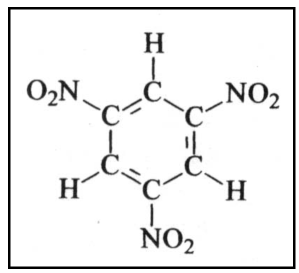

Figure 21 Trinitrobenzine Aromatic Molecule (Cooper)

The aromatic compounds are composed of a benzene ring with various side chains attached to the benzene ring, see Figure 21. The benzene ring is composed of six carbon atoms linked by chemical bonds in such a way as to form a ring structure. Attached to the carbon atoms are other groups of atoms. In the example shown in Figure 22,Trinitrobenzine Aromatic Molecule , they are H and NO_2. Note, carbon double bond, C=C, contains more energy than the carbon single bond C-C.

5.1.3.1.1.2 Electromagnetic, Ionic and covalent bond, Exothermic, Single Compound, Organic compounds, Aliphatic

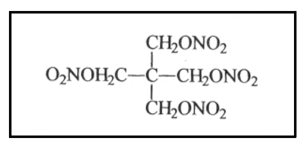

Figure 22 Nitroglycol Aliphatic Molecule (Cooper)

The aliphatic compound is a long chain molecule with various side chains attached to the chain and do not contain the benzine ring. Some of the chemical bonds are single, double, or even triple. See Figure 14, Nitroglycol Aliphatic Molecule. Now things get complicated.

Subsets of Aliphatic molecules are ring molecules and known as cyclic aliphatic compounds. They are not considered aromatic because they do not contain the benzene ring. See Figure 23, RDX Cyclic Aliphatic Molecule. This molecule contains three carbon and three nitrogen atoms in a ring structure not the six carbon atoms in the ring structure

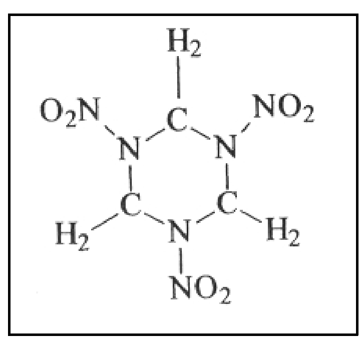

Figure 23 RDX Cyclic Aliphatic Molecule (Cooper)

5.1.3.1.2 Electromagnetic, Ionic and covalent bond, Exothermic, Single Compound, Inorganic compounds:

Inorganic compounds do not contain carbon and/or hydrogen atoms in the molecule. When these molecules dissociate they produce heat. The molecule disassociates exothermically. E.g., see Figure 24, Ammonium Nitrate.

$$NH_4NO_3 + energy_1 \downarrow \approx 2\bullet N + 4\bullet H + 3\bullet O + energy_2 \uparrow = N_2 + 2\bullet H_2O + 0.5\bullet O_2 + energy_3 \uparrow$$

Figure **24** Ammonium Nitrate

5.1.3.2 Electromagnetic, Ionic and covalent bond, Exothermic, Mixture compounds:

A mixture compound contains two or more different chemicals which are necessary and sufficient for the exothermic reaction. The chemicals act as an oxidizer and a reducer.

5.1.3.2.1 Electromagnetic, Ionic and covalent bond, Exothermic, Mixture compounds, Oxidizer

An oxidizer provides oxygen atoms or similar chemicals to the reaction. This is where definitions and reactions can become complicated. Some single component chemicals also function as an oxidizer in dual component compounds. An example of this type of reaction can be seen in the nitroglycerine molecule. Nitroglycerine can be considered a single compound, because it will completely disassociate producing CO_2, H_2O, and N_2, or an oxidizer because it produces excess oxygen. See Figure 25, Nitroglycerine disassociation.

$$C_3H_5N_3O_9 + energy_1 \downarrow \rightarrow 3\bullet C^+ + 5\bullet H^+ + 3\bullet N + 9\bullet O^- + energy_2 \uparrow \rightarrow \approx 3\bullet CO_2 + 2.5\bullet H_2O + 0.25\bullet O_2 + 1.5\bullet N_2 + energy_3 \uparrow$$
$$energy_1 < energy_2 < energy_3$$

Figure **25** Nitroglycerine disassociation

The oxidizer may or may not decompose. If it decomposes, it may or may not decompose exothermically. However, the oxidizer/fuel mixture must react and produce a net energy surplus.

The oxidizers can be organic chemicals (contain both hydrogen and carbon) or inorganic chemicals (does not contain hydrogen and/or carbon)

5.1.3.2.1.1 Electromagnetic, Ionic and covalent bond, Exothermic, Mixture compounds, Oxidizer, Organic

An example of an organic oxidizing compound is nitroglycerine, see Figure 25, Nitroglycerine disassociation. The nitroglycerine is an organic chemical (contains both carbon and hydrogen) and decomposes liberating oxygen for use by the fuel. Nitroglycerine is also known as nitroglycerol, glycerol trinitrate, propane-1,2,3-Tryl Trinitrate.

5.1.3.2.1.2 Electromagnetic, Ionic and covalent bond, Exothermic, Mixture compounds, Oxidizer, Inorganic

An example of an inorganic oxidizing compound is ammonium perchlorate. See Figure 26 Ammonium perchlorate. It produces excess oxygen during decomposition to be used by the fuel.

$$NH_4ClO_4 + energy_1 \downarrow \rightarrow N + 4\bullet H + Cl + 4\bullet O + energy_2 \uparrow \rightarrow \approx 0.5\bullet N_2 + 1.5\bullet H_20 + HCl + 1.25\bullet O_2 + energy_3 \uparrow$$

Figure **26** Ammonium perchlorate

Some oxidizers decompose. An example is liquid oxygen which decomposes, and must vaporize before it can react with the fuel. See Figure 27, Liquid Oxygen

$$\text{Liquid } O_2 + \text{energy}_1\downarrow + C \rightarrow \text{gaseous } O_2 + C \rightarrow CO_2 + \text{energy}_2\uparrow$$

Figure **27** Liquid Oxygen

5.1.3.2.2 Electromagnetic, Ionic and covalent bond, Exothermic, Mixture compounds, Reducer (fuel)

The fuel must decompose prior to reacting with an oxidizer to complete the reaction and produce a net excess of energy. The fuel decomposition may or may not decompose, and may or may not decompose exothermically. However the oxidizer/fuel mixture must react and produce a net energy surplus. These types of fuels can be categorized into organic and inorganic.

5.1.3.2.2.1 Electromagnetic, Ionic and covalent bond, Exothermic, Mixture compounds, Reducer (fuel), Organic

An example of an organic fuel is Lactose, Figure 28, Lactose decomposition .

$$C_{12}H_{22}O_{11}H_2O + \text{energy}_1\downarrow \rightarrow 12\bullet C + 12\bullet H_2O$$

Figure **28** Lactose decomposition

5.1.3.2.2.2 Electromagnetic, Ionic and covalent bond, Exothermic, Mixture compounds, Reducer (fuel), Inorganic

An example of an inorganic fuel is Aluminum, Figure 29, Aluminum decomposition.

$$\text{Solid Al} + \text{energy}_1\downarrow \rightarrow \text{Gaseous Al}$$

Figure **29** Aluminum decomposition

Another class of energetic materials requires additional energy. No chemical change takes place. The forces include momentum, pressure, temperature, and electromagnetic potential. Examples of these materials include gases stored in high pressure cylinders or an Ion Thruster powered by electricity with a Xenon working fluid. Since no chemical reaction takes place, these will not be considered.

5.2.Van der Waals bonds

Van der Waals forces are weaker than ionic or covalent bonds and do not play a significant role in most chemical reactions. Van de Waals forces will not be discussed.

6 Conclusion

Based upon the above discussion, many types of definitions are possible, and are best determined by the technical background of the audience.

The following are suggested definitions for the chemist/chemical engineer/scientist:

- ΔG > 0, spontaneous reaction with sufficient energy to perform useful work.

- Single or multiple chemicals engaged in spontaneous exothermic rapid reactions, producing liquid or gaseous products sufficient to perform useful work.
- Spontaneous chemical reaction where Enthalpy is negative, Entropy positive, sufficient to perform useful work.

For the lay audience:

- Chemical reaction producing heat sufficient to perform work (propulsion, explosion, pyrotechnics).
- Universal: “Oh wow!”

Appendix 1:

Table 1: Energetic Materials

Name	Abbreviation	Table	Formula(6)	Ref
?	HTPS	?	$C_{4.765}H_{7.505}O_{2.131}N_{0.088}$	Journal of Pyrotechnics
(2-difuoro-2,2 dinitroethyl-2, 2-dinitropropoy) formal	MF-1	?	?	Teipel
1, 1-diamino-2, d-dinitroethene	Fox-7	Single compound, Aromatic	?	Teipel
1, 3, 3-trinitroazetidine	TNAZ	Single compound Inorganic, ring	?	Teipel
2, 4, 6-Trinitrotoluene	TNT		$C_7H_5N_3O_6$	Journal of Pyrotechnics, Conkling
3, 3-bis(azidomethyl) oxetane polymer	BAMO	Mixture Compounds Reducer organic (Propellant)	$C_5H_8N_6O$	Yang
3-azidomethyl-3methyloxetane polymer	AMMO	Mixture Compounds Reducer organic linear (Propellant)	$C_5H_9N_3O_3$	Yang
3-nitratomethyl-3-methyl oxetane	NMMO	Mixture Compounds Reducer organic (Propellant)		Yang
Accroides resin	Red gum	Mixture reducer organic	?	Journal of Pyrotechnics,
Aluminum	Al	Mixture Compounds Reducer Inorganic (Propellant)	Al	Conkling
Amber powder		Mixture reducer compound organic	?	Journal of Pyrotechnics
Ammonia		Mixture Compounds Reducer Inorganic (Propellant)	NH_4OH	Koelle
Ammonium dinitramide	ADN	Mixture Compounds Inorganic Oxidizer	$NH_4N(NO_2)_2$	Yang
Ammonium dinitramine	AND	Mixture Compounds Inorganic Oxidizer	$NH_4N_4O_4$	Yang
Ammonium nitrate	AN	Single compound Inorganic	NH_4NO_3	Conkling
Ammonium nitrate	AN	Mixture Compounds Inorganic Oxidizer	NH_4NO_3	
Ammonium perchlorate	AP	Mixture Compounds Inorganic Oxidizer	NH_4ClO_4	Conkling
Ammonium picrate		Single compound, Aromatic	$C_6H_2(NO_2)_3ONH_4$	Sutton
Anthracene		Mixture Compounds Reducer Organic (Propellant)	$C_{14}H_{10}$	Conkling
Antimony trisulfide		Mixture reducer compound inorganic	Sb_2S_3	Journal of Pyrotechnics
Argon	Ar	Mono Propellant Inorganic	Ar	
Arsenic sulfide		Mixture reducer compound inorganic	AS_2S_2	Journal of Pyrotechnics
Asphalt		Mixture Compounds Reducer Organic (Propellant)	?	Koelle
Barium Chlorate		Mixture Compounds Inorganic Oxidizer	$Ba(ClO_3)_2H_2O$	Journal of Pyrotechnics
Barium Chromate		Mixture Compounds Inorganic Oxidizer	$BaCrO_4$	Conkling
Barium nitrate		Mixture Compounds Inorganic Oxidizer	$Ba(NO_3)_2$	Journal of Pyrotechnics
Barium peroxide		Mixture Compounds Inorganic Oxidizer	BaO_2	Conkling
Beryllium	Be	Mixture Compounds Reducer Inorganic (Propellant)	Be	
Bis(2-fluoro-2, 2-dinitroethyl)-difluoroformal	DFF		$C_5H_4N_4O_{10}F_4$	Teipel
Bis(2-fluoro-2,3-dinitroethyl formal	FEFO		$C_5H_6N_4O_{10}F_2$	Teipel
Bis(2,2-dinitropropyl) formal	BDNPF		$C_7H_{12}N_4O_{10}$	Teipel
Bis(fluorodinitroethyl) nitramine	FDNEN		?	
Boron	B	Mixture Compounds Reducer Inorganic (Propellant)	B	Conkling
Bromine pentafluoride			BrF_5	Koelle
Carbon	C	Mixture Compounds Reducer Inorganic (Propellant)	C	
Carbon Dioxide		Mono Propellant Inorganic	CO_2	
Caroxyl-terminated polybutadiene	CTPB	Mixture Compounds Reducer Organic (Propellant)	?	
Cellulose(7)		Mixture Compounds Reducer Organic (Propellant)	$(C_6H_{10}O_5)n$	Cooper
Chlorine terifluoride		oxidizer	ClF_3	Koelle

Table 1: Energetic Materials

Name	Abbreviation	Table	Formula[6]	Ref
Copper azide		Single compound Inorganic	?	
Copper oxide		Mixture Compounds Inorganic Oxidizer	CuO	Cooper
Cyanotetrazolatopentaamine cobalt III perchlorate	CP	Single compound Inorganic	?	
Cylotetramethyllenetetranitramine	HMX	Single compound organic aromatic	$C_4H_8N_8O_8$	
Dextrine		Mixture compound, organic, fuel	$(-C_6H_{10}O_5-)nH_2O$	Journal of Pyrotechnics
Diazdinitrophenol	DINO or DDNP	Single compound, Aromatic	?	
Diborane		oxidizer	B_2H_6	Koelle
Dibutyl phthalate	DBP	Mixture Compounds Reducer Organic (Propellant)	$C_{16}H_{22}O_4$	Chemical Industry
Diethyl phthalate	DEP	Mixture Compounds Reducer Organic (Propellant)	$C_{12}H_{14}O_4$	Chemical Industry
Diethylene glycol dinitrate	DEGDN/DEGN	Mixture Compounds Organic Oxidizer alphatic	$(CH_2CH_2ONO_2)O_2$	Sutton
Diethylenetriamine		oxidizer	$(NH_2(CH_2)_2)_2NH_2$	Koelle
Dimethyl phthalate	DMP	Mixture Compounds Reducer Organic (Propellant)	$C_{10}H_{10}O_4$	Chemical Industry
Dinitramidic acid	DNA	Inorganic, ring	$HN(NO_2)_2$	Yang
Dinitrotolunene	DNT		$CH_3C_6H_3(NO_2)_2$	Sutton
Dioctile phthalate		Mixture Compounds Reducer Organic (Propellant)	?	
Ethyl alcohol		Mixture Compounds Reducer Organic (Propellant)	C_2H_5OH	
Ethyl centralite	EC	Mixture Compounds Reducer Organic (Propellant)	$C_{17}H_{20}N_2O$	Chemical Industry
Ethyl picrate		Single compound, Aromatic	?	
Ethyl Tetryl		Single compound, Aromatic	?	
Ethylene oxide		mono propellant	$(CH_2)_2O$	Koelle
Ethylenediamine		Mixture Compounds Reducer organic (Propellant)	$NH_2(CH_2)_2$	Koelle
Ethylenedinitramine	EDNA	Single Compound, Organic, Aliphatic	$C_2H_6N_4O_4$	Chemical Industry
Ferro Silicon		Mixture reducer compound inorganic	$FeSi$	Journal of Pyrotechnics
Fluorine	F	Mixture Compounds Inorganic Oxidizer	F_2	
Glucose		Mixture Compounds Reducer Organic (Propellant)	$C_6H_{12}O_6$	
Glycidyl azide polymer	GAP	Mixture Compounds Reducer organic (Propellant)	$C_3H_5N_3O_2$	Yang
Guanidine Nitrate			$NH{:}C(NH_2)HNO_3$	Journal of Pyrotechnics
Helium	He	Mono Propellant Inorganic	He	
hemicellulose		Mixture Compounds Reducer Organic (Propellant)	?	
Hexachloroethane		Mixture Compounds Reducer Inorganic (Propellant)	C_2Cl_6	Conkling
Hexahydrotrinitrotriazine (Cyclotetramethylene trinitramine	RDX	Single Compound, Organic aromatic	$C_3H_6N_6O_6$	Conkling
Hexanitroazobenzene	HNAB	Single compound, Aromatic	?	
Hexanitrohexazaisowurtzetane	HNIW, CL-20	Single compound, other, organic, aliphatic	$C_6H_6O_{12}N_{12}$	Yang, Teipel
Hexanitrostibene	HNS	Single compound, Aromatic	?	
Hydrazine		Single compound Inorganic	N_2H_4	
Hydrazine		Mixture Compounds Reducer Inorganic (Propellant)	N_2H_4	
Hydrazinium diperchlorate	HP2		?	Yang
Hydrazinium monoperchlorate	HP		?	Yang
Hydrazinium nitrate	HN		?	Yang
Hydrazinium nitroformate	HNF		?	Yang
Hydrazoic Acid		?	HN_3	Yang
Hydrocarbon liquid fuels[8]		Mixture Compounds Reducer Organic (Propellant)		
Hydrogen Peroxide		Single compound Inorganic	H_2O_2	
Hydrogen Peroxide		Mixture Compounds Inorganic Oxidizer	H_2O_2	
Hydrooxylammonium perchlorate	HAP		?	
Hydroxy-terminated polybutadiene	HTPB	Mixture Compounds Reducer Organic (Propellant)	?	
Hydroxyl Ammonium Nitrate	HAN	Single compound Inorganic	$NH^2OH^+NO_3$	Sutton

Table 1: Energetic Materials

Name	Abbreviation	Table	Formula(6)	Ref
hydroxyl-terminated polyethylene	HTPE	Mixture Compounds Reducer Organic (Propellant)	$C_{5.194}H_{9.84}O_{1.608}N_{0.194}$	Journal of Pyrotechnics
Hydyne		Mixture Compounds Reducer Inorganic (Propellant)	?	
Iron		Mixture reducer compound inorganic	Fe	Journal of Pyrotechnics
Iron Oxide (black)		Mixture Compounds Inorganic Oxidizer	Fe_3O_4	
Iron Oxide (red) hematite		Mixture Compounds Inorganic Oxidizer	Fe_2O_3	
Krypton	Kr		Kr	Sutton
Lactose		Mixture Compounds Reducer Organic (Propellant)	$C_{12}H_{22}O_{11}H_2O$	
Lead azide		Single compound Inorganic	$Pb(N_3)_2$	Conkling
Lead chromate		Mixture Compounds Inorganic Oxidizer	$PbCrO_4$	Conkling
Lead dioxide		Single compound inorganice	PbO_2	Conkling
Lead oxide			PbO	
Lead styphante		Single compound, Aromatic	$(NO_2)_3C_6HO_2Pb$	Brown
Lead tetroxide (red lead)		Mixture Compounds Inorganic Oxidizer	Pb_3O_4	Conkling
Led Peroxide		Mixture Compounds Inorganic Oxidizer	PbO_2	Conkling
Lignin		Mixture Compounds Reducer Organic (Propellant)		
Lithium perchlorate		Mixture Compounds Inorganic Oxidizer	$LiClO_4$	Cooper
Magnalium		Mixture reducer compound inorganic	MgAl	Journal of Pyrotechnics
Magnesium	Mg	Mixture Compounds Reducer Inorganic (Propellant)	Mg	Journal of Pyrotechnics
Mercury fulminate		Single compound Inorganic	$Hg(ONC)_2$	Conkling
Methane		Mixture Compounds Reducer Organic (Propellant)	CH_4	Sutton
Methyl nitrate		mono propellant, organic	CH_2NO_3	Koelle
Methylinitrate		Single Compound, Organic, Aliphatic	?	
Monomethyl hydrazine	MMH	Mixture Compounds Reducer Inorganic (Propellant)	CH_3NHNH_2	Sutton
n-Propyl Nitrate		mono propellant	$C_3H_7NO_3$	Koelle
Naphthalene			$C_{10}H_8$	Conkling
Nitric Acid		Mixture Compounds Inorganic Oxidizer	HNO_3	Suttton
Nitrocellulose		Mixture Compounds Reducer Organic (Propellant)	$C_6H_7O_2(ONO_2)_3$	Sutton
Nitrocelluole			$(C_6H_{10-x}O_{5-x}(ONO_2)_x)n$	
Nitrogen	N	Mono Propellant Inorganic	N	
Nitrogen Tetroxide		Mixture Compounds Inorganic Oxidizer	N_2O_4	
Nitroglycerine	NG	Single Compound, Organic, Aliphatic	$C_3H_5N_3O_9$	Conkling, Cooper
Nitroglycol		Single Compound, Organic, Aliphatic	$C_2H_4N_2O_6$	Chemical Industry
Nitroguanidine	NQ, NIGU	Single Compound, Organic, Aliphatic	$CH_4N_4O_2$	Chemical Industry, Teipel
Nitromethane		mono propellant, organic	CH_3NO_2	Koelle
Octahydrotetranitrotetrazine	HMX, octogen	Single Compound, Organic, Aliphatic	$C_4H_8N_8O_8$	Chemical Industry
Octanitrocubane	ONC	Single compound Inorganic, ring	$C_8(NO_2)_8$	Teipel
Oil		Organic fuel	C_8H_{18}	Brown
Oxygen	O, LOX	Mixture Compounds Inorganic Oxidizer	O_2	
Oxygen difluoride			OF_2	Koelle
Pentaborane		Mixture Compounds Reducer Inorganic (Propellant)	B_5H_9	Koelle
Pentaerythriloltetranitrate	PETN	Single Compound, Organic, Aliphatic	?	
Pentaerythritoltrinitrate	PETRIN	Single Compound, Organic, Aliphatic	?	
Perchloryl fluoride		oxidizer	ClO_3F	Koelle
Phosphorus	P	Mixture Compounds Reducer Inorganic (Propellant)	P	Conkling
Picric Acid, Trinitrophenol, Lyddite		Single compound, Aromatic	$C_6H_3N_3O_7$	Chemical Industry
Picryl chloride		Single compound, Aromatic	$C_6H_2ClN_3O_6$	Chemical Industry
Polobutadiene acrylonitrile acrylic acid	PBAN	Mixture Compounds Reducer Organic (Propellant)	$C_{10}H_{13}NO_2$	Chemical Industry

Table 1: Energetic Materials

Name	Abbreviation	Table	Formula(6)	Ref
polybutadiene acrylic acid	BPAA	Mixture Compounds Reducer Organic (Propellant)	?	
Polycarprolactone glycol	PEG	Mixture Compounds Reducer Organic (Propellant)	?	
Polycarprolactone polyol	PCP	Mixture Compounds Reducer Organic (Propellant)	?	
Polyglycol adipate	PGA	Mixture Compounds Reducer Organic (Propellant)	?	
Polyisobutylene		organic fuel	?	Cooper
Polypropylene glycol	PPG	Mixture Compounds Reducer Organic (Propellant)	$C_6H_{14}O_3$	Chemical Industry
Polysulfide		organic fuel	?	Cooper
Polyurethane polyester or polyether	PU	Mixture Compounds Reducer Organic (Propellant)	$C_{25}H_{42}N_2O_6$	Chemical Industry
Polyvinl chloride	PVC	Mixture Compounds Reducer Organic (Propellant)	$(-CH_2CHCL-)n$	Conkling
Potassium Chlorate		Mixture Compounds Inorganic Oxidizer	$KClO_3$	Conkling
Potassium dichromate		Mixture Compounds Inorganic Oxidizer	$K_2Cr_2O_7$	Journal of Pyrotechnics
Potassium dinitramide	KDN	Mixture Compounds Inorganic Oxidizer	$KN(NO_2)_2$	Yang
Potassium nitrate	KN	Mixture Compounds Inorganic Oxidizer	KNO_3	Conkling
Potassium perchlorate	KP	Mixture Compounds Inorganic Oxidizer	$KClO_4$	Conkling
Propanedial-dinitrate	PDN	Mixture Compounds Organic Oxidizer	?	
Red Lead			PB_3O_4	Journal of Pyrotechnics
Rocket Propellant 1	RP-1	Mixtrue Compounds Organic Fuel	$CH_{(1.9-2.0)}$	Brown, C.
Rosin		Mixture reducer compound organic	?	Journal of Pyrotechnics
Shellac		Mixture Compounds Reducer Organic (Propellant)	$C_{16}H_{24}O_5$	Conkling
Silcon	Si	Mixture Compounds Reducer Inorganic (Propellant)	Si	Journal of Pyrotechnics
Silver acetylide		Single compound Inorganic	C_2AG_2	Cooper
Silver azide		Single compound Inorganic	AgN_3	Cooper
Silver fulminate		Single compound Inorganic	AgONC	Cooper
Sodium azide		Single compound Inorganic	NaN_3	Cooper
Sodium nitrate		Mixture Compounds Inorganic Oxidizer	$NaNO_3$	Journal of Pyrotechnics
starch		Mixture Compounds Reducer Organic (Propellant)	$(C_6H_{10}O_5)n$	Conkling
Stearic acid			$C_{18}H_{36}O_{11}$	
Strontium nitrate		Mixture Compounds Inorganic Oxidizer	$Sr(NO_3)_2$	Journal of Pyrotechnics
Sugar, sucrose	cane sugar	Mixture Compounds Reducer Organic (Propellant)	$C_{12}HJ_{22}O_{11}$	Journal of Pyrotechnics
Sulfur	S	Mixture Compounds Reducer Inorganic (Propellant)	S	Journal of Pyrotechnics
Tetranitroniline	TNA	Single compound, Aromatic	?	
Tetronitromethane		mono propellant	$C(NO_2)_4$	Koelle
Tetryl		Single compound, Aromatic	?	
Titanium	Ti	Mixture Compounds Reducer Inorganic (Propellant)	Ti	Journal of Pyrotechnics
Triacetin	TA	Mixture Compounds Reducer Organic (Propellant)	$C_9H_{14}O_6$	Chemical Industry
Triaminotrinitrobenzene	TATB	Single compound, Aromatic	?	Teipel
Triethylene glycol dinitrate	TEGDN	Mixture Compounds Organic Oxidizer, alphatic	$C_6H_{12}N_2O_8$	Teipel
Trimethylolethane trinitrate	TMETN	Mixture Compounds Organic Oxidizer, alphatic	$C_5H_9N_3O_9$	Teipel
Trinitroaniline, Picramide	TNA	Single compound, Aromatic	$C_6H_4N_4O_6$	Teipel, chemical industry
Trinitroanisol		Single compound, Aromatic	?	
Trinitrobenzene	TNB	Single compound, Aromatic	$C_6H_3N_3O_6$	Chemical Industry
Trinitrobenzoic acid	TNBA	Single compound, Aromatic	$C_7H_3N_3O_8$	Chemical Industry
Trinitrocresol	TNC	Single compound, Aromatic	?	

Table 1: Energetic Materials

Name	Abbreviation	Table	Formula(6)	Ref
Trinitrorescorinol (styphnic acid)		Single compound, Aromatic	?	
Tungsten	W	Mixture Compounds Reducer Inorganic (Propellant)	W	
Unsymmetrical Dimethylhydrazine	UDMH	Mixture Compounds Reducer Inorganic (Propellant)	$(CH_3)_2NNH_2$	
Zinc	Zn	Mixture Compounds Reducer Inorganic (Propellant)	Zn	Journal of Pyrotechnics
Zirconium	Zr	Mixture Compounds Reducer Inorganic (Propellant)	Zr	

Appendix 2:

Table 2: List of Abbreviations

Abbreviation	Name
ADN	Ammonium dinitramide
Al	Aluminum
AMMO	3-azidomethyl-3methyloxetane polymer
AN	Ammonium nitrate
AN	Ammonium nitrate
AND	Ammonium dinitramine
AP	Ammonium perchlorate
BAMO	3, 3-bis(azidomethyl) oxetane polymer
BDNPF	Bis(2,2-dinitropropyl) formal
Be	Beryllium
BPAA	polybutadiene acrylic acid
cane sugar	Sugar, sucrose
CP	Cyanotetrazolatopentaamine cobalt III perchlorate
CTPB	Caroxyl-terminated polybutadiene
DBP	Dibutyl phthalate
DEGDN/DEGN	Diethylene glycol dinitrate
DEP	Diethyl phthalate
DFF	Bis(2-fluoro-2, 2-dinitroethyl)-difluoroformal
DINO or DDNP	Diazdinitrophenol
DMP	Dimethyl phthalate
DNA	Dinitramidic acid
DNT	Dinitrotolunene
EC	Ethyl centralite
EDNA	Ethylenedinitramine
F	Fluorine
FDNEN	Bis(fluorodinitroethyl) nitramine
FEFO	Bis(2-fluoro-2,3-dinitroethyl formal
Fox-7	1, 1-diamino-2, d-dinitroethene
GAP	Glycidyl azide polymer
HAN	Hydroxyl Ammonium Nitrate
HAP	Hydrooxylammonium perchlorate
HMX	Cylotetramethyllenetetranitramine
HMX, octogen	Octahydrotetranitrotetrazine
HN	Hydrazinium nitrate
HNAB	Hexanitroazobenzene
HNF	Hydrazinium nitroformate
HNIW, CL-20	Hexanitrohexazaisowurtzetane
HNS	Hexanitrostibene
HP	Hydrazinium monoperchlorate
HP2	Hydrazinium diperchlorate
HTPB	Hydroxy-terminated polybutadiene
HTPE	hydroxyl-terminated polyethylene
HTPS	?
KDN	Potassium dinitramide
KN	Potassium nitrate
KP	Potassium perchlorate
MF-1	(2-difuoro-2,2 dinitroethyl-2, 2-dinitropropoy) formal
MMH	Monomethyl hydrazine
N	Nitrogen
NG	Nitroglycerine
NMMO	3-nitratomethyl-3-methyl oxetane
NQ, NIGU	Nitroguanidine
O, LOX	Oxygen
ONC	Oxtanitrocubane
PBAN	Polobutadiene acrylonitrile acrylic acid
PCP	Polycarprolactone polyol
PDN	Propanedial-dinitrate
PEG	Polycarprolactone glycol
PETN	Pentaerythriloltetranitrate
PETRIN	Pentaerythritoltrinitrate
PGA	Polyglycol adipate
PPG	Polypropylene glycol
PU	Polyurethane polyester or polyether
PVC	Polyvinl chloride
RDX	Hexahydrotrinitrotriazine (Cyclotetramethylene trinitramine
Red gum	Accroides resin
RP-1	Rocket Propellant 1
TA	Triacetin
TATB	Triaminotrinitrobenzene
TEGDN	Triethylene glycol dinitrate
TMETN	Trimethylolethane trinitrate
TNA	Tetranitroniline
TNA	Trinitroaniline, Picramide
TNAZ	1, 3, 3-trinitroazetidine
TNB	Trinitrobenzene
TNBA	Trinitrobenzoic acid
TNC	Trinitrocresol
TNT	2, 4, 6-Trinitrotoluene
UDMH	Unsymmetrical Dimethylhydrazine
Zn	Zinc
Zr	Zirconium

Nomenclature

C - degrees Calceus
F - degrees Fahrenheit
g - gram
h - hour
in - inches
J - Jouls
K - degrees Kelvin

Kcal - kilocalories
KJ - kilojoules
km - kilometer
mm - milimieter
R - degrees Rankin
sec - second

↓ - added to the reaction
↑ - given off by the reaction
→ - next reaction
= - equals
≡ - defind as
≈- approximatlye equals

Throughout this paper, examples of chemical reactions are used to clarify the descriptions of the concepts. The nomenclature for chemical formulas is the following: The chemical equation is highlighted in a figure 30, Combustion of Methane

.

$$CH_4 + 2\bullet O_2 + energy_1\downarrow \rightarrow C + 4\bullet H + 4\bullet O \rightarrow CO_2 + 2\bullet H_2O + energy_2\uparrow$$

Figure **30** Combustion of Methane

The standard chemical formula is give for the reactions. As an example when methane (NH_4) is burned with oxygen (O_2), it produces carbon dioxide (CO_2), water (H_2O), and heat (energy↑). The equation is balanced. Energy↓ is endothermic, energy is added to the reaction. Energy↑ is exothermic, energy is given off by the reaction.

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Endnotes

1. Of the five states of matter, solid, liquid, gas, plasma, and Bose Einstein condensate, only the first three will be considered.

2. Discussion of dark matter and dark energy were not included, since this is an emerging area of study and little is known compared to the forces of gravity, electromagnetic, strong and weak interactions.

3. Dutch scientist Johannes Diderik van der Waals, (1837-1923) Nobel Laureate

4. Sonic, sub sonic and super sonic refer to the speed of sound in the energetic materials, not the speed of sound in air.

5. Note the change in enthalpy is positive (+) when energy is added, and negative (-) when energy is liberated.

6. The formulation varied between some references.

7. Cellulose is a general category of products (solids, liquids, gases) derived from plant material (cellulose, hemicellulose, lignin).

8. Hydrocarbon Fuels is a general category which includes liquid fuels derived from petroleum, coal, natural gas, and cellulosic feedstocks.