- <u>Introduction:</u>

The word "deflagrate" comes from Latin "*deflagrare",* from *de-* + *flagrare* to burn. The dictionary defines it as "to burn rapidly with intense heat and sparks being given off". Simply put, deflagrating reactions are chemical reactions between very finely divided fuel and oxidizer particles. The fuel and/or oxidizer can be in either solid, liquid or gaseous state. Gaseous mixtures have a lower energy density per volume, and liquid mixtures are far more likely to undergo detonation than they are to deflagrate so this page will mostly deal with solid state deflagrants. The oxygen percentage per weight of the oxidizer, its decomposition temperature, the fuel ignition temperature, its caloric output, and specially, the grain size of both the fuel and the oxidizer particles will allow affect how quickly the flame travels through the mixture. Some deflagrants can be spectacularly exothermic, such as Aluminium/Potassium Perchlorate flash powder, which will put out 2.2kilocalories per gram, incredibly brilliant, as in U.S. Type III Flash Powder (Potassium Perchlorate/Barium Nitrate/Aluminium) which produces 0.82 billion candlepower for 40 milliseconds at 31.9 million candlepower/second in a 60pound charge. Other mixtures can also be surprisingly violent, such as thermite mixtures utilizing Silver Oxide as an oxidizer, or mixtures that employ Red Phosphorous as a fuel, which combust at supersonic velocities and explode even when unconfined.

My interest in deflagrants lies in their usefulness as high performance rocket propellants, which is their number one use right now. Other uses include high altitude night photography and blasting for mining applications, although high explosives have taken over in this field over the years.

- <u>A brief overview of the components in a deflagrating mixture:</u>

<u>Fuel:</u>

The fuel in a deflagrating mixture will determine its properties to a very great extent. Fuels with very high caloric outputs, such as metals, will result in very hot and bright deflagrations. Fuels with very low ignition points such as Phosphorous and Sulfur will result in mixtures which are very sensitive to ignition, and that once ignited burn extremely fast and often explode without the need for any confinement. Sometimes fuels are mixed so that the best properties of the two can be achieved in the mixture, such as in the case of black powder, where Carbon provides a reasonably high caloric output, but burns slowly, and sulfur burns fast but with less energy, so by mixing the two a hot, easily initiated and reasonably fast burning deflagrant can be obtained.

<u>Oxidizer:</u>

The oxidizer in a deflagrating mixture provides oxygen by decomposing under heat. Nitrates, Chlorates, Perchlorates, Permanganates, transition metal Oxides, Peroxides, and other unstable, high oxygen content molecules can all be used. One example would be Potassium Nitrate ($KNO_3$), the oxidizer used in black powder. On heating it decomposes to yield oxygen and potassium nitrite. The ease with which the oxidizer decomposes will determine to a large extent the sensitivity and combustion rate of the mixture; formulas utilizing peroxides, permanganates, and some of the more unstable Chlorates will often be shock sensitive and typically burn fast enough to explode when ignited. Formulas utilizing Perchlorates and Nitrates are safer to handle but do not burn as violently.

## Mixture properties:

Regardless of what makes up the deflagrating mixture, the more finely divided the oxidizer and the fuel are, and the more intimately mixed they are, the faster it will burn. A coal briquette will not burn to any great extent if it is sitting on top of some potassium nitrate, but if both the $KNO_3$ and the coal are pulverized combustion can take place at a couple hundred meters per second.

Deflagrating mixtures are not capable of Detonation to any appreciable degree. Detonation *can* be induced on some special mixtures employing blasting caps on atomized fuels and oxidizers, but these are very special cases and initiation is provided by a high explosive blasting cap. In general, if ignited, a deflagrating mixture will not yield a shockwave. This, however, does not mean that it can not explode; any deflagrating mixture is capable of self confining; if 50 grams of commercial flash power are ignited out in the open, the pressure produced by its combustion will result in supersonic expansion of the exhaust gases and the pile will explode with considerable force. Some mixtures require far less than 50 grams to self confine, whilst others will not self confine at all. Adding any kind of confinement to a deflagrating mixture will result in increased combustion pressures and thus increase the chances of an explosion. Firecrackers are nothing more than a fraction of a gram of flash powder inside a cardboard tube sealed on both ends. When the flash powder burns it produces a very quick burst of pressure which ruptures the casing and causes a supersonic gas expansion. Even a small firecracker with under one gram of pyrotechnic mixture will be able to blow fingers off, and their manufacture is strongly discouraged by the author of this page.

- ## PowerLabs deflagration demo:

I have experimented with Carbon, Sulphur, Epoxies, Rubbers, Sugars, Magnesium, Zinc, Iron, Aluminium and plastics as fuels, and used Peroxides, Oxides, Nitrates, Perchlorates, Permanganates, Chromates, Dichromates, Bromates and Iodates as oxidizers. Of my countless experiments with oxidizers, a few stand out from the rest by their unexpected results, such as the time when I attempted to make flash powder using Sodium Peroxide as the oxidizer. I pulverized some $Na_2O_2$ pellets, mixed them with Sulphur and Aluminium powder and started rolling the mixture backwards and forward on a sheet of paper (the safe, correct method of mixing powders). Immediately I noticed that the mixture was clumping together around the oxidizer granules. I didn't even have time to figure out what that meant because within seconds of having been mixed the mixture exploded and burned a hole on the table I was working on. When mixing energetic fuels with unstable oxidizers one must be aware that the unexpected can and will happen, and must be prepared for such an event. On my case I had goggles and a lab coat on, and the mixture I was working with was on the centre of a large sheet of paper, and did not consist in a dangerous amount, therefore no harm was caused.

Chromium Trioxide exploded in a similar fashion with Magnesium Powder. The mixtures are too many to describe, but I have compiled a list of some formulas I have attempted, and some I am aware off on the bottom of this page for informational purposes.

One mixture I have always been fond of is the Potassium Bromate/Sulphur/Mannitol deflagrant. I came up with this formula myself after some experimentation. Potassium Bromate is similar to $KNO_3$ as an oxidizer, but because of the larger Bromine molecule holding on to the Oxygen it is more unstable and therefore results in a more violent reaction. Similarly, Mannitol being a light sugar combusts spectacularly fast. The Sulphur helps yield a mixture that is even faster burning. This mixture is, as one would expect, friction, impact and heat sensitive and shouldn't be used for anything other than small demonstrations. Nonetheless, it is quite possibly *the* fastest burning deflagrant mixture I have ever experimented with that does not involve ultra fine metal powders, burning faster than even some commercial flash powder grades.

| Reactants: | Materials: |
|---|---|
| Potassium Bromate ($KBrO_3$) | Sheet of Paper |
| Sulphur (S) | Hour Glass |
| Mannitol ($C_6H_{14}O_6$) | Glass rod |
| Sulphuric Acid ($H_2SO_4$) | |

The reactants were all finely pulverized and than thoroughly mixed together by rolling backwards and forwards on a large sheet of paper. I can't find the correct proportions since I've lost my notes for this experiment. As I recall, I arrived at the ideal proportions by varying the fuel/oxidizer ratio and analyzing the combustion products: If there was any molten Potassium Bromate on the Hour Glass I would add more Mannitol in order to balance out the oxygen surplus. If there were carbon stains on the Hour Glass that meant that there was not enough oxygen to fully combust the Mannitol and I would add more $KBrO_3$. It is easy to notice when the mixture is optimal because it will combust extremely fast when that happens.

Once the mixture had been prepared it was placed on an Hour Glass and a glass rod was dipped in 98% Sulphuric acid. The mixture deflagrates violently with a puff of smoke when touched by the Sulphuric Acid.

The picture to the left shows a still frame capture from the video at the moment the mixture deflagrates. Notice the intense purple light from the Potassium in the oxidizer. Also notice the incredibly large amount of smoke (Mostly water vapor, with some $CO_2$, KBr and $SO_2$) it produces for such a small amount.

Click on the picture to watch the video. It is quite small (only 122K, MPEG format) but definitely worth watching!

- A Few more examples of Deflagrating mixtures:

## Chlorate Mixtures:

Chlorates are very unstable and powerful oxidizers. They have generally been replaced by perchlorates in most commercial formulas as those are just as powerful and more stable. Some older formulas list chlorates with sulfur. This extremely dangerous practice has lead to countless accidents due to the fact that the sulfur will gradually convert into sulfuric acid in the presence of moisture and this will lead to the generation of Chlorine Trioxide, an extremely unstable gas that causes the mixture to ignite spontaneously. Chlorate explosives must also not be stored together with ammonium nitrate explosives, since ammonium chlorate which is formed when these two substances are brought in contact causes them to explode. Chlorate mixtures containing Sulphur are listed here for curiosity purposes only and should not be attempted!

General formula: $KClO_3$ + 2 Al --> KCl + $Al_2O_3$ + energy

| | | | |
|---|---|---|---|
| Oxidizer, % by weight | Fuel, % by weight | Speed # | Notes |
| Potassium chlorate 67% | Sulphur 33% | 5 | Friction/impact sensitive; Unstable |
| Potassium chlorate 50% | Sugar 35%, Charcoal 15% | 5 | Fairly slow burning; unstable |
| Potassium chlorate 50% | Sulphur 25% Magnesium or Aluminium dust | 8 | Extremely unstable |

| | | | |
|---|---|---|---|
| | 25% | | |
| Potassium chlorate 67% | Magnesium or Aluminium dust 33% | 8 | Unstable |
| Potassium chlorate 75% | Charcoal dust 15% Sulphur 10% | 6 | Unstable |
| Potassium chlorate 75% | Phosphorus sesquisulfide 25% | 8 | Used to make strike-anywhere matches |
| Potassium chlorate 67% Red phosphorus 27% Calcium carbonate 3% | Sulphur 3% | 7 | Very unstable, impact sensitive |
| Nitrate Mixtures: | Nitrate mixtures containing magnesium can self ignite in the presence of moisture. | If the mixture smells of ammonia it contains moisture and is prone to self ignition. | $4KNO_3 + 10Mg$ --> $2K_2O + 2N_2 + 10MgO$ + energy |
| Potassium nitrate 75% | Charcoal 15% Sulphur 10% | 7 | This is black powder |
| Potassium Nitrate 50% | Sulfur 30% Aluminum 20% | | |
| Barium nitrate 57% | Aluminum (fine mesh) 29% Sulfur 14% | | Relatively unsensitive. |
| Potassium nitrate 60% | Powdered iron or magnesium 40% | 1 for iron, ? Mg | Burns very hot |
| Sodium nitrate 65% | Magnesium dust 30% Sulphur 5% | ? | Unpredictable Burn Rate, yellow flash |
| Permanganate Mixtures | Permanganate mixtures are unstable and moisture sensitive, and also very violent. | Not recommended. | $6KMnO_4 + 14Al$ --> $3K_2O + 7Al_2O_3 + 6Mn$ + energy |

| | | | |
|---|---|---|---|
| Potassium permanganate 67% | Sulphur 33% | 5 | Unstable |
| Potassium permanganate 60% | Glycerine 40% | 4 | Delay before ignition depends on grain size |
| Potassium permanganate 50% | Powdered sugar 25% Al or Mg dust 25% | 7 | Unstable, ignites if wet |
| Potassium permanganate 50% | Sugar 50% | 3 | ? |
| Ammonium perchlorate 70% | Aluminium dust 30% and small amount of iron oxide | 6 | Solid fuel base for space shuttle |
| Barium peroxide 90% | Magnesium dust 5% Aluminium dust 5% | 10 | Alternate flash powder |

## Perchlorate mixtures:

Potassium Perchlorate is the standard today at the fireworks industry. Very powerful, and safer than most other mixtures.

$3KClO_4 + 8Al \rightarrow 3KCl + 4Al_2O_3 + \text{energy}$

| Oxidizer, % by volume | Fuel, % by Volume | Notes |
|---|---|---|
| Potassium perchlorate 50%<br><br>(Or NaClO4) | Aluminium (or Magnesium) 23% sulphur 27% | Sulphur can be replaced by antimony trisulfide |
| Potassium perchlorate 70% | Aluminium (dark pyro) 30% | One of the best. Four ounces equals a stick of dynamite! |
| Potassium perchlorate 65 - 70% | Aluminium powder 35 – 30% | Larger percentage of aluminum results in a stronger flash |
| Potassium Perchlorate 43% | Aluminium, 400 mesh 43% Sulphur 14% | |

| | | |
|---|---|---|
| Potassium perchlorate 80% | Aluminium 27%<br><br>Sulphur 3% | |
| Potassium perchlorate 64% | Aluminium 23%<br><br>Sulphur 13% | Loudest report possible with perchlorate. |
| Potassium Perchlorate 72% | Aluminium 28% | Safer than the above, but less powerful |
| Potassium perchlorate 70% | Coal 18% Sulphur 12% Starch +2% | Same as above, safer, but less energetic |
| Potassium perchlorate 70% | Coal 30% Starch +2% | Same as above, safer, but less energetic |
| Potassium perchlorate 30% Barium Nitrate 30% | Aluminium (atomised) 40% | 120million candlepower per 250grams! |
| Potassium perchlorate 70%<br><br>Potassium bichromate 5% | Coal 30% Starch +2% | Potassium bichromate catalyses the decomposition of the potassium perchlorate |
| Potassium Perchlorate 37%<br><br>Cupric Oxide 11%<br><br>Strontium nitrate 11% | Magnesium 37%<br><br>PVC 4% | Purple flash |
| Potassium Perchlorate 43% Barium Nitrate 21% | Aluminium Powder 36% | Green Flash |
| Potassium Chlorate 75% | Coal 25%, Starch +2% | Relatively insensitive |
| Potassium permanganate 42% | Aluminium (or Mg) 24% Sulphur 34% | Unstable, sensitive, powerful. |
| Barium sulphate 50% | Magnesium or Aluminium 50% | Easy to ignite, very fast burning, greenish flash with Mg |
| Barium nitrate 68% | Aluminium (dark pyro) 23%, Sulphur 9% | |
| Barium nitrate 58% | Aluminium (fine mesh) 28% Sulphur 14% | Relatively insensitive |

| | | |
|---|---|---|
| Sodium Nitrate 85% | Magnesium 15% | Yellow Flash |
| Zirconium 28%<br><br>Barium Nitrate 30%<br><br>Barium Oxide 25% | Magnesium 7%<br><br>Zirconium Hydride 7%<br><br>Starch 5% | Smokeless Flash Powder |
| Red Iron Oxide 50% | Aluminium Powder 50% | Thermite |
| Copper Oxide 50% | Zinc 50% | Explosive Thermite |

*Comments:* This energetic burst charge can be used for small shells, but is unsuitable for the smallest diameters (2...3 inch). It is much safer to handle than the H3 bursting charge since it contains no chlorates.
*Preparation:*
Potassium perchlorate............................70
Hemp coal (or Paulownia coal)....................18
Sulfur..........................................12
Glutinous rice starch............................+2%
*Comments:* Shimizu lists this composition as ‘burst charge No. 44’. The potassium bichromate catalyses the decomposition of the potassium perchlorate. This composition’s sensitivity is quite low, although higher than that of black powder. The explosive force of this composition is lower than that of the ‘Potassium perchlorate bursting charge #1’. This burst charge is often used in shells of middle and large diameter (6...10 inch).
*Preparation:*
Potassium perchlorate............................70
Hemp coal (or Paulownia coal)....................30
Potassium bichromate.............................5
Glutinous rice starch............................+2%
**Purple Flash**
*Source:* rec.pyrotechnics
*Comments:*
*Preparation:*
Magnesium.......................................10
Potassium perchlorate............................10
Cupric oxide....................................3
Strontium nitrate................................3
PVC.............................................1
**Green flash**
*Source:* rec.pyrotechnics
*Comments:*
*Preparation:*

potassium perchlorate............................6
barium nitrate...................................3
Aluminum powder..................................5

**Whistle mix #1**

*Source:* rec.pyrotechnics. Composition from Ellern[4].
*Comments:*
*Preparation:*
Potassium perchlorate............................72.5
Sodium salicylate................................27.5

**Whistle mix #2**

*Source:* rec.pyrotechnics. Composition from Ellern[4].
*Comments:*
*Preparation:*
Potassium nitrate................................30
Potassium dinotrophenate..........................70

**Whistle mix #3**

*Source:* rec.pyrotechnics. Composition from Ellern[4] and Shimizu[1].
*Comments:*
*Preparation:*
Potassium perchlorate............................70
Sodium benzoate..................................30

**Whistle mix #4**

*Source:* rec.pyrotechnics. Composition from Oztap
*Comments:*
*Preparation:*
Potassium chlorate................................40
Sodium chlorate..................................10
Potassium nitrate................................30
Sodium salicylate................................10
Paraffin oil.....................................10
Ferric oxide.....................................+0.2

**Whistle mix #5**

*Source:* rec.pyrotechnics. Composition from Lancaster[2].
*Comments:* This mixture is quite sensitive to friction and shock.
*Preparation:*
Potassium chlorate................................75
Gallic acid......................................25