Fireworks over Auckland Harbour, celebrating the opening of the Rugby World Cup 2011, Firefly Photography.

The chemistry of fireworks

NZASE resource

Fireworks are pure redox, and the chemistry is fascinating. NZASE Science Communicator Mike Stone investigates.

History

Chinese people are credited with the invention of fireworks. By 800 AD, Chinese alchemists had discovered that saltpetre (or potassium nitrate) mixed with ***charcoal*** and sulfur was explosive; this mix was called black powder, or gunpowder. Early firecrackers and a type of sparkler, using black powder in bamboo tubes, were part of their celebrations.

By the twelfth century, fireworks were also being incorporated into weapons, attached to ***projectiles***, from a catapult or on arrows. Gunpowder weaponry was used in the Crusades; fireworks and weapons having spread along the Silk Road to the Middle East, and later reaching Europe.

In the eighteenth century the Italians developed aerial shells and colours, and the optimum (and current) formulation of black powder was found: 75% potassium nitrate, 15% charcoal and 10% sulfur.

Reactants

Fireworks are essentially a ***combustion*** reaction, requiring a fuel, oxygen and a source of heat.

The ***fuel*** is the carbon and sulfur in the black powder – aluminium, magnesium and titanium are also used. All these substances act as reducing agents.

As oxygen is only 20% of the atmosphere, these reactions need extra oxygen provided by oxidising agents – potassium nitrate (from the black powder), chlorate or perchlorate.

Two extra ingredients are also found in fireworks. A binder of moistened dextrin holds the mixture together. And a chlorine donor helps strengthen some colours.

The explosion of fireworks can also be described as an ***exothermic redox*** reaction.

The reaction

The heat source is a flame lighting the fuse, which ignites the black powder. The sulfur melts first at 113°C, flowing over the potassium nitrate and charcoal, which then react.

The potassium nitrate undergoes ***thermal decomposition*** into potassium oxide, nitrogen and oxygen. The carbon and sulfur burn to produce oxides as gases. The production of gases and the rapid increase in temperature causes a large increase in pressure which creates the explosion.

The speed of this reaction (the speed of energy release) can be controlled by how tightly packed the black powder is, the size of the granules, and the amount of moisture. In the open air, black powder's heat and gas dissipate quickly.

The key to fireworks' success is to trap the heat and gas in a confined space, until the pressure of the trapped gas builds to such a force that, when it escapes, it hurls the firework high into the air or explodes the firework open.

Types of fireworks

Fireworks can be divided into three types – aerial displays, sparklers and firecrackers.

Firecrackers were one of the earliest types of fireworks. They are simply black powder wrapped in paper. When ignited the combustion reaction produces gases which expand and blow apart the paper wrapper.

Sparklers are a little more complex. They are made up of a fuel, an oxidiser, metal powder (Al, Mg or Ti), and a binder.

The components are mixed with water to form a slurry, then shaped onto a wire and dried.

When sparklers are ignited

Sparkler, photo by Nong on Unsplash.

at one end they burn slowly but at a temperature of more than 1,000°C. The production of gases during the reaction forcibly ejects bits of the burning powdered metal from the sparkler.

A skyrocket is a common form of firework, although the first skyrockets were used in warfare. They have a stick to embed in the ground or in a bottle, and a ***fuse*** which ignites the explosive substances in the neck of the rocket to set off the stars at the top.

Structure of aerial fireworks

One of the most common types of commercial aerial fireworks, often used in public displays, looks like a cylinder and functions like a rocket.

The firework itself is wrapped in a cardboard shell which sits inside a tube called the mortar. The shell is filled with small pellets, known as stars, each containing the reaction mix (fuel, ***oxidant***, ***reductant***, colouring agent and binders). The stars are expertly arranged and packed into shells with a charge of black powder.

The firework is set off when the fuse is lit, manually or with an electrical device. The heat travels along the fuse until it reaches the bottom of the firework shell, igniting the lift charge of black powder. This charge reacts, creating hot gases and lots of energy, which escape through a small hole to launch the shell out of the mortar.

Once the firework is safely above onlookers a timed fuse ignites, activating the burst charge of black powder. When this second charge explodes it ignites the stars, creating the firework's special sound and light effects as they explode. The appearance of each firework depends on the type, size, and quantity of stars it contains.

Fireworks can be engineered as a "multibreak" shell, where several isolated chambers contain different chemical mixtures. The chambers ignite in series producing different visual and sound effects.

Most fireworks are still made by hand because sparks or static electricity from metal machinery would ignite the explosives. To protect workers, buildings must be separated by concrete blast walls and roofs weakened to ensure that any explosion travels upwards rather than outwards.

Light and sound effects

Some elements give off a specific colour when burnt.

Colour	Element formulation
Red	Strontium or lithium nitrate, carbonate, sulfate or chloride
Orange	Calcium carbonate, sulfate or chloride
Yellow	Sodium nitrate, chloride or bicarbonate
Green	Barium nitrate, carbonate, chloride or chlorate
Blue	Copper carbonate, chloride or oxide
Purple	Copper and strontium compounds
Silver/ white	Metallic magnesium and aluminium

The metal compound is added to the star to give the colour wanted. The energy from the bursting charge is absorbed by the metal compound and released as light of specific colours, a process known as ***luminescence***. An electron in the vapour absorbs energy and is excited into a higher orbital; when it returns to its original place it releases a photon of light of a specific wavelength or colour.

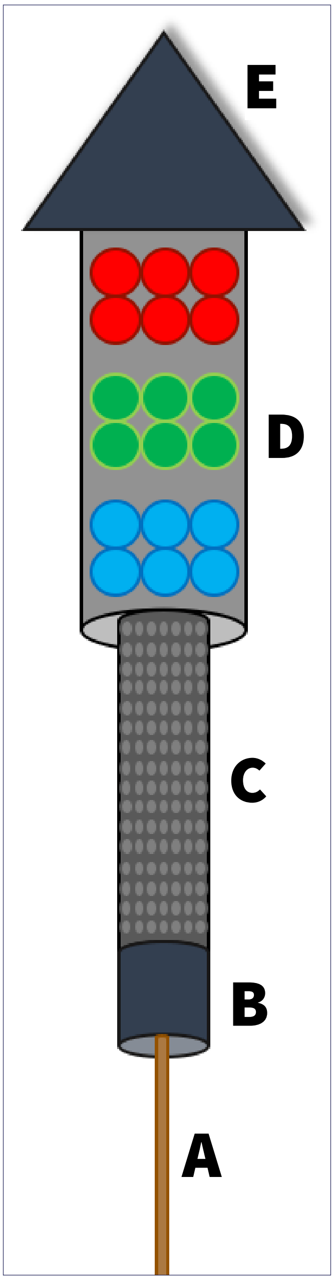

Diagram of a skyrocket. B–E make up the shell. From GlamSci blog.

Blue has been a challenge to achieve, largely because copper compounds are easily destroyed at the high temperatures involved, over 2,000°C.

Some metal flakes can be added to the stars to give an effect of sparkles, as ***incandescent*** solids. Aluminium, magnesium and titanium all produce white sparks; iron gives gold, and charcoal produces red and orange.

The sound effects associated with fireworks come from the rapid production of a large amount of gas.

If a firework has a small opening for the gas to exit through, it will produce a whistling sound. The speed of the gas and size of the opening will vary the sound of the whistle.

In some fireworks, potassium benzoate or sodium salicylate is packed tightly into a tube, where it burns and releases gas slowly, which also creates a whistling sound in the tube.

Potassium chlorate results in a louder sound, while the use of bismuth creates a crackling or popping effect.

Humming fireworks are those which produce a very sharp hissing noise. The gas comes out of a small tube at an angle which makes the tube spin in the air, causing the hiss to become a hum.

Making a boom is much easier – engineer an explosion in a confined space with nowhere for the gas to go. This sound, actually a ***sonic boom*** or shock wave, is the result of gases from the chemical reaction expanding faster than the speed of sound.

Preparing fireworks that have the desired colours, effects, and size without being too dangerous is a complex challenge.

Environmental concerns

Fireworks add pollutants to the atmosphere, including:

- Suspended fine particulates including soot
- Gases such as ozone, sulfur dioxide, and nitrogen oxides
- Fine aerosols of K, Mg, Sr, Ba and Cu ions
- Organic substances such as dioxins
- Nitrates and perchlorates.

All of these have adverse health effects, and have been measured at extremely high concentrations. However, some believe the public health hazard is not significant as these fireworks displays are rare, detonate at altitude and burn outdoors, where the pollutants can be dispersed in a large volume of air.

Concern over pollutants and consumer safety have restricted the sale and use of consumer fireworks in many countries, although professional displays remain popular. Pyrotechnic competitions are held in many countries every year, the biggest in Montreal and Manila.

Research into environmentally friendly alternatives is underway, so far studying iodine replacing chlorine and boron replacing barium, although these are not yet cost-effective. Silent fireworks are also being investigated.

Questions for students

1. Write word and balanced equations for the three reactions that occur when black powder ignites.
2. What causes the explosions of fireworks?
3. Find examples of physical and chemical changes in the article.
4. What aspects of fireworks relate to the gas laws?
5. By what name is black powder more commonly known?
6. Identify the five parts of the sky rocket, A to E.
7. Why do we see the fireworks before we hear the explosion?
8. Why might we want silent fireworks?
9. Explain the terms in bold italics: charcoal, projectile, fuel, oxidant, reductant, combustion, exothermic, redox, fuse, thermal decomposition, luminescence, incandescent, sonic boom.
10. Research the health effects of some of the pollutants.
11. Observe the colours of metallic ions in a practical or watch this video.
12. Although science can create fireworks, should we? Approach this as a socio-scientific issue: What are the pros and cons; what are the impacts on people and the environment; what are some different perspectives on the use of fireworks? Think about tiakitanga, and consider advice from pet owners, fire brigades and other sources. Include your own opinion.

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Compound Chemistry infographic posters by Andy Brunning: 2014, Gunpowder, Sparklers, and Fireworks chemistry; 2015, Fireworks sounds; and 2017, Environmental effects.

Ngā Kupu

Hāora – Oxygen
Pahū ahi – Fireworks
Pakū – To explode; explosion
Paura – Gunpowder
Pungatara – Sulfur
Tākirirangi – Rocket
Tauhohe ngingiha – Combustion reaction
Tiripapā – To explode in succession; cracker, firework
Totepita – Saltpetre, potassium nitrate
Waro – Charcoal.

Te Aka Māori Dictionary and *Paekupu*