Introduction to Pyrotechnics

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Chapter 1

Pyrotechnics

Pyrotechnics gerbs used in the entertainment industry.

Pyrotechnics is the science of using materials capable of undergoing self-contained and self-sustained exothermic chemical reactions for the production of heat, light, gas, smoke and/or sound. Pyrotechnics include not only the manufacture of fireworks but items such as safety matches, oxygen candles, explosive bolts and fasteners, and components of the automotive airbag.

Pyrotechnic devices combine high reliability with very compact and efficient energy storage, in the form chemical energy which is converted to expanding hot gases either through deflagration or detonation. The controlled action of a pyrotechnic device (initiated by any of several means, including an electrical signal, optical signal or mechanical impetus) makes possible a wide range of automated and/or remote mechanical actions; for example, the deployment of safety equipment and services, precisely timed release sequences, etc. The majority of the technical pyrotechnic devices use propellants in their function, a minority use materials that are classified as primary or secondary explosives to obtain very fast and powerful mechanical (mostly cutting) actions; for example cable cutters, exploding bolts, or similar pyrotechnic fasteners.

Individuals responsible for the safe storage, handling, and functioning of pyrotechnic devices are referred to as pyrotechnicians.

Proximate pyrotechnics

Explosions, flashes, smoke, flames, fireworks or other propellant driven effects used in the entertainment industry are referred to as pyrotechnic special effects, theatrical effects, or proximate pyrotechnics. Proximate refers to the pyrotechnic device's location relative to an audience. In the majority of jurisdictions, special training and licensing must be obtained from local authorities to legally prepare and use proximate pyrotechnics.

Rammstein uses pyrotechnics numerous times in their shows, such as this performance of Feuer Frei.

Pyrotechnics stunt exhibition by "Giant Auto Rodéo", Ciney, Belgium.

Many musical groups use pyrotechnics to enhance their live shows as pioneered by the rock band KISS. Some of the earliest bands to use pyrotechnics were The Who, Pink Floyd and Queen. German industrial metal band Rammstein are renowned for their large variety of pyrotechnics, which range from flaming costumes to face-mounted flamethrowers. Nightwish and Lordi are also known for their vivid pyrotechnics in concert. Many professional wrestlers have also used pyrotechnics as part of their entrances to the ring.

Modern pyrotechnics are, in general, divided into categories based upon the type of effect produced or manufacturing method. The most common categories are:

- Airburst - Hanging charges designed to burst into spheres of sparks.
- Binary kits - Powders divided into oxidizer and fuel intended to be mixed before use.
- Comets (meteor) - Rising shots resembling shooting stars.

- Preloaded Comet
- Preloaded Mine - Tubes containing a lift charge intended to project stars, sparks, confetti or streamers.
- Preloaded Smoke Pot - Cartridges designed to release a mushroom cloud of smoke.
- Preloaded Report (concussion tube) - Tubes designed to create a loud report.
- Falls - Devices intended to drop like falling stars.
- Fireballs / Mortar Hits - Containers creating mushroom clouds of flame.
- Flame Projector - Columns shooting pillars of flame.
- Flare (Torch) - Short, high intensity flames or various colours.
- Flash Cotton (Sparkle String) - Cotton string impregnated with nitrocellulose.
- Flashpaper - Sheets of nitrocellulose resembling tissue paper.
- Flash Pot - A container for creating a bright flash and smoke.
- Flash Tray (split mine) - A long tube creating a wide, bright flash.
- Gerb (including fountain, whistle, and waterfall) - A fountain of sparks.
- Lance - A small brightly colored fountaĉin that produces few sparks.
- Line Rockets - Whistling gerbs traveling across wires.
- Multi-Tube Article (multi-shot plate, multiple shot repeater boards and bombardo boards; designed to function in sequence) - Multiple effects chained together.
- Pre-Mixed Powder - Powders intended to create various effects. (Concussions, flashes, etc.)
- Squib - A small, pre-matched device typically used to replicate bullet hits.
- Strobe - A device intended to create bright repetitive flashes.
- Wheel (Saxon) - Tubes that create a spinning wheel of sparks.
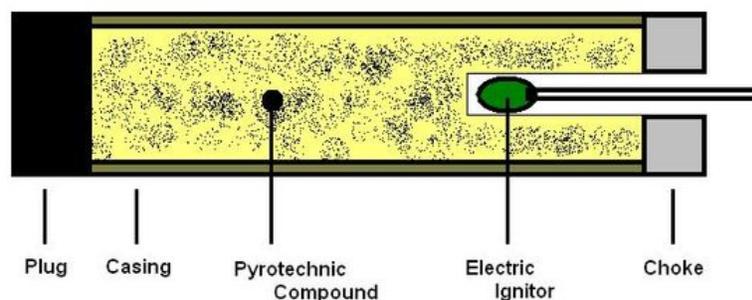
A basic pyrotechnic device

A basic theatrical effect, designed to create a jet or fountain of sparks, is referred to as a gerb. A gerb consists of a sufficiently strong and non-flammable container to hold the pyrotechnic compound. Typical pyrotechnic formulations consist either of flammable materials such as nitrocellulose and/or black powder or a mixture of a fuel and oxidizer blended in situ. A plug placed at one end of the container with a small orifice, called a choke, constricts the expulsion of the ignited pyrotechnic compound, increasing the size and aggressiveness of the jet.

Pyrotechnics are widely used in professional wrestling, including the WWE, to enhance the event.

Various ingredients may be added to pyrotechnic devices to provide colour, smoke, noise or sparks. Special additives and construction methods are used to modify the character of the effect produced, either to enhance or subdue the effect; for example, sandwiching layers of pyrotechnic compounds containing potassium perchlorate, sodium salicylate or sodium benzoate with layers that do not creates a fountain of sparks with an undulating whistle.

In general, such pyrotechnic devices are initiated by a remotely controlled electrical signal that causes an electric match, or e-match, to produce ignition. The remote control may be manual, via a switch console, or computer controlled according to a pre-programmed sequence and/or a sequence that tracks the live performance via stage cues.

Display pyrotechnics

The 2008/2009 NYE Melbourne fireworks display as seen from Alexandra Gardens

Display pyrotechnics, also known as commercial fireworks, are pyrotechnic devices intended for use outdoors, where the audience can be further away, and smoke and fallout is less of a concern. Generally the effects, though often similar to proximate pyrotechnics, are of a larger size and more vigorous in nature. It will typically take an entire day to setup a professional fireworks display. The size of these fireworks can range from 50 mm (2") to over 600 mm (24") diameter depending on the type of effect and available distance from the audience. In most jurisdictions, special fireworks training and licensing must be obtained from local authorities to legally prepare and use display pyrotechnics.

Consumer pyrotechnics

Consumer pyrotechnics are devices readily available for purchase to the general public with little or no special licensing or training. These items are considered *relatively* low hazard devices but, like all pyrotechnics, can still be hazardous and should be stored, handled and used appropriately. Some of the most common examples of consumer pyrotechnics encountered include recreational fireworks (including whistling and sparking types), model rocket motors, highway and marine distress flares, sparklers and caps for toy guns. Pyrotechnics are also indirectly involved in other consumer products such as powder actuated nail guns, ammunition for firearms, and modern fireplaces. Some types, including bird scarers, shell crackers, whistle crackers and flares, may be designed to be fired from a 12-gauge pistol or rifle.

Safety

Pyrotechnics are dangerous and must be handled and used properly. Recently, several high profile incidents involving pyrotechnics have re-enforced the need to respect these explosives at all times. Proximate pyrotechnics is an area of expertise that requires additional training beyond that of other professional pyrotechnics areas and the use of devices specifically manufactured for indoor, close proximity use.

Homemade devices

Homemade flashpots built without any safety mechanisms

A common low-budget pyrotechnic flash pot is built using modified screw-in electric fuses in a common light fixture. Homemade devices commonly fail to include the appropriate safety features and can provide numerous hazards, including:

- The firing circuit using direct unisolated AC line voltage, which is a shock hazard to the operator and bystanders.
- The use of high-current fuses as ignitors can cause large main circuit breakers and building-wide and street level fuses to trip, due to the sudden inrush of hundreds of amperes through a dead-shorted circuit

- With a home-made device, there is usually no indication of whether the source is powered. Screwing a powder-loaded fuse into an unknowingly powered socket will result in immediate ignition of the pyrotechnics, injuring the operator.

Proper commercial flash pots include safety features such as warning pilot lamps, preignition grounding, and safing circuits. They also use isolated and low-voltage power sources, and have keyed power connections to help prevent accidental ignition.

Pyrotechnic incidents

My Chemical Romance performing live with pyrotechnics, on the stage, probably while playing "Mama" or "Famous Last Words"

Pyrotechnics are dangerous substances that must always be treated with the utmost respect and with the proper training. Due to the hazardous nature of these materials, precautions must always be taken to ensure the safety of all individuals in the vicinity of pyrotechnics. Despite all precautions, accidents and errors occur from time to time, which may result in property damage, injury and in severe cases loss of life. These incidents may be the result of poorly manufactured product, unexpected or unforeseen events, or in many cases, the result of operator error.

Some of the more widely publicized incidents involving pyrotechnics in recent history include:

In 2003, improper use of pyrotechnics caused a fire in a Rhode Island nightclub called The Station. The Station nightclub fire was started when the fireworks the band Great White were using accidentally ignited inflammable soundproofing foam. The pyrotechnics in question were not appropriate. The foam caused combustion to spread rapidly and the resulting fire led to 100 deaths, apparently because their quick escape was blocked by ineffective exit doors. While the type of foam used and the lack of a sprinkler system were important factors in the fire, the Great White fire could likely have been prevented had those involved paid attention to standard safety practices around the use of pyrotechnics.

A similar pyrotechnic-induced fire in 2004 destroyed the Republica Cromagnon nightclub in Buenos Aires, Argentina, killing 194 people.

In May 2000, a small fire led to two massive explosions at the SE Fireworks Depot in Enschede, Holland, leaving 23 people dead, 947 people were injured and an estimated 2,000 homes damaged or destroyed.

Chapter 2

Fireworks

Fireworks over Sydney on New Year's Eve

Fireworks closer view

A fireworks display on Taipei 101 in Taiwan, which in 2005 held the world's first fireworks display on a supertall skyscraper

Fireworks are a class of explosive pyrotechnic devices used for aesthetic and entertainment purposes. The most common use of a firework is as part of a **fireworks display**. A **fireworks** event (also called a **fireworks show** or **pyrotechnics**) is a display of the effects produced by firework devices. Fireworks competitions are also regularly held at a number of places. Fireworks (devices) take many forms to produce the four primary effects: noise, light, smoke, and floating materials (confetti for example). They may be designed to burn with colored flames and sparks including red, orange, yellow, green, blue, purple, and silver. Displays are common throughout the world and are the focal point of many cultural and religious celebrations.

Fireworks were invented in ancient China in the 12th century to scare away evil spirits, as a natural extension of the Four Great Inventions of ancient China of gunpowder. Such important events and festivities as Chinese New Year and the Mid-Autumn Moon Festival were and still are times when fireworks are guaranteed sights. China is the largest manufacturer and exporter of fireworks in the world.

Fireworks are generally classified as to where they perform, either as a ground or aerial firework. In the latter case they may provide their own propulsion (skyrocket) or be shot into the air by a mortar (aerial shell).

The most common feature of fireworks is a paper or pasteboard tube or casing filled with the combustible material, often pyrotechnic stars. A number of these tubes or cases are often combined so as to make, when kindled, a great variety of sparkling shapes, often variously colored. The skyrocket is a common form of firework, although the first skyrockets were used in war. Such rocket technology has also been used for the delivery of mail by rocket and is used as propulsion for most model rockets. The aerial shell, however, is the backbone of today's commercial aerial display, and a smaller version for consumer use is known as the festival ball in the United States.

Ground fireworks, although less popular than aerial ones, create a stunning exhibition. These types of fireworks can produce various shapes, ranging from simple rotating circles, stars and 3D globes.

History

An etching of the 'Royal Fireworks' display on the Thames, London, England in 1749.

Fireworks at the London Eye in London on New Year's Eve

The earliest documentation of fireworks dates back to 7th century China where they were first used to frighten away evil spirits with their loud sound (鞭炮/鞭砲 *biān pào*) and to pray for happiness and prosperity.

Eventually the art and science of firework making developed into an independent profession. In ancient China, pyrotechnicians (firework-masters) were respected for their knowledge and skill in mounting dazzling displays of light and sound. A record in 1264 states that the speed of the rocket-propelled 'ground-rat' firework frightened the Empress Dowager Gong Sheng during a feast held in her honor by her son Emperor Lizong of Song (r. 1224–1264). By the 14th century rocket propulsion was common in warfare, as

evidenced by the *Huolongjing* compiled by Liu Ji (1311–1375) and Jiao Yu (fl. c. 1350–1412).

However, in China, fireworks for ceremonies and celebrations were mostly for royalties and the rich before the 14th century. It was only in the Ming Dynasty that any event for common people — a birth, a wedding, a business opening, or a New Year's Eve celebration — became a fitting occasion for fireworks and other noisemakers.

Amédée-François Frézier published a "Treatise on Fireworks" in 1706, covering the recreational and ceremonial uses of fireworks, rather than their military uses. The book became a standard text for fireworks makers.

Music for the Royal Fireworks was composed by George Frideric Handel in 1749 to celebrate the peace Treaty of Aix-la-Chapelle, which had been declared the previous year.

Safety

Preparing fireworks at Sayn Castle, Germany

Improper use of fireworks may be dangerous, both to the person operating them (risks of burns and wounds) and to bystanders; in addition, they may start fires after landing on

flammable material. For this reason, the use of fireworks is generally legally restricted. Display fireworks are restricted by law for use by professionals; consumer items, available to the public, are smaller versions containing limited amounts of explosive material to reduce potential danger. Fireworks may pose a problem for animals, both domestic and wild, who can be terrified by the noise, leading to them running away or hurting themselves on fences or in other ways in an attempt to escape.

Competitions

A burning ground firework during a traditional Maltese feast.

A ground firework showing various technical parts mentioned here, such as the chain and a set of gears.

The grand finale showing also the jets that produce power. A picture taken from the back so the stars and flowers are not so clearly visible.

Pyrotechnical competitions involving fireworks are held in many countries. One of the most prestigious fireworks competition is the Montreal Fireworks Festival, an annual competition held in Montreal, Quebec, Canada. Another magnificent competition is Le Festival d'Art Pyrotechnique held in the summer annually at the Bay of Cannes in Côte d'Azur, France. The World Pyro Olympics is an annual competition amongst the top fireworks companies in the world. It is held in Manila, Philippines. The event is one of the largest and most intense international fireworks competitions.

Fireworks world records

The current Guinness World Records as of 5 November 2007 are

Largest Catherine wheel

A self-propelled vertical firework wheel 25.95 m (85 ft) in diameter was designed by the Newick Bonfire Society Ltd and fired for at least one revolution on 30 October 1999 at the Village Green, Newick, East Sussex, UK.

Largest firework display

The record for the largest firework display consisted of 66,326 fireworks and was achieved by Macedo'S Pirotecnia Lda. in Funchal, Madeira, Portugal, on 31 December 2006.

Longest firework waterfall

The world's longest firework waterfall was the 'Niagara Falls', which measured 3,125.79 m (10,255 ft 2.5 in) when ignited on 24 August 2003 at the Ariake Seas Fireworks Festival, Fukuoka, Japan.

Most firework rockets launched in 30 seconds

The record for the most firework rockets launched in 30 seconds is 56,405, in an attempt organized by Dr Roy Lowry (UK), executed by Fantastic Fireworks, at the 10th British Firework Championship in Plymouth, UK, on 16 August 2006.

Largest bonfire

The largest bonfire had an overall volume of 1,401.6 m³ (49,497 ft³). The bonfire was built by Colin Furze (UK) in Thistleton, Leicestershire, UK, and lit on 14 October 2006.

Tallest bonfire

The world's tallest bonfire tondo measured 37.5 m (123 ft) high, with a base of 8 m² (86 ft²) and an overall volume of 800 m³ (28,251 ft³). The event was organized by Kure Commemorative Centennial Events Committee, and lit on 9 February 2003 at Gohara-cho, Hiroshima, Japan, as part of a traditional ceremony to encourage good health and a generous harvest.

Clubs

Enthusiasts in the United States have formed clubs which unite hobbyists and professionals. The groups provide safety instruction and organize meetings and private "shoots" at remote premises where members shoot commercial fireworks as well as fire pieces of their own manufacture. Clubs secure permission to fire items otherwise banned by state or local ordinances. Competition among members and between clubs, demonstrating everything from single shells to elaborate displays choreographed to music, are held. One of the oldest clubs is CrackerJacks, Inc., organized in 1976 in the Eastern Seaboard region of the U.S.

Pyrotechnics Guild International

The Pyrotechnics Guild International, Inc. or PGI, founded in 1969, is an independent worldwide nonprofit organization of amateur and professional fireworks enthusiasts. It is

notable for its large number of members, around 3,500 in total. The PGI exists solely to further the safe usage and enjoyment of both professional grade and consumer grade fireworks while both advancing the art and craft of pyrotechnics and preserving its historical aspects. Each August the PGI conducts its annual week-long convention, where some the world's biggest and best fireworks displays occur. Vendors, competitors, and club members come from around the USA and from various parts of the globe to enjoy the show and to help out at this all-volunteer event. Aside from the nightly firework shows, the competition is a highlight of the convention. This is a completely unique event where individual classes of hand-built fireworks are competitively judged, ranging from simple fireworks rockets to extremely large and complex aerial shells. Some of the biggest, best, most intricate fireworks displays in the United States take place during the convention week.

Amateur and professional members can come to the convention to purchase fireworks, paper goods, novelty items, non-explosive chemical components and much more at the PGI trade show. Before the nightly fireworks displays and competitions, club members have a chance to enjoy open shooting of any and all legal consumer or professional grade fireworks, as well as testing and display of hand-built fireworks. The week ends with the Grand Public Display on Friday night, which gives the chosen display company a chance to strut their stuff in front of some of the world's biggest fireworks aficionados. The stakes are high and much planning is put into the show. In 1994 a shell of 36 inches (910 mm) in diameter was fired during the convention, more than twice as large as the largest shell usually seen in the USA, and shells as large as 24 inches (610 mm) are frequently fired.

Halloween

In Ireland (both the Republic of Ireland and Northern Ireland), during the Halloween season, there are many fireworks displays. The largest are in the cities of Belfast, Derry and Dublin. In 2010, the Halloween fireworks display in Derry captivated an audience of over 20,000 people. The sale of fireworks is strongly restricted in the Republic of Ireland, though many illegal fireworks are sold throughout October or smuggled over the Northern Ireland border (where there is a large black market for fireworks). In the Republic, the punishment for possessing fireworks without a licence is a €10,000 fine for possessing them, and/or a five year prison sentence. The punishment for having or lighting fireworks in a public place is the same.

Both fireworks and firecrackers are a popular tradition during Halloween in Nova Scotia and Vancouver, although apparently this is not the custom elsewhere in Canada. The two known firework displays used during All Hallows' Eve in the United States are the annual "Happy Hallowishes" show at Walt Disney World's Magic Kingdom "Mickey's Not-So-Scary Halloween Party" event, which began in 2005, and the "Halloween Screams" at Disneyland Park, which began on the 25 September 2009.

Fireworks celebrations throughout the world

Japanese fireworks festivals

During the summer in Japan, fireworks festivals (花火大会 *hanabi taikai*ˀ) are held nearly every day someplace in the country, in total numbering more than 200 during August. The festivals consist of large fireworks shows, the largest of which use between 100,000 and 120,000 rounds (Tondabayashi, Osaka), and can attract more than 800,000 spectators. Street vendors set up stalls to sell various drinks and staple Japanese food (such as Yakisoba, Okonomiyaki, Takoyaki, kakigori (shaved ice)), and traditionally held festival games, such as Kingyo-sukui, or Goldfish scooping.

Even today, men and women attend these events wearing the traditional Yukata, summer Kimono, or Jinbei (men only), collecting in large social circles of family or friends to sit picnic-like, eating and drinking, while watching the show.

The first fireworks festival in Japan was held in 1733.

Indian fireworks celebrations

North and South Indians throughout the world celebrate with fireworks as part of their popular "festival of lights" (Diwali) in Oct-Nov every year. Quieter varieties of fireworks are more popular for this festival.

Singapore fireworks celebrations

Singapore Fireworks Festival 2006, 8 August 2006

The Singapore Fireworks Celebrations (previously the *Singapore Fireworks Festival*) is an annual event held in Singapore as part of its National Day celebrations. The festival features local and foreign teams which launch displays on different nights. While currently non-competitive in nature, the organizer has plans to introduce a competitive element in the future.

The annual festival has grown in magnitude, from 4,000 rounds used in 2004, 6,000 in 2005, to over 9,100 in 2006.

United Kingdom fireworks festivals

Hogmanay Fireworks in Edinburgh

One of the biggest occasions for fireworks in the UK is Guy Fawkes Night held each year on 5 November, while the biggest in Northern Ireland takes place at Halloween. Guy Fawkes Night is a celebration of the foiling of the Gunpowder Plot on 5 November 1605, an attempt to kill King James I.

Britain's Biggest Fireworks Events (as of 30 October 2008):

  Battle Fireworks, East Sussex
  After Dark fireworks, Sheffield
  Sparks in the Park (Cardiff Round Table charity fireworks), Cardiff
  Flaming Tar Barrels, Ottery St Mary
  Blackheath Fireworks, London
  Fireworks with Vikings, Tutbury, Staffordshire
  Bangers on the Beach (Holyhead Round Table charity fireworks), Holyhead
  Bught Park fireworks, Inverness
  Glasgow Green fireworks
  Halloween Happening fireworks, Derry
  Midsummer Common, Cambridge

There are many firework societies in the counties of East Sussex and West Sussex which were at one time a single county. The societies predate the county boundary changes and are still known collectively as Sussex Bonfire Societies.

United States fireworks celebrations

America's earliest settlers brought their enthusiasm for fireworks to the United States. Fireworks and black ash were used to celebrate important events long before the American Revolutionary War. The very first celebration of Independence Day was in 1777, six years before Americans knew whether the new nation would survive the war; fireworks were a part of all festivities. In 1789, George Washington's inauguration was also accompanied by a fireworks display. This early fascination with their noise and color continues today.

In 1999, Walt Disney World in Lake Buena Vista, Florida, pioneered the commercial use of aerial fireworks launched with compressed air rather than gunpowder for the Epcot night time spectacular, IllumiNations: Reflections of Earth. The display shell explodes in the air using an electronic timer. The advantages of compressed air launch are a reduction in fumes, and much greater accuracy in height and timing.

The Walt Disney Company is the largest consumer of fireworks in the United States.

Uses other than public displays

Consumer fireworks are fireworks the general public can buy. They typically have less explosive power than professional fireworks, but can still produce an acceptable show. Some examples of consumer fireworks are firecrackers, rockets, cakes (multishot aerial fireworks) and smoke balls.

Fireworks can also be used in an agricultural capacity as bird scarers.

Fireworks classifications in the United States

The United States government has classified fireworks and similar devices according to their potential hazards.

Independence Day fireworks in San Diego

Previous US Department of Transportation explosives classifications

Explosives, including fireworks, were previously divided into three classifications for transportation purposes by the DOT.

- **Class A** explosives included high explosives such as dynamite, TNT, blasting caps, packages of flash powder, bulk packages of black powder and blasting agents such as ANFO and other slurry types of explosives.
- **Class B** explosives included low explosives such as "display fireworks" which were the larger and more powerful fireworks used at most public displays.

- **Class C** explosives included other low explosives such as igniters, fuses and "common fireworks", which were the smaller and less powerful fireworks available for sale to and use by the general public.

At the time most purchases and use of all of these explosives, with specific exceptions for high explosives purchased and used in state, black powder used for sporting purposes and common fireworks, required either a Bureau of Alcohol, Tobacco and Firearms (ATF) license or permit to purchase and use, and/or a state or local license or permit to purchase and use.

New explosives classes

The U.S. government now uses the United Nations **explosives shipping classification system**. This new system is based on hazard in shipping only, vs. the old USA system of both shipping and use hazards. The BATF and most states performed a direct substitution of **Shipping Class 1.3** for **Class B**, and **Shipping Class 1.4** for **Class C**. This allows some hazardous items that would have previously been classified as **Class B** and regulated to be classified as **Shipping Class 1.4** due to some packaging method that confines any explosion to the package. Being **Shipping Class 1.4**, they can now be sold to the general public and are unregulated by the BATF.

A code number and suffix (such as **1.3G**) is not enough to fully describe a material and how it is regulated, especially in **Shipping Class 1.4G**. It also must have a **UN Number** that exactly describes the material. For example, common consumer fireworks are **UN0336**, or **Shipping Class 1.4G UN0336**.

Here are some *common* fireworks classes:

- **Class 1.1G** (Mass Explosion Possible:Pyrotechnics) **UN0094** Flashpowder
- **Class 1.1G** (Mass Explosion Possible:Pyrotechnics) **UN0333** Fireworks (Salutes in bulk or in manufacture)
- **Class 1.2G** (Projection but not mass explosion:Pyrotechnics) **UN0334** Fireworks (Rarely used)
- **Class 1.3G** (Fire, Minor Blast:Pyrotechnics) **UN0335** Fireworks (Most Display Fireworks) Current federal law states that without appropriate ATF license/permit, the possession or sale of any display/professional fireworks is a felony punishable by up to 5 years in prison.
  - Any ground salute device with over 50 milligrams of explosive composition
  - Torpedoes (except for railroad signaling use)
  - Multi-tube devices containing over 500 grams of pyrotechnic composition and without 1/2" space between each tube
  - Any multiple tube fountains with over 500 grams of pyrotechnic composition and without 1/2" space between each tube
  - Any reloadable aerial shells over 1.75" diameter
  - Display shells

- o Any single-shot or reloadable aerial shell/mine/comet/tube with over 60 grams of pyrotechnic composition
- o Any Roman candle or rocket with over 20 grams of pyrotechnic composition
- o Any aerial salute with over 130 milligrams of explosive composition
- **Class 1.4G** (Minor Explosion Hazard Confined To Package:Pyrotechnics) **UN0336** Fireworks (Consumer or Common Fireworks) Most popular consumer fireworks sold in the US.
  - o Reloadable aerial shells 1.75" or less sold in a box with not more than 12 shells and one launching tube
  - o Single-shot aerial tubes
  - o Bottle rockets
  - o Skyrockets and missiles
  - o Ground spinners, pinwheels and helicopters
  - o Flares & fountains
  - o Roman candles
  - o Smoke and novelty items
  - o Multi-shot aerial devices, or "cakes"
  - o Firecracker packs. Although some firecracker items may be called "M-80's", "M-1000's", "Cherry bombs" or "Silver Salutes" by the manufacturer, they must contain less than 50 milligrams of flash or other explosive powder in order to be legally sold to consumers in the United States.
  - o Sparklers
  - o Catherine wheel
  - o black snakes and strobes
  - o Mines
- **Class 1.4S** (Minor Explosion Hazard Confined To Package: Packed As To Not Hinder Nearby Firefighters) **UN0336** Fireworks (Consumer or Common Fireworks)
- **Class 1.4G** (Minor Explosion Hazard Confined To Package:Pyrotechnics) **UN0431** ARTICLES, PYROTECHNIC for technical purposes (Proximate Pyrotechnics)
- **Class 1.4S** (Minor Explosion Hazard Confined To Package: Packed As To Not Hinder Nearby Firefighters) **UN0432** ARTICLES, PYROTECHNIC for technical purposes (Proximate Pyrotechnics)

Fireworks tubes are made by rolling thick paper tightly around a former, such as a dowel. They can be made by hand, most firework factories use machinery to manufacture tubes. Whenever tubes are used in fireworks, at least one end is always plugged with clay to keep both chemicals and burning gases from escaping through that end. The tooling is always made of non-sparking materials such as aluminium or brass. Experts at handling explosives, called pyrotechnicians, add chemicals for special effects.

British fireworks classification

Britain has its own system of classifying fireworks.

- **Category 1** - indoor fireworks, for use in small areas.

- **Category 2** - garden fireworks; must be safely viewable from 5 meters and must not scatter debris beyond 3 meters.

- **Category 3** - display fireworks; must be safely viewable from 25 meters and must not scatter debris beyond 50 meters.

- **Category 4** - professional fireworks; a person must have adequate insurance and storage to purchase and use these fireworks. Insurance can only be obtained once they have a knowledge of the safe use and storage of Category 4 fireworks. There is no such thing as a "license" to buy or use Category 4 fireworks.

Pyrotechnic compounds

Copper compounds glow green or blue-green in a flame.

Colors in fireworks are usually generated by *pyrotechnic stars*—usually just called *stars*—which produce intense light when ignited. Stars contain five basic types of ingredients.

- A **fuel** which allows the star to burn
- An **oxidizer**—a compound which produces (usually) oxygen to support the combustion of the fuel
- **Color**-producing chemicals

- A **binder** which holds the pellet together.
- A **chlorine donor** which provides chlorine to strengthen the color of the flame. Sometimes the oxidizer can serve this purpose.

Some of the more common color-producing compounds are tabulated here. The color of a compound in a firework will be the same as its color in a flame test (shown at right). Not all compounds that produce a colored flame are appropriate for coloring fireworks, however. Ideal colorants will produce a pure, intense color when present in moderate concentration.

Color	Metal	Example compounds
Red	Strontium (intense red)	$SrCO_3$ (strontium carbonate)
	Lithium (medium red)	Li_2CO_3 (lithium carbonate) LiCl (lithium chloride)
Orange	Calcium	$CaCl_2$ (calcium chloride)
Yellow	Sodium	$NaNO_3$ (sodium nitrate)
Green	Barium	$BaCl_2$ (barium chloride)
Blue	Copper halides	$CuCl_2$ (copper chloride), at low temperature
Indigo	Cesium	$CsNO_3$ (cesium nitrate)
Violet	Potassium	KNO_3 (potassium nitrate)
	Rubidium (violet-red)	$RbNO_3$ (rubidium nitrate)
Gold	Charcoal, iron, or lampblack	
White	Titanium, aluminium, beryllium, or magnesium powders	

The brightest stars, often called **Mag Stars**, are fueled by aluminium. Magnesium is rarely used in the fireworks industry due to its lack of ability to form a protective oxide layer. Often an alloy of both metals called magnalium is used.

Many of the chemicals used in the manufacture of fireworks are non-toxic, while many more have some degree of toxicity, can cause skin sensitivity, or exist in dust form and are thereby inhalation hazards. Still others are poisons if directly ingested or inhaled.

Abstract reference of chemicals used in fireworks industry

The following table is an educational guideline for the chemistry of fireworks.

Symbol	Name	Fireworks Usage
Al	Aluminum	Aluminum is used to produce silver and white flames and sparks. It is a common component of sparklers.
Ba	Barium	Barium is used to create green colors in fireworks, and it can also help stabilize other volatile elements.
C	Carbon	Carbon is one of the main components of black powder, which is

		used as a propellent in fireworks. Carbon provides the fuel for a firework. Common forms include carbon black, sugar, or starch.
Ca	Calcium	Calcium is used to deepen firework colors. Calcium salts produce orange fireworks.
Cl	Chlorine	Chlorine is an important component of many oxidizers in fireworks. Several of the metal salts that produce colors contain chlorine.
Cs	Cesium	Cesium compounds help to oxidize firework mixtures. Cesium compounds produce an indigo color in fireworks.
Cu	Copper	Copper produces blue-green colors in fireworks and halides of copper are use to make shades of blue.
Fe	Iron	Iron is used to produce sparks. The heat of the metal determines the color of the sparks.
K	Potassium	Potassium compounds help to oxidize firework mixtures. Potassium nitrate, potassium chlorate, and potassium perchlorate are all important oxidizers. The potassium content can impart a violet-pink color to the sparks.
Li	Lithium	Lithium is a metal that is used to impart a red color to fireworks. Lithium carbonate, in particular, is a common colorant.
Mg	Magnesium	Magnesium burns a very bright white, so it is used to add white sparks or improve the overall brilliance of a firework.
Na	Sodium	Sodium imparts a yellow color to fireworks, however, the color is often so bright that it frequently masks other, less intense colors.
O	Oxygen	Fireworks include oxidizers, which are substances that produce oxygen in order for burning to occur. The oxidizers are usually nitrates, chlorates, or perchlorates. Sometimes the same substance is used to provide oxygen and color.
P	Phosphorus	Phosphorus burns spontaneously in air and is also responsible for some glow in the dark effects. It may be a component of a firework's fuel.
Ra	Radium	Radium would create intense green colors in fireworks, but it is far too hazardous to use.
Rb	Rubidium	Rubidium compounds help to oxidize firework mixtures. Rubidium compounds produce a violet-red color in fireworks.
S	Sulfur	Sulfur is a component of black powder, and as such, it is found in a firework's propellant/fuel.
Sb	Antimony	Antimony is used to create firework glitter effects.
Sr	Strontium	Strontium salts impart a red color to fireworks. Strontium compounds are also important for stabilizing fireworks mixtures.
Ti	Titanium	Titanium metal can be burned as powder or flakes to produce silver sparks.
Zn	Zinc	Zinc is a bluish white metal that is used to create smoke effects for fireworks and other pyrotechnic devices.

Types of effects

Peony

A spherical break of colored stars that burn without a tail effect. The peony is the most commonly seen shell type.

Chrysanthemum

A spherical break of colored stars, similar to a peony, but with stars that leave a visible trail of sparks.

Dahlia

Essentially the same as a peony shell, but with fewer and larger stars. These stars travel a longer-than-usual distance from the shell break before burning out. For instance, if a 3" peony shell is made with a star size designed for a 6" shell, it is then considered a dahlia. Some dahlia shells are cylindrical rather than spherical to allow for larger stars.

Willow

Similar to a **chrysanthemum**, but with long-burning silver or gold stars that produce a soft, dome-shaped weeping willow-like effect.

Ground Bloom Flower

Small twirling ground firework. Emits sparks, fire as well as a Glow. Usually changes colors once to twice.

Palm

A collection of palm-shell fireworks illuminating the beach of Tybee Island, Georgia

A shell containing a relatively few large comet stars arranged in such a way as to burst with large arms or tendrils, producing a palm tree-like effect. Proper palm shells feature a thick rising tail that displays as the shell ascends, thereby simulating the tree trunk to further enhance the "palm tree" effect. One might also see a burst of color inside the palm burst (given by a small insert shell) to simulate coconuts.

Ring

A shell with stars specially arranged so as to create a ring. Variations include smiley faces, hearts, and clovers.

Diadem

A type of **Peony** or **Chrysanthemum** with a center cluster of non-moving stars, normally of a contrasting color or effect.

Kamuro

A typical kamuro effect

Kamuro is a Japanese word meaning "Boys Haircut" which is what this shell looks like when fully exploded in the air. A dense burst of glittering silver or gold stars which leave a heavy glitter trail and are very shiny in the night's sky.

Crossette

A shell containing several large stars that travel a short distance before breaking apart into smaller stars, creating a crisscrossing grid-like effect. Strictly speaking, a crossette star should split into 4 pieces which fly off symmetrically, making a cross. Once limited to silver or gold effects, colored crossettes such as red, green, or white are now very common.

Spider

A typical spider effect

A shell containing a fast burning tailed or charcoal star that is burst very hard so that the stars travel in a straight and flat trajectory before slightly falling and burning out. This appears in the sky as a series of radial lines much like the legs of a spider.

Horsetail

Named for the shape of its break, this shell features heavy long-burning tailed stars that only travel a short distance from the shell burst before free-falling to the ground. Also known as a waterfall shell. Sometimes there is a glittering through the "waterfall."

Time rain

An effect created by large, slow-burning stars within a shell that leave a trail of large glittering sparks behind and make a sizzling noise. The "time" refers to the fact that these stars burn away gradually, as opposed to the standard brocade "rain" effect where a large amount of glitter material is released at once.

Multi-break shells

A large shell containing several smaller shells of various sizes and types. The initial burst scatters the shells across the sky before they explode. Also called a bouquet shell. When a shell contains smaller shells of the same size and type, the effect is usually referred to as "Thousands". Very large bouquet shells (up to 48 inches) are frequently used in Japan.

Fish

Inserts that propel themselves rapidly away from the shell burst, often looking like fish swimming away.

Salute

A shell intended to produce a loud report rather than a visual effect. Salute shells usually contain flash powder, producing a quick flash followed by a very loud report. Titanium may be added to the flash powder mix to produce a cloud of bright sparks around the flash. Salutes are commonly used in large quantities during finales to create intense noise and brightness. They are often cylindrical in shape to allow for a larger payload of flash powder, but ball shapes are common and cheaper as well. Salutes are also called Maroons. Another type of salute is the lampare. A lampare shell has the flash powder used in a regular salute, but is filled with a flammable liquid. When the shell explodes it has a loud report with a fireball.

Mine

A mine (aka. pot à feu) is a ground firework that expels stars and/or other garnitures into the sky. Shot from a mortar like a shell, a mine consists of a canister with the lift charge on the bottom with the effects placed on top. Mines can project small reports, serpents, small shells, as well as just stars. Although mines up to 12 inches in diameter appear on occasion, they are usually between 3 and 5 inches in diameter.

Bengal fire

Bengal fire or Bengal light produces a steady, vivid, blue-colored light. It is often made using combinations of potassium nitrate and copper compounds.

Roman candle

A Roman candle is a long tube containing several large stars which fire at a regular interval. These are commonly arranged in fan shapes or crisscrossing shapes, at a closer proximity to the audience. Some larger Roman candles contain small shells (bombettes) rather than stars.

Cake

A cake is a cluster of individual tubes linked by fuse that fires a series of aerial effects. Tube diameters can range in size from ¼ inch to 4 inches, and a single cake can have over 1,000 shots. The variety of effects within individual cakes is often such that they defy descriptive titles and are instead given cryptic names such as "Bermuda Triangle", "Pyro Glyphics","Summer Storm", "Waco Wakeup", and "Poisonous Spider", to name a few. Others are simply quantities of 2.5"-4" shells fused together in single-shot tubes.

Noise-related effects

Bangs and Report
The bang is the most common effect in fireworks and sounds like a gunshot, technically called a report.

Crackle
The firework produces a crackling sound.

Hummers
Tiny tube fireworks that are ejected into the air spinning with such force that they shred their outer coating, in doing so they whizz and hum.

Whistle
High pitched often very loud screaming and screeching created by the resonance of gas. This is caused by a very fast strobing (on/off burning stage) of the fuel. The rapid bursts of gas from the fuel vibrate the air many hundreds of times per second causing the familiar whistling sound. It is not - as is commonly thought - made in the conventional way that musical instruments are using specific tube shapes or apertures. Common whistle fuels contain Benzoate or Salicylate compounds and a suitable oxidizer such as Potassium Perchlorate.

Laws and politics

Safety of commercial and display fireworks in Canada

Fireworks safety is considered to be extremely important in Canada. The use, storage and sale of commercial-grade fireworks in Canada is licensed by Natural Resources Canada's Explosive Regulatory Division (ERD). Unlike their consumer counterpart, commercial-

grade fireworks function differently, and come in a wide range of sizes from 50 mm (2 inches) up to 300 mm (12 inches) or more in diameter.

Commercial grade fireworks require a "Fireworks Operator certificate", obtained from the ERD by completing a one day safety course. Certification system consists of three levels: Assistant, Supervisor and Supervisor with Endorsements. Assistant can only work under direct supervision of the Display Supervisor. Supervisors certification is gained after assisting three shows within the past five years. Supervisors can independently use and fire most commercial grade pyrotechnics. Supervisor with Endorsements can be obtained after supervising three shows within the past five years, and allows the holder to fire from barges, bridges, rooftops and over unusual sites.

Since commercial-grade fireworks are shells which are loaded into separate mortars by hand, there is danger in every stage of the setup. Setup of these fireworks involves the placement and securing of mortars on wooden or wire racks; loading of the shells; and if electronically firing, wiring and testing. The mortars are generally made of FRE (Fiber-Reinforced Epoxy) or HDPE (High-Density Polyethelene), some older mortars are made of Sheet Steel, but have been banned by most countries due to the problem of shrapnel produced during a misfire.

Setup of mortars in Canada for an oblong firing site require that a mortar be configured at an angle of 10 to 15 degrees down-range with a safety distance of at least 200 meters down-range and 100 meters surrounding the mortars, plus distance adjustments for wind speed and direction. In June 2007, the ERD approved circular firing sites for use with vertically fired mortars with a safety distance of at least 175 meter radius, plus distance adjustments for wind speed and direction.

Loading of shells is a delicate process, and must be done with caution, and a loader must ensure not only the mortar is clean, but also make sure that no part of their body is directly over the mortar in case of a premature fire. Wiring the shells is a painstaking process; whether the shells are being fired manually or electronically, any "chain fusing" or wiring of electrical ignitors, care must be taken to prevent the fuse (an electrical match, often incorrectly called a squib) from igniting. If the setup is wired electrically, the electrical matches are usually plugged into a "firing rail" or "breakout box" which runs back to the main firing board; from there, the Firing Board is simply hooked up to a car battery, and can proceed with firing the show when ready. After the display, the operators must ensure the site is inspected for misfired or unfired materials within 30 minutes of the conclusion of the show. Further, they must return the next day, during day time, to re-inspect the area again.

Safety of consumer fireworks in Great Britain

Safety of Consumer Fireworks in England, Scotland and Wales is always a widely discussed topic around Guy Fawkes Night, November 5. The most common injuries are burns from hand-held fireworks such as sparklers. There are also injuries due to people being hit by projectiles fired from fireworks, although these can usually be explained by

people setting up fireworks incorrectly. Other issues include the dangers of falling rocket sticks, especially from larger rockets containing metal motors. "Shock" adverts have been used for many years in an attempt to restrict injuries from fireworks, especially targeted at young people. The vast majority of fireworks are "Category 3, (Display Fireworks)" all of which state that spectators must be at least 25 metres away when the firework is fired. This is a safety concern as few people have access to that amount of private space. Other categories include "Category 2 (Garden Fireworks)" for which spectators must be a minimum of 8 metres away when the firework is fired, and "Category 4 - Professional Use Only". Any firework classed as Category 4 may only be used by professional pyrotechnists and must not be sold to the general public.

Safety of commercial and display fireworks in the United Kingdom

In the UK, responsibility for the safety of firework displays is shared between the Health and Safety Executive, fire brigades and local authorities. Currently, there is no national system of licencing for fireworks operators, but in order to purchase display fireworks, operators must have licenced explosives storage and public liability insurance.

Safety of consumer fireworks in the United States

Consumer fireworks are illegal in Stafford, Texas, United States

An example of a consumer firework in California

Availability and use of consumer fireworks are hotly debated topics. Critics and safety advocates point to the numerous injuries and accidental fires that are attributed to fireworks as justification for banning or at least severely restricting access to fireworks. Complaints about excessive noise created by fireworks and the large amounts of debris and fallout left over after shooting are also used to support this position. There are numerous incidents of consumer fireworks being used in a manner that is supposedly disrespectful of the communities and neighborhoods where the users live.

Meanwhile, those who support more liberal firework laws look at the same statistics as the critics and conclude that, when used properly, consumer fireworks are a safer form of recreation than riding bicycles or playing soccer.

The Consumer Product Safety Commission has guidelines concerning the standard of consumer fireworks sold in the US. Together with US Customs, they are very proactive in enforcing these rules, intercepting imported fireworks that don't comply and issuing recalls on unacceptable consumer fireworks that are found to have "slipped through". Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF) is the federal agency that regulates explosives, including Display Fireworks in the US.

Many states have laws which further restrict access to and use of consumer fireworks, and some of these states such as New Jersey vigorously enforce them. Each year, there are many raids on individuals suspected of illegally possessing fireworks.

The U.S. Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF) as well as the U.S. Consumer Product Safety Commission (CPSC) have general jurisdiction over what types of fireworks may be legally sold in the United States. The federal law is only the minimum standard however, and each state is free to enact laws that are more stringent if they so choose. Citing concerns over fireworks safety, some states, such as California, have enacted legislation restricting fireworks usage to devices that do not leave the ground, such as fountains. North Carolina limits fireworks to a charge of 200 grams of blackpowder. States such as New York, New Jersey, Massachusetts, and Delaware ban all consumer fireworks completely. Rhode Island and Arizona have recently passed bills legalizing certain types of small fireworks. Maine only allows sparklers. On the other hand, states such as South Dakota, South Carolina and Tennessee allow most or all legal consumer fireworks to be sold and used throughout the year. New Mexico in some cases, will not allow fireworks from individual residents if the fireworks are said to detonate over 5 feet (1.5 m) in height.

Illinois only permits sparklers, snake/glow worm pellets, smoke devices, trick noisemakers, and plastic or paper caps. However, many users travel to neighboring states such as Indiana, Missouri, Kentucky, and Wisconsin to obtain fireworks for use in Illinois. This situation is similar to the plight of many St. Louis residents as fireworks are illegal within both city and county limits. However, fireworks are readily available in nearby St. Charles County.

Pennsylvania is somewhere in between; the law only allows fireworks that don't leave the ground to be sold and used by residents. Yet residents from out of state and Pennsylvania residents with a permit can buy any consumer fireworks from an outlet.

Differences in legislation among states have led many fireworks dealers to set up shop along state borders in order to attract customers from neighboring states where fireworks are restricted. Some Native American tribes on reservation lands show similar behavior, often selling fireworks that are not legal for sale outside of the reservation.

The type of fireworks sold in the United States vary widely, from fireworks which are legal under federal law, all the way to illegal explosive devices/professional fireworks that are sold on the black market. Both the illicit manufacture and diversion of illegal explosives to the consumer market have become a growing problem in recent years.

Pollution

Fireworks produce smoke and dust that may contain residues of heavy metals, sulfur-coal compounds and some low concentration toxic chemicals. These by-products of fireworks combustion will vary depending on the mix of ingredients of a particular firework. (The color green, for instance, may be produced by adding the various compounds and salts of Barium, some of which are toxic, and some of which are not.) Some fisherman have noticed and reported to environmental authorities that firework residues can hurt fish and other water-life because some may contain toxic compounds such as antimony sulfide. This is a subject of much debate because large-scale pollution from other sources makes

it difficult to measure the amount of pollution that comes specifically from fireworks. The possible toxicity of any fallout may also be affected by the amount of black powder used, type of oxidizer, colors produced and launch method.

Fireworks have also been noted as a source of perchlorate in lakes. The U. S. Environmental Protection Agency's Richard Wilkin and colleagues, have conducted research on the use of pyrotechnic devices over bodies of water noting concerns over the effects of environmental perchlorate on human health and wildlife. Sources of perchlorate range from lightning and certain fertilizers to the perchlorate compounds in rocket fuel and explosives. Scientists long suspected community fireworks displays were another source, but few studies had been done on the topic. Wilkin's group has now established fireworks displays as a source of perchlorate contamination by analyzing water in an Oklahoma lake before and after fireworks displays in 2004, 2005 and 2006. Within 14 hours after the fireworks, perchlorate levels rose 24 to 1,028 times above background levels. Levels peaked about 24 hours after the display, and then decreased to the pre-fireworks background within 20- to 80 days. The study is detailed in the June 1, 2007 issue of the journal Environmental Science & Technology. (Environ. Sci. Technol., 2007, 41 (11), pp 3966–3971)

Perchlorate, a type of salt in its solid form, dissolves and moves rapidly in groundwater and surface water. Even in low concentrations in drinking water supplies, perchlorate is known to inhibit the uptake of iodine by the thyroid gland. While there are currently no federal drinking water standards for perchlorate, some states have established public health goals, or action levels, and some are in the process of establishing state maximum contaminant levels. For example, the US Environmental Protection Agency have studied the impacts of perchlorate on the environment as well as drinking water. California has also issued guidance regarding perchlorate use.

Several states have enacted drinking water standard for perchlorate including Massachusetts in 2006. California's legislature enacted AB 826, the Perchlorate Contamination Prevention Act of 2003, requiring California's Department of Toxic Substance Control (DTSC) to adopt regulations specifying best management practices for perchlorate and perchlorate-containing substances. The Perchlorate Best Management Practices were adopted on December 31, 2005 and became operative on July 1, 2006. California issued drinking water standards in 2007. Several other states, including Arizona, Maryland, Nevada, New Mexico, New York, and Texas have established non-enforceable, advisory levels for perchlorate.

The courts have also taken action with regard to perchlorate contamination. For example, in 2003, a federal district court in California found that Comprehensive Environmental Response, Compensation and Liability Act (CERCLA) applied because perchlorate is ignitable and therefore a "characteristic" hazardous waste.

Pollutants from fireworks raise concerns because of potential health risks associated with hazardous by-products. For most people the effects of exposure to low levels of toxins from many sources over long periods are unknown. For persons with asthma or multiple

chemical sensitivity the smoke from fireworks may aggravate existing health problems. Environmental pollution is also a concern because heavy metals and other chemicals from fireworks may contaminate water supplies and because fireworks combustion gases might contribute to such things as acid rain which can cause vegetation and even property damage. However, gunpowder smoke and the solid residues are basic, and as such the net effect of fireworks on acid rain is debatable. The carbon used in fireworks is produced from wood and does not lead to more carbon dioxide in the air. What is not disputed is that most consumer fireworks leave behind a considerable amount of solid debris, including both readily biodegradable components as well as nondegradable plastic items. Concerns over pollution, consumer safety, and debris have restricted the sale and use of consumer fireworks in many countries. Professional displays, on the other hand, remain popular around the world.

Others argue that alleged concern over pollution from fireworks constitutes a red herring, since the amount of contamination from fireworks is minuscule in comparison to emissions from sources such as the burning of fossil fuels. In the US some states and local governments restrict the use of fireworks in accordance with the Clean Air Act which allows laws relating to the prevention and control of outdoor air pollution to be enacted. Few governmental entities, by contrast, effectively limit pollution from burning fossil fuels such as diesel fuel or coal. Coal fueled electricity generation alone is a much greater source of heavy metal contamination in the environment than fireworks.

Some companies within the U.S. fireworks industry claim they are working with Chinese manufacturers to reduce and ultimately hope to eliminate of the pollutant perchlorate.

Laws governing consumer fireworks

Australia

Fireworks over Sydney Harbour

In Australia, Type 1 fireworks are permitted to be sold to the public. For anything that has a large explosion or gets airborne, users need to register for a Type 2 Licence. On August 24, 2009 the ACT Government announced a complete ban on backyard fireworks. The Northern Territory allows fireworks to be sold to residents 18 years or older in the days leading up to Northern Territory Day (July 1) for personal purposes. The types of fireworks allowed for sale is restricted to quieter fireworks, which can only be used at the address provided to the seller.

Chile

New Year fireworks in Valparaiso, Chile

In Chile, the manufacture, importation, possession and use of fireworks is prohibited to unauthorized individuals; only certified firework companies can legally use fireworks. As they are considered a type of explosive, offenders can be tried before military courts, though this is not often used.

Finland

In Finland those under 18 years old have not been allowed to buy any fireworks since 2009. Safety goggles are required. The use of fireworks is generally allowed on the evening and night of New Year's Eve, December 31. In some municipalities of Western Finland it is allowed to use fireworks without a fire station's permission on the last weekend of August. With the fire station's permission, fireworks can be used year round.

France

A fireworks display at the Eiffel Tower in Paris

In France, fireworks are traditionally displayed on the eve of Bastille day (July 14) to commemorate the French revolution and the storming of the Bastille on that same day in 1789. Every city in France lights up the sky for the occasion with a special mention to Paris that offers a spectacle around the Eiffel Tower.

Iceland

In Iceland, the Icelandic law states that anyone may purchase and use fireworks during a certain period around New Year's Eve. Most places that sell fireworks in Iceland make

their own rules about age of buyers; usually it is around 16. The people of Reykjavík spend enormous sums of money on fireworks, most of which are fired as midnight approaches on December 31. As a result, every New Year's Eve the city is lit up with fireworks displays.

Ireland

In the Republic of Ireland, fireworks are illegal and possession is punishable by huge fines and/or prison. However, around Halloween a large amount of fireworks are set off, due to the ease of being able to purchase from Northern Ireland.

Italy

In Italy only certified fireworks are legal. Homemade fireworks and fireworks not approved by Italian authorities are illegal. Fireworks are divided into three classes: "free fireworks" which can be sold to people over the age of 14, Cat. V fireworks can be purchased by people over the age of 18 and Cat. IV professional fireworks that require a gun licence.

Netherlands

In the Netherlands, fireworks cannot be sold to anyone under the age of 16. They may only be sold during a period of three days before a new year. If one of these days is a Sunday, that day is excluded from sale and sale may commence one day earlier.

New Zealand

Fireworks in New Zealand are available from the 2nd to the 5th November, around Guy Fawkes Day, and may be purchased only by those 18 years of age and older (up from 14 years pre-2007). Despite the restriction on when fireworks may be sold, there is no restriction regarding when fireworks may be used. The types of fireworks available to the public are multi-shot "cakes", Roman candles, single shot shooters, ground and wall spinners, fountains, cones, sparklers, and various novelties, such as smoke bombs and Pharaoh's serpents.

Sweden

In Sweden, people under the age of 18 are not allowed to purchase fireworks. The most common and only type on the market for the general public in Sweden is rockets. Fire cracker types are banned since 1 December 2001 because of a statistically high number of accidents reported past years.

Switzerland

In Switzerland Fireworks are often used on the 1 August, which is a national celebration day, and on New Year's Eve

United Kingdom

In the United Kingdom fireworks cannot be sold to people under the age of 18 and are not permitted to be set off between 11 p.m. and 7 a.m. with exceptions only for:

- New Year (Midnight New Year's Eve, valid until 1 a.m.)
- Bonfire Night (5 November) (Valid until midnight)
- The Chinese New Year (Valid until 1 a.m.)
- Diwali (Valid until 1 a.m.)

The legal NEC (Net Explosive Content) of a UK Firework available to the public is 2 kilograms. Jumping Jacks, Strings of Firecrackers, Shell Firing tubes, Bangers and Mini-Rockets were all banned during the late 1990s. In 2004 single shot Air Bombs and Bottle Rockets were banned, and rocket sizes were limited. From March 2008 any firework with over 5% flashpowder per tube will be classified 1.3G. The aim of these measures was to eliminate "pocket money" fireworks, and to limit the disruptive effects of loud bangs.

United States

A fireworks show celebrating Independence Day in the United States

In the United States, the laws governing consumer fireworks vary widely from state to state, or from county to county. It is common for consumers to cross state and county lines in order to purchase types of fireworks which are outlawed in their home-jurisdictions. Fireworks laws in urban areas typically limit sales or use by dates or

seasons. Municipalities may have stricter laws than their counties or states do. In the United States, fireworks dealers generally only sell to people over 18 years of age.

The American Pyrotechnic Association maintains a directory of state laws pertaining to fireworks.

Four states (Delaware, Massachusetts, New Jersey, and New York) ban the sale of all consumer fireworks including novelties and sparklers by the general public.

One state (Arizona) permits residents to purchase and use only novelties, However a new fireworks law effective December 2010 will allow all non-aerial fireworks such as fountains, sparklers, smoke bombs, while still prohibiting firecrackers.

Three states (Illinois, Iowa, and Maine) permit residents to purchase and use only wire or wood stick sparklers and other novelties.

Twenty states (California, Colorado, Connecticut, Florida, Georgia, Kentucky, Idaho, Maryland, Michigan, Minnesota, Nebraska, North Carolina, Oregon, Pennsylvania, Rhode Island, Utah, Virginia, Wisconsin, West Virginia, and the District of Columbia) allow residents to purchase and use non-aerial and non-explosive fireworks like novelties, fountains and sparklers. Wisconsin also allows the purchase of aerial explosive fireworks, but only allows their launch in designated areas in each county.

For example: California has very specific requirements for the types of consumer fireworks that can be sold to and used by residents. Even then each city can and often does place restrictions on sale and use. However, the manufacture of fireworks is legal throughout the state if they are to be used as an artform and not further distributed.

Another example: In Minnesota only consumer fireworks that do not explode or fly through the air are now permitted to be sold to and used by residents. In Nebraska the sale and use of all consumer fireworks are prohibited in Omaha, while in Lincoln there is a two-day selling period and in other parts of the state all of the permitted types can be sold and used by residents.

Because some states restrict the in-state use of fireworks by purchasers, large fireworks stores, like this one near Richmond, Indiana, are sometimes located on state borders.

Twenty one states—Alabama, Alaska, Arkansas, Indiana, Kansas, Louisiana, Mississippi, Missouri, Montana, New Hampshire, New Mexico, North Dakota, Ohio, Oklahoma, South Carolina, South Dakota, Tennessee, Texas, Vermont, Washington, Wyoming and Pennsylvania permit the sale of all or most types of consumer fireworks to residents. Many of these states have selling seasons around Independence Day and/or Christmas and New Year's Eve. Some of these states also allow local laws or regulations to further restrict the types permitted or the selling seasons.

For example: Missouri permits all types of consumer fireworks to be sold to residents with two selling seasons; June 20–July 10 and December 20–January 2. South Carolina permits all types of consumer fireworks except small rockets less than ½" in diameter and 3" long to be sold and used by residents year round.

Two states (Hawaii and Nevada) allow each county to establish their own regulations. For example, Clark County, Nevada, where Las Vegas is located, allows residents to purchase and use only non-explosive and non-aerial consumer fireworks during Independence Day, while other counties permit all types of consumer fireworks.

Many states have stores with all types of consumer fireworks that sell to non-residents with the provision they are to remove the purchased fireworks from that state. This is why there are so many stores selling all types of consumer fireworks in states like Pennsylvania, Ohio, Florida, Missouri, Nevada and Wisconsin, even though residents are limited or prohibited from buying or using those very same consumer fireworks unless they have the appropriate licenses and/or permits.

Many Native American Tribes have consumer fireworks stores on reservation lands that are exempt from state and local authority and will sell to people that are not in the tribe.

Chapter 3

Pyrotechnic Incidents

Pyrotechnics are dangerous substances that must always be treated with the utmost respect and with the proper training. Due to the hazardous nature of these materials, precautions must always be taken to ensure the safety of all individuals in the vicinity of pyrotechnics. Despite all precautions, accidents and errors occur from time to time, which may result in property damage, injury and in severe cases loss of life. These incidents may be the result of poorly manufactured product, unexpected or unforeseen events, or in many cases, the result of operator error.

Some of the more widely publicized incidents involving pyrotechnics in recent history include:

Sporting events

In August 2006, when TNA Wrestling held its annual Pay Per View Hard Justice, a fire ignited in the rafters where the pyrotechnics were held. Everybody was evacuated from the building. The fire lasted about 20 minutes and the show was continued.

On March 30, 2008, WWE had pyrotechnics go off for the ending of WrestleMania XXIV, but the pyrotechincs cable snapped and sparks flew down from the upper decks to the lower and middle decks. 45 fans were injured, but only 3 needed medical attention from a doctor.

At the 2010 Elimination Chamber Pay Per View, Professional Wrestler The Undertaker suffered burns to chest and neck as a result of a pyrotechnic accident. A mistake allowed a huge flame of fire to erupt directly under his feet. Remarkably, he competed in his match.

Concerts

- In 2003, improper use of pyrotechnics caused a fire in a Rhode Island nightclub called The Station. The Station nightclub fire was started when the fireworks the band Great White were using accidentally ignited inflammable soundproofing foam. The pyrotechnics in question were not appropriate. The foam caused combustion to spread rapidly and the resulting fire led to 100 deaths, apparently because their quick escape was blocked by ineffective exit doors. While the type of foam used and the lack of a sprinkler system were important factors in the fire, the Great White fire could have been prevented had those involved paid attention to standard safety practices around the use of pyrotechnics.

- Metallica's James Hetfield suffered burns during a performance of "Fade to Black". He suffered from second and third degree burns.

- Motley Crue drummer Tommy Lee was hospitalized in 2005 when he was hit by sparks from a pyrotechnic stunt while he was swinging on a wire between drum sets suspended several feet above the stage.

Film

Margaret Hamilton was badly burned during a scene in which her character 'vanished' in a burst of flame and smoke, a delay in activating a trap-door catching her in the pyrotechnic device during the filming of The Wizard of Oz (1939 film). Her stuntwoman was also injured in a scene involving a smoking broomstick.

Manufacturing and retail

A powerful blast razed a fireworks factory 50 kilometers south of the Philippines capital Manila in January 2009, killing at least eight people and injuring more than 70 others.

- December 2007 Bocaue fire

Broadcast

Keith Moon and Pete Townshend were injured during the taping of an episode of *The Smothers Brothers Comedy Hour* in 1967.

Anthea Turner was set alight by a pyrotechnic display in 1989 during the filming of an episode of the program *UP2U*.

Michael Jackson had suffered from injuries sustained when a pyrotechnic went wrong during filming for a Pepsi advertisement on January 27, 1984, when they went off too early and caused him to suffer from burns to his hair and scalp.

Public events

A pyrotechnic-induced fire incident similar to The Station nightclub fire in 2004 destroyed the Republica Cromagnon nightclub in Buenos Aires, Argentina, killing 194 people.

Another incident in Russia saw the roof catch fire of the Lame Horse nightclub in the Ural mountain city of Perm. Smoke inhalation and stampede caused 112 deaths.

Chapter 4

Flare (Pyrotechnic)

Illumination rounds are fired during Operation Tora Arwa V in the Kandahar province during Operation Enduring Freedom. The illumination rounds were fired from M777 howitzers and are used to help illuminate a certain area the soldiers need to see.

A **flare**, also sometimes called a **fusee**, is a type of pyrotechnic that produces a brilliant light or intense heat without an explosion. Flares are used for signaling, illumination, or defensive countermeasures in civilian and military applications. Flares may be ground pyrotechnics, projectile pyrotechnics, or parachute-suspended to provide maximum illumination time over a large area. Projectile pyrotechnics may be dropped from aircraft, fired from rocket or artillery, or deployed by flare guns or handheld percussive tubes.

Flares produce their light through the combustion of a pyrotechnic composition. The ingredients are varied, but often based on strontium nitrate, potassium nitrate, or potassium perchlorate and mixed with a fuel such as charcoal, sulfur, sawdust, aluminum, magnesium, or a suitable polymeric resin. Flares may be colored by the inclusion of pyrotechnic colorants. Calcium flares are used underwater to illuminate submerged objects.

Civilian use

Red flare - maritime distress signal
- COLREGS Annex IV (i)

In the civilian world, flares are commonly used as signals, and may be ignited on the ground or fired as an aerial signal from a pistol-like flare gun. Flare guns are commonly found in marine survival kits.

Maritime distress signal

A "*rocket parachute flare or a hand flare showing a **red light**"..."indicates distress and need of assistance*" at sea is one type of maritime distress signals. "*The use or exhibition of any of the foregoing signals [as a hand flare showing a red light or rockets or shells, throwing red stars] except for the purpose of indicating distress and need of assistance and the use of other signals which may be confused with any of the above signals is prohibited.*" from the COLREGS ANNEX IV - Distress signals 1. (c), (i).

Other usage

Flares are routinely used in countries around Europe and South America, during football games, in order to aid the build-up of the atmosphere within the stadium. Hardcore supporter groups known as Ultras, often light flares at the beginning of games, when their team has scored, or at the end of a game, if their team has won.

Fusee

An IHB brakeman uses a fusee to demonstrate a hand signal indicating "stop".

Another type of flare is the *fusee*, which burns for 10–60 minutes with a bright red light. Fusees are commonly used to indicate obstacles or advise caution on roadways at night; in this usage they are also called *highway flares*, *road flares*, or *ground flares*. They are commonly found in roadside emergency kits.

Fusees are also known as *railroad flares* and are used to perform hand signals in rail transport applications. Since they can be used only once, fusees nowadays are usually intended for emergency use (as opposed to the incandescent lanterns typically used during normal operating conditions). However, in the days before train radio communications, fusees were used to keep trains apart on un-signaled lines. A railroad fusee was timed to burn for ten minutes and quantities were dropped behind a train to ensure a safe spacing. If a following train encountered a burning fusee it was not to pass until the fusee burned out. Fusees made specifically for railroad use can be distinguished from highway fusees by a sharp steel spike at one end, used to embed the fusee upright in a wooden railroad tie.

In forestry and firefighting, fusees are sometimes used in wildland fire suppression and in the ignition of controlled burns. They ignite at 375 °F (191 °C) and burn as hot as 3,000 °F (1,600 °C). They are especially effective in igniting burnouts or backburns in

very dry conditions, but not so effective when fuel conditions are moist. Since controlled burns are often done during relatively high humidity levels (on the grounds that they could not be safely contained during periods of very low humidity), the driptorch is more effective and more often used. Fusees are also commonly carried by wildland firefighters for emergency use, to ignite an escape fire in surrounding fuels in case of being overrun by a fire if no other escape routes are available.

Calcium phosphide is often used in naval flares, as in contact with water it liberates phosphine which self-ignites in contact with air; it is often used together with calcium carbide which releases acetylene.

Air

A special variety of flare is used in military aircraft as a defensive countermeasure against heat-seeking missiles. These flares are usually discharged individually or in salvoes by the pilot or automatically by tail-warning devices, and are accompanied by vigorous evasive maneuvering. Since they are intended to deceive infrared missiles, these flares burn at temperatures of thousands of degrees, incandescing in the visible spectrum as well. Soids are floating flares that are effective only in the terminal phase of missiles with infrared signature seeker heads.

Non-perchlorate flares

Many in-service colored signal flares and spectrally balanced decoy flares contain perchlorate oxidizers. Perchlorate, a type of salt in its solid form, dissolves and moves rapidly in groundwater and surface water. Even in low concentrations in drinking water supplies, perchlorate is known to inhibit the uptake of iodine by the thyroid gland. While there are currently no federal drinking water standards for perchlorate, some states have established public health goals, or action levels, and some are in the process of establishing state maximum contaminant levels. For example, the US Environmental Protection Agency have studied the impacts of perchlorate on the environment as well as drinking water. California has also issued guidance regarding perchlorate use.

Several states have enacted drinking water standard for perchlorate including Massachusetts in 2006. California's legislature enacted AB 826, the Perchlorate Contamination Prevention Act of 2003, requiring California's Department of Toxic Substance Control (DTSC) to adopt regulations specifying best management practices for perchlorate and perchlorate-containing substances. The Perchlorate Best Management Practices were adopted on December 31, 2005 and became operative on July 1, 2006. California issued drinking water standards in 2007. Several other states, including Arizona, Maryland, Nevada, New Mexico, New York, and Texas have established non-enforceable, advisory levels for perchlorate.

US courts have taken action regarding the use of perchlorate in manufacturing pyrotechnic devices such as flares. For example, in 2003, a federal district court in California found that Comprehensive Environmental Response, Compensation and

Liability Act (CERCLA) applied because perchlorate is ignitable and therefore a "characteristic" hazardous waste.

One example of perchlorate related problems was found at the Olin Flare Facility, Morgan Hill, California - Perchlorate contamination beneath a former flare manufacturing plant in California was first discovered in 2000, several years after the plant had closed. The plant had used potassium perchlorate as one of the ingredients during its 40 years of operation. By late 2003, the state of California and the Santa Clara Valley Water District had confirmed a groundwater plume currently extending over nine miles through residential and agricultural communities.

The Regional Water Quality Control Board and the Santa Clara Valley Water District have engaged in a major outreach effort that has received extensive press and community response. A well testing program is underway for approximately 1,200 residential, municipal, and agricultural wells in the area. Large ion exchange treatment units are operating in three public water supply systems that include seven municipal wells where perchlorate has been detected. The potentially responsible parties, Olin Corporation and Standard Fuse Incorporated, are supplying bottled water to nearly 800 households with private wells. The Regional Water Quality Control Board is overseeing potentially responsible party (PRP) cleanup efforts.

The U. S. Environmental Protection Agency's Richard Wilkin and colleagues, have conducted research on the use of pyrotechnic devices over bodies of water noting concerns over the effects of environmental perchlorate on human health and wildlife. Sources of perchlorate range from lightening and certain fertilizers to the perchlorate compounds in rocket fuel and explosives. Scientists long suspected community fireworks displays were another source, but few studies had been done on the topic. Wilkin's group has now established fireworks displays as a source of perchlorate contamination by analyzing water in an Oklahoma lake before and after fireworks displays in 2004, 2005 and 2006. Within 14 hours after the fireworks, perchlorate levels rose 24 to 1,028 times above background levels. Levels peaked about 24 hours after the display, and then decreased to the pre-fireworks background within 20- to 80 days. The study is detailed in the June 1, 2007 issue of the journal Environmental Science & Technology. (Environ. Sci. Technol., 2007, 41 (11), pp 3966–3971)

According to the May 2005 Government Accountability Office (GAO) Perchlorate Report, an EPA official has estimated about 10 million people may have been exposed to perchlorate through their drinking water. Accordingly, there is an urgent need to develop perchlorate-free compositions for pyrotechnic flare devices.

Some examples of efforts to create non-perchlorate flares include both spectrally balanced decoy and colored flare compositions which included nitrate or oxide oxidizers. Because nitrate oxidizers are less reactive than perchlorate oxidizers, high-energy fuels have used to compensate for this energy shortfall. Some of these high-energy fuels were produced using mechanical alloying technology.

Chapter 5

Propellant

A **propellant** is a material that is used to move ("propel") an object. Common chemical propellants consist of a fuel; like gasoline, jet fuel, rocket fuel, and an oxidizer, or can be an inert pressurant.

Propellants are used in pressurised dispensing systems, such as aerosol sprays, to force a material through a nozzle.

In rockets, the propellant produces an exhaust and the exhausted material is usually expelled under pressure through a nozzle. The pressure may be from a compressed gas, or a gas produced by a chemical reaction. The exhaust material may be a gas, liquid, plasma, or, before the chemical reaction, a solid, liquid or gelled.

In aircraft, the propellant is usually a fuel and is combusted to generate energy to power the aircraft's flight.

Aerosol sprays

In aerosol spray cans, the propellant is simply a pressurized gas in equilibrium with its liquid (at its saturated vapour pressure). As some gas escapes to expel the payload, more liquid evaporates, maintaining an even pressure.

Propellant used for propulsion

Technically, the word **propellant** is the general name for chemicals used to create thrust. For vehicles, the term propellant refers only to chemicals that are stored within the vehicle prior to use, and excludes atmospheric gas or other material that may be collected in operation.

Amongst the English-speaking laymen, used to having fuels propel vehicles on Earth, the word **fuel** is inappropriately used. In Germany, the word *Treibstoff*—literally "drive-stuff"—is used; in France, the word *ergols* is used; it has the same Greek roots as hypergolic, a term used in English for propellants which combine spontaneously and do not have to be set ablaze by auxiliary ignition system.

In rockets, the most common combinations are *bipropellants*, which use two chemicals, a fuel and an oxidiser. There is the possibility of a tripropellant combination, which takes advantage of the ability of substances with smaller atoms to attain a greater exhaust velocity, and hence propulsive efficiency, at a given temperature.

Although not used in practice, the most developed tripropellant systems involves adding a third propellant tank containing liquid hydrogen to do this.

Solid propellant

In ballistics and pyrotechnics, a **propellant** is a generic name for chemicals used for propelling projectiles from guns and other firearms.

Propellants are usually made from low explosive materials, but may include high explosive chemical ingredients that are diluted and burned in a controlled way (deflagration) rather than detonation. The controlled burning of the propellant composition usually produces thrust by gas pressure and can accelerate a projectile, rocket, or other vehicle. In this sense, common or well known **propellants** include, for firearms, artillery and solid propellant rockets:

- Gun propellants, such as:
    - Gunpowder (black powder)
    - Nitrocellulose-based powders
    - Cordite
    - Ballistite
    - Smokeless powders
- Composite propellants made from a solid oxidizer such as ammonium perchlorate or ammonium nitrate, a rubber such as HTPB, or PBAN (may be replaced by energetic polymers such as polyglycidyl nitrate or polyvinyl nitrate for extra energy) , optional high explosive fuels (again, for extra energy) such as RDX or nitroglycerin, and usually a powdered metal fuel such as aluminum.
- Some amateur propellants use potassium nitrate, combined with sugar, epoxy, or other fuels / binder compounds.
- Potassium perchlorate has been used as an oxidizer, paired with asphalt, epoxy, and other binders.

Propellants that explode in operation are of little practical use currently, although there have been experiments with Pulse Detonation Engines.

Grain

Propellants are used in forms called grains. A grain is any individual particle of propellant regardless of the size or shape. The shape and size of a propellant grain determines the burn time, amount of gas and rate produced from the burning propellant and consequently thrust vs time profile.

There are three types of burns that can be achieved with different grains.

Progressive Burn
> Usually a grain with multiple perforations or a star cut in the center providing a lot of surface area.

Digressive Burn
> Usually a solid grain in the shape of a cylinder or sphere.

Neutral Burn
> Usually a single perforation; as outside surface decreases the inside surface increases at the same rate.

Composition

There are four different types of solid propellant compositions:

> Single Based Propellant: A single based propellant has nitrocellulose as its chief explosives ingredient. Stabilizers and other additives are used to control the chemical stability and enhance the propellant's properties.
> Double Based Propellant: Double based propellants consist of nitrocellulose with nitroglycerin or other liquid organic nitrate explosives added. Stabilizers and other additives are used also. Nitroglycerin reduces smoke and increases the energy output. Double based propellants are used in small arms, cannons, mortars and rockets.

Triple Based Propellant
> Triple based propellants consist of nitrocellulose, nitroquanidine, nitroglycerin or other liquid organic nitrate explosives. Triple based propellants are used in cannons.

Composite
> Composites contain no nitrocellulose, nitroglycerin, nitroquanidine or any other organic nitrate. Composites usually consist of a fuel such as metallic aluminum, a binder such as synthetic rubber, and an oxidizer such as ammonium perchlorate. Composite propellants are used in large rocket motors.

Liquid propellant

Common propellant combinations used for liquid propellant rockets include:

- Red fuming nitric acid (RFNA) and kerosene or RP-1
- RFNA and Unsymmetrical dimethyl hydrazine (UDMH)
- Dinitrogen tetroxide and UDMH, MMH and/or hydrazine
- Liquid oxygen and kerosene or RP-1

- Liquid oxygen and liquid hydrogen
- Liquid oxygen and ethanol
- Hydrogen peroxide and alcohol or RP-1
- Chlorine pentafluoride and hydrazine

Common monopropellant used for liquid rocket engines include:

- Hydrogen peroxide
- Hydrazine
- Red fuming nitric acid (RFNA)

Chapter 6

Pyrotechnic Composition

A **pyrotechnic composition** is a substance or mixture of substances designed to produce an effect by heat, light, sound, gas or smoke or a combination of these, as a result of non-detonative self-sustaining exothermic chemical reactions. Pyrotechnic substances do not rely on oxygen from external sources to sustain the reaction.

Basic types of pyrotechnic compositions are:

- flash powder – burns very fast, produces explosions and/or bright flashes of light
- gunpowder – burns slower than flash powder, produces large amount of gases
- solid propellants – produce large amount of hot gases, used as sources of kinetic energy for rockets and projectiles
- pyrotechnic initiators – produce large amount of heat, flames, and/or hot sparks, used to ignite other compositions
- gas generators – produce large amount of gas, either high volume at short time (for actuators and ejection charges, often using solid propellants) or controlled flow rate (e.g. chemical oxygen generators, often using thermite-like compositions)
- ejection charges – burn fast, produce large amount of gas at short time, used to eject payloads from containers
- burst charges – burn fast, produce large amount of gas at short time, used to fragment a container and eject its content
- smoke compositions – burn slowly, produce smoke, plain or colored
- delay compositions – burn at constant slow speed, used to introduce delays into the firing train
- pyrotechnic heat sources – produce large amount of heat and little to no gases, slow-burning, often thermite-like compositions
- sparklers – producing white or colored sparks
- flares – burn slowly, produce high amount of light, used for illumination or signaling

- coloured fireworks compositions – produce light, white or colored

Some pyrotechnic compositions are used in industry and aerospace for generation of large volumes of gas in gas generators (e.g. in airbags), in pyrotechnic fasteners, and in other similar applications. They are also used in military pyrotechnics, when production of large amount of noise, light, or infrared radiation is required; eg. missile decoy flares, flash powders, and stun grenades. A new class of reactive material compositions is now under investigation by military.

Many pyrotechnic compositions – especially involving aluminium and perchlorates – are often highly sensitive to friction, impact, and static electricity. Even as little as 0.1–10 millijoules spark can set off certain mixtures.

Materials used

Pyrotechnic compositions are usually homogenized mixtures of small particles of fuels and oxidizers. The particles can be grains or flakes. Generally, the higher the surface area of the particles, the higher the reaction rate and burning speed. For some purposes, binders are used to turn the powder into a solid material.

Fuels

Typical fuels are based on metal or metalloid powders. A flash powder composition may specify multiple different fuels. Some fuels can also serve as binders. Common fuels include:

- Metals
    - Aluminium – most common fuel in many classes of mixtures, also a combustion instability suppressant. Less energy per mass than carbon but less gas evolution, retaining heat in the reaction mixture. High-temperature flame with solid particles, which interfere with flame colorants. Reacts with nitrates, except ammonium nitrate, yielding nitrogen oxides, ammonia, and heat (the reaction is slow at room temperature but violent at above 80 °C and may spontaneously ignite); the reaction can be inhibited by a weak acid, e.g. boric acid. Corroded by alkaline substances. Flake particles easier to ignite and better for pyrotechnics than spherical ones. In presence of moisture reacts with potassium chlorate and perchlorate, yielding hydrogen. Particle size selected according to the required burn rate.
    - Magnesium – more sensitive and violent than aluminium, increases probability of spontaneous ignition in storage. Used in fireworks to increase flame temperature. Less interference with flame color than aluminium.
    - Magnalium – aluminium-magnesium alloy, more stable and less expensive than magnesium; less reactive than magnesium, easier to ignite than aluminium

- o Iron – makes gold sparks, frequently used
- o Steel – an alloy of iron and carbon, makes branching yellow-orange sparks
- o Zirconium – produces hot particles, good for ignition mixtures, eg. the *NASA Standard Initiator*, also a combustion instability suppressant
- o Titanium – produces hot particles, increases sensitivity to impact and friction; sometimes the Ti4Al6V alloy is used which gives a bit brighter white sparks; together with potassium perchlorate it is used in some pyrotechnic igniters; coarse powder produces beautiful branching blue-white sparks
- o Ferrotitanium – iron-titanium alloy, produces bright yellow-white sparks, used in pyrotechnic stars, rockets, comets, and fountains
- o Ferrosilicon – iron-silicon alloy, used in some mixtures, sometimes replacement of calcium silicide
- o Manganese – used to control burn rates, e.g. in delay compositions
- o Zinc – used in some smoke compositions, together with sulfur used in some early amateur rocket fuels, also in pyrotechnic stars; heavy, zinc-based compositions may require additional lift to fly high enough; moisture-sensitive; can spontaneoulsy ignite; rarely used as primary fuel except in smoke compositions, can be encountered as a secondary enhancement fuel
- o Copper – used as a blue colorant with other fuels
- o Brass – a zinc-copper alloy used in some fireworks formulas, as a blue colorant for its copper content
- o Tungsten – used to control and slow down burn rates of compositions, also in delay compositions
- o Zirconium-nickel alloy – used in some military delay compositions
- Metal hydrides (generally safer than the corresponding metals, release hydrogen during burning which may serve as a secondary fuel):
  - o Titanium(II) hydride – together with potassium perchlorate it is used in some igniters
  - o Zirconium(II) hydride – together with potassium perchlorate it is used in some igniters
  - o Decaborane – experimented with for some rocket fuels
- Metal carbides
  - o Zirconium carbide – used in some rocket fuels, also a combustion instability suppressant
- Metalloids
  - o Silicon – high flame temperature, burns producing molten glass, used in some ignition compositions and delay charges
  - o Boron – used in some ignition mixtures
  - o Antimony – used in some fireworks for glitter effects, toxic, burns bright white; usually used as 200–300 mesh; with potassium nitrate and sulfur produces white fires
- Non-metallic inorganic
  - o Sulfur – ignition promoter, increases burn rate; increases sensitivity to temperature, impact and friction, dangerous in combination with chlorates;

commonly used with nitrates; used as an additive; may contain residual acids, combination with carbonates or other alkaline stabilizers is advised in acid-sensitive compositions

- o Red phosphorus – extremely dangerous, especially in combination with chlorates (Armstrong's mixture); used in caps; also used in matches and some military infrared flares; toxic
- o White phosphorus – used in incendiary weapons and to make some military smoke screens, ignites spontaneously in air; even more toxic
- o Calcium silicide – used in some special compositions
- o Antimony trisulfide – ignition promoter; fine powder increases sensitivity, sharpens the boom of salutes; toxic and sensitive to static electricity; emits bright white light, crystals also used as a fuel in glitter compositions and in white comets and pyrotechnic stars. Sensitive to friction and impact; the degree of sensitisation depends on the oxidizer (sensitive to friction and impact with potassium chlorate, friction with potassium perchlorate, impact with ammonium perchlorate, and insensitive to either with potassium nitrate).
- o Arsenic sulfide (realgar) – toxic, sensitive to impact and friction. Used for report compositions due to its sensitivity with chlorate even in small amounts. Used in yellow smoke compositions due to its low boiling point.
- o Phosphorus trisulfide – used to make matches
- o Calcium phosphide – liberates phosphine when wet, used in some naval signal flares
- o Potassium thiocyanate
- Carbon-based
  - o Carbon
    - Charcoal – makes dim gold sparks
    - Graphite – also used as opacifier in rocket fuels to prevent heat transfer by radiation into lower layers of fuels and avoid the related explosions
    - Carbon black – produces long lasting fine gold sparks in fireworks, also used as opacifier in rocket fuels
  - o Asphaltum – carbon-based fuel, also used as a binder. Some forms contain ammonia; should not be combined with chlorates.
  - o Wood flour
- Organic chemicals
  - o Sodium benzoate – often used in whistle mixes together with potassium perchlorate
  - o Sodium salicylate – used in some whistle mixes
  - o Gallic acid – used in some whistle mixes; sensitive to impact and friction, there are safer alternatives
  - o Potassium picrate – used in some whistle compositions, safer than gallic acid but still dangerous, with heavy metals (e.g. lead) forms explosive salts
  - o Terephthalic acid – a fuel in some smoke compositions
  - o Hexamine – a low-reactivity, accessory fuel

- o Anthracene – a fuel in some smoke compositions, produces black smoke
- o Naphthalene – a fuel in some smoke compositions
- o Lactose – used together with potassium chlorate in many smoke compositions; cheap low-reactivity accessory fuel
- o Dextrose – used in some amateur solid rocket fuels
- o Sucrose – used in some smoke compositions
- o Sorbitol – used together with potassium nitrate as an amateur solid rocket fuel
- o Dextrin – also a binder
- o Stearin, stearic acid – accessory fuel, a possible replacement for charcoal and/or sulfur in some compositions; lengthens flames, can reduce friction sensitivity; phlegmatizing agent
- o Hexachloroethane – used in many military smoke compositions
- Organic polymers and resins, also sometimes serving as binders
  - o Teflon, Viton and other fluoropolymers – sometimes also working as oxidizer – used in military pyrolant compositions, eg. Magnesium/Teflon/Viton; extremely reactive in contact with some fine metal powders
  - o Hydroxyl-terminated polybutadiene (HTPB), used together with aluminium and ammonium nitrate in composite rocket fuels as a fuel and binder
  - o Carboxyl-terminated polybutadiene (CTPB), used in composite rocket fuels as a fuel and binder
  - o PBAN, used together with aluminium and ammonium nitrate in composite rocket fuels as a fuel and binder
  - o Polysulfide, used in composite rocket fuels as a fuel and binder
  - o Polyurethane, used in composite rocket fuels as a fuel and binder
  - o Polyisobutylene
  - o Nitrocellulose
  - o Polyethylene
  - o Polyvinyl chloride, also serving as chlorine donor and a binder
  - o Polyvinylidene chloride, also serving as chlorine donor
  - o Shellac, good especially for colored flame compositions
  - o Accroides resin (red gum), higher burning rate than shellac, burns well even with potassium perchlorate. Suitable for chrysanthemum stars.

When metallic fuels are used, the metal particle size is important. A larger surface area to volume ratio leads to a faster reaction; this means that smaller particle sizes produce a faster-burning composition. The shape also matters. Spherical particles, like those produced by atomizing molten metal, are undesirable. Thin and flat particles, like those produced by milling metal foil, have higher reaction surface and therefore are ideal when faster reaction is desired. Using nanoparticles can drastically affect the reaction rates; metastable intermolecular composites exploit this.

A suitable metal fuel may be dangerous on its own, even before it is mixed with an oxidizer. Careful handling is required to avoid the production of pyrophoric metal powders.

Oxidizers

Perchlorates, chlorates and nitrates are the most commonly used oxidizers for flash powders. Other possibilities include permanganates, chromates, and some oxides. Generally, the less the oxidizer, the slower the burning and the more light produced. For use at very high temperatures, sulfates can be used as oxidizers.

Oxidizers in use include:

- Perchlorates (also serving as chlorine donors):
    - Potassium perchlorate – common, relatively stable. Almost non-hygroscopic. Low solubility in water. Produces high temperature flame and smoke of potassium chloride. Safer replacement of potassium chlorate. Impact-sensitive with phosphorus,
    - Ammonium perchlorate – the most common oxidizer for modern solid rocket fuels; more sensitive to mechanical stimuli than potassium perchlorate. Uncommon in fireworks; creates hot flame, enhances barium, strontium and copper colorants by acting as a chlorine donor. Reacts with magnesium when wet and liberates heat and ammonia, can self-ignite. In contact with potassium nitrate (e.g. in black powder) produces potassium perchlorate and hygroscopic ammonium nitrate; no such reaction with sodium nitrate. Reacts with potassium chlorate, producing unstable, gradually decomposing ammonium chlorate; such combination has to be avoided.
    - Nitronium perchlorate
- Chlorates (also serving as chlorine donors, incompatible with ammonium salts because of forming unstable explosive ammonium chlorate, incompatible with sulfur and other acidic chemicals because of production of spontaneously igniting chlorine dioxide; very dangerous with phosphorus; should not be combined with hydrocarbon fuels/binders, e.g. asphalt or gum arabic; should be replaced with safer perchlorates wherever possible):
    - Potassium chlorate – much less stable than perchlorate, hazardous, avoid if possible. High burning speed, easy ignition. Slightly more hygroscopic than potassium nitrate. Produces smoke of potassium chloride. Can act as a chlorine donor. High impact and friction sensitivity with sulfur and sulfides. With ammonium salts produces unstable ammonium chlorate. Used in match head compositions, some colored smokes, and small firecrackers and toy caps.
    - Barium chlorate – also serves as a green colorant in fireworks; sensitive, better to avoid. Almost non-hygroscopic. Compositions may spontaneously combust in sunlight. Very good green colorant, even in lower-temperature flames.

- o Sodium chlorate – much less stable than perchlorate, hazardous, also serves as yellow colorant, hygroscopic
- Nitrates (when mixing with aluminium, boric acid should be added as a stabilizer):
  - o Potassium nitrate – very common, used in black powder and wide variety of compositions. Not very hygroscopic. At lower temperatures (with ordinary fuels like rosin or shellac) not very efficient, does not burn well, produces potassium nitrite. At higher temperatures, with charcoal and sulfur or with magnesium, decomposes well. Does not produce sufficient temperature to make colored flames, except when magnesium is added. Makes good sparks. Presence in dust makes the dust hazardous and very flammable.
  - o Sodium nitrate – also a yellow colorant, hygroscopic. Gives intense yellow light, used for illumination compositions. Presence in dust makes the dust hazardous. At lower temperatures produces nitrite ash, at higher temperatures decomposes completely.
  - o Calcium nitrate – also a red-orange colorant, enhances other colors
  - o Ammonium nitrate – used in some less common composite rocket propellants, hygroscopic, decomposes at too low temperature; when dry reacts with Al, Zn, Pb, Sb, Bi, Ni, Cu, Ag, Cd; when wet reacts also with Fe. Forms an explosive compound with copper.
  - o Barium nitrate – most common oxidizer/colorant for green and white colors, but with somewhat weak colorant effect;requires a chlorine donor. Also used in flash powders and some military infrared flares. Barium also serves as a stabilizer for the mixtures; decomposes at higher temperatures than nitrates of lighter metals and promotes higher burning temperatures. With aluminium produces bright silver sparks; when used with aluminium, addition of boric acid as stabilizer is advised. Not very hygroscopic.
  - o Strontium nitrate – most common oxidizer/colorant for red colors in flares, fires, and stars; strontium also serves as a stabilizer for the mixtures. At lower temperatures (with organic fuels) produces strontium nitrite ash which can smother the flame; decomposes completely at higher temperatures (with magnesium). Colorant for low-temperature flames, colorant and oxidizer for hot flames.
  - o Caesium nitrate – used in some military infrared flare compositions
- Permanganates:
  - o Potassium permanganate – used in early mixtures, now considered to be sensitive and unstable
  - o Ammonium permanganate – a moderately powerful explosive
- Chromates:
  - o Barium chromate – used in delay compositions, e.g. in fireworks rockets
  - o Lead chromate – used in delay compositions
  - o Potassium dichromate – used infrequently as an oxidizer; can be used as a surface treatment for passivation of magnesium particles, also as a catalyst and in some matches; potassium perchlorate often added
- Oxides and peroxides:

- o Barium peroxide – unstable, spontaneously decomposes, compositions containing it should not be stored
- o Strontium peroxide
- o Lead tetroxide – versatile but toxic
- o Lead dioxide – used in friction-sensitive compositions, eg. matches
- o Bismuth trioxide – used as a safe alternative to lead tetroxide in some compositions
- o Iron(III) oxide – a high temperature oxidizer, a catalyst
- o Iron(II,III) oxide – an oxidizer in Thermite and Thermate
- o Manganese(IV) oxide – an oxidizer in manganese thermite, a catalyst
- o Chromium(III) oxide – an oxidizer in chromium thermite
- o Tin(IV) oxide – an oxidizer in some delay charges
- Sulfates (reactions require high temperatures):
  - o Barium sulfate – a high-temperature oxidizer for e.g. strobe compositions, a green colorant
  - o Calcium sulfate – a high-temperature oxidizer for e.g. strobe compositions, a red-orange colorant; calcium salts used to deepen fireworks colors
  - o Potassium sulfate – a high-temperature oxidizer, a purple colorant
  - o Sodium sulfate – a high-temperature oxidizer, a yellow colorant
  - o Strontium sulfate – a high-temperature oxidizer, a red colorant
- Organic chemicals
  - o Guanidine nitrate – used in some high power rocket fuels, propellants, and blue firework compositions
  - o Hexanitroethane – used in some special military compositions
  - o Cyclotrimethylene trinitramine – used in some double-base propellants
  - o Cyclotetramethylene Tetranitramine – used in some double-base propellants
- Others
  - o Sulfur – oxidizer for zinc in zinc-sulfur fuels
  - o Teflon – oxidizer for some metal fuels
  - o Boron – oxidizer for titanium, forming titanium diboride

Corresponding sodium salts can be substituted for potassium ones.

Additives

- **Flame suppressants**. Potassium nitrate and potassium sulfate are commonly used.

- **Opacifiers**. Some solid rocket propellants have problems with radiative heat transfer through the material, which may lead to explosion. Carbon black and graphite are often used to inhibit this effect.

- **Colorants**, sometimes in combination with sources of chlorine. Usually salts of suitable metals, often barium, strontium, calcium, sodium, copper, etc. The salt

may simultaneously serve as an oxidizer. Copper metal can be also used. Copper acetoarsenite with potassium perchlorate provides richest blue.

- **Chlorine donors**. Used together with colorants. Presence of chlorides increases the volatility of the color-imparting metals and enhances the color intensity. Polyvinyl chloride, polyvinylidene chloride, Saran, chlorinated paraffins, chlorinated rubber (e.g. Parlon), hexachloroethane, hexachlorobenzene (most common chlorine donor until 1970's, now rarely used), and some other organochlorides and inorganic chlorides (e.g. ammonium chloride, mercurous chloride) are used as chlorine donors. Perchlorates and chlorates play this role together with their main use as oxidizers. Chlorine donors are often used also in smoke compositions, e.g. hexachloroethane together with zinc oxide to produce smoke based on zinc chloride.

- **Catalysts**. Propellant formulas often require a catalyst to burn faster and more stably. Transition metal ions and complexes tend to be used. Certain oxidizers often serve as catalysts. E.g. ammonium dichromate is used as a catalyst in ammonium nitrate based propellant formulas. Other catalysts are e.g. iron(III) oxide, hydrated ferric oxide, manganese dioxide, potassium dichromate, copper chromite, lead salicylate, lead stearate, lead 2-ethylhexoate, copper salicylate, copper stearate, lithium fluoride, n-butyl ferrocene, di-n-butyl ferrocene.

- **Stabilizers**. Some mixtures, eg. containing chlorates, tend to degrade and create acidic byproducts. Carbonates (eg. sodium, calcium, or barium carbonate) or other mildly alkaline materials can be added to scavenge such acids. Boric acid can be used to inhibit the sensitivity of aluminium to moisture, and to stabilize mixtures of metals with nitrates (which can otherwise form amides which react exothermically with metals and can cause spontaneous initiation). Many organic nitrated amines are used as stabilizers as well, e.g. 2-nitrodiphenylamine. Petroleum jelly, castor oil, linseed oil, etc. can be used as stabilizers, also to add hydrophobicity to particles and protect metals (especially iron and magnesium) from corrosion. Ethyl centralite and 2-nitrodiphenylamine are used in some rocket propellants.

- **Anticaking agents**. Eg. fumed silica. For powder compositions, e.g. flash powder or gunpowder. Graphite is used in some cases to coat the grains, lubricate them, and dissipate static electricity. Magnesium carbonate used too, together with its function as carbonate stabilizer.

- **Binders**. Often gums and resins, e.g. gum arabic, red gum, guar gum, copal, carboxymethyl cellulose, nitrocellulose, rice starch, cornstarch, shellac, dextrin. Binders can also serve as fuels. Camphor can be used as a plasticizer. Binders are used in manufacture of compact compositions, e.g. pyrotechnic stars. Polymers like HTPB and PBAN are often used for rocket fuels. Other polymers used are e.g. polyethylene or polyvinyl chloride can be encountered as well.

- **Plasticizers**. Improve the mechanical properties of the propellant particles. For composite rocket propellants, dioctyl adipate, isodecyl pelargonate, and dioctyl phthalate are often used. Plasticizers can also be other energetic materials (common in smokeless powders), e.g. nitroglycerine, butanetriol trinitrate, dinitrotoluene, trimethylolethane trinitrate, diethylene glycol dinitrate, triethylene glycol dinitrate, bis(2,2-dinitropropyl)formal, bis(2,2-dinitropropyl)acetal, 2,2,2-trinitroethyl 2-nitroxyethyl ether, and others.

- **Curing and crosslinking agents**. Used to harden the polymer component of composite rocket propellants. They include paraquinone dioxime, toluene-2,4-diisocyanate, tris(1-(2-methyl) aziridinyl) phosphine oxide, N,N,O-tri(1,2-epoxy propyl)-4-aminophenol, and isophorone diisocyanate.

- **Bonding agents**. Used to increase the level of bonding between the binder and the fuel/oxidizer particles. They include tris(1-(2-methyl) azirinidyl) phosphine oxide and triethanolamine.

Chapter 7

Pyrotechnic Initiator

A **pyrotechnic initiator** (also **initiator** or **igniter**) is a device containing a pyrotechnic composition used primarily to ignite other, more difficult-to-ignite materials, e.g. thermites, gas generators, and solid-fuel rockets. The name is often used also for the compositions themselves.

Pyrotechnic initiators are often controlled electrically (called **electro-pyrotechnic initiators**), e.g. using a heated bridgewire or a *bridge resistor*. They are somewhat similar to blasting caps or other detonators, but they differ in that there is no intention to produce a shock wave. An example of such pyrotechnic initiator is an electric match.

Composition

The energetic material used, often called **pyrogen**, is usually a pyrotechnic composition made of a fuel and oxidizer, where the fuel produces a significant amount of hot particles that cause/promote the ignition of the desired material.

Initiator compositions are similar to flash powders, but they differ in burning speed, as explosion is not intended, and have intentionally high production of hot particles. They also tend to be easier to ignite than thermites, with whom they also share similarities.

Common oxidizers used are potassium perchlorate and potassium nitrate. Common fuels used are titanium, titanium(II) hydride, zirconium, zirconium hydride, and boron. The size of the fuel particles is determined to produce hot particles with the required burning time.

More exotic materials can be used, e.g. carboranes.

For special applications, pyrophoric igniters can be used which burst into flame in contact with air. Triethylborane was used as an igniter for the Lockheed SR-71 jet engines.

Common compositions

Metal-oxidizer

ZPP

One of the most common initiators is **ZPP**, or **zirconium – potassium perchlorate** – a mixture of metallic zirconium and potassium perchlorate. It is also known as **NASA Standard Initiator**. It yields rapid pressure rise, generates little gas, emits hot particles when ignited, is thermally stable, has long shelf life, and is stable under vacuum. It is sensitive to static electricity.

BPN

Another common igniter formula is **BPN**, **BKNO3**, or **boron – potassium nitrate**, a mixture of 25% boron and 75% potassium nitrate by weight. It is used e.g. by NASA. It is thermally stable, stable in vacuum, and its burn rate is independent of pressure.

In comparison with black powder, BPN burns significantly hotter and leaves more of solid residues, therefore black powder is favored for multiple-use systems.

BPN's high temperature makes it suitable for uses where rapid and reproducible initiation is critical, e.g. for airbags, rocket engines, and decoy flares. It is however relatively expensive.

BPN can be also used as an ingredient of solid rocket propellants.

BPN can be ignited by a laser. A semiconductor laser of at least 0.4 watts output can be used for ignition in vacuum.

Others

Other mixtures encountered are aluminium-potassium perchlorate and titanium-aluminium-potassium perchlorate.

Metal hydride-oxidizer

Metal hydride-oxidizer mixtures replace the metal with its corresponding hydride. They are generally safer to handle than the corresponding metal-oxidizer compositions. During burning they also release hydrogen, which can act as a secondary fuel. Zirconium hydride, titanium hydride, and boron hydride are commonly used.

ZHPP

ZHPP (**zirconium hydride – potassium perchlorate**) is a variant of ZPP that uses zirconium hydride instead of pure zirconium. It is significantly safer to handle than ZPP.

THPP

THPP (titanium hydride potassium perchlorate) is a mixture of titanium(II) hydride and potassium perchlorate. It is similar to ZHPP. Like ZHPP, it is safer to handle than titanium-potassium perchlorate.

Intermetallics

Formation of an intermetallic compound can be a strongly exothermic reaction, usable as an initiator.

Titanium-boron

Titanium-boron composition is one of the hottest pyrotechnic reactions in common usage. It is solid-state, gasless. It can be used as a pyrotechnic initiator or for heating confined gas to perform mechanical work.

Nickel-aluminium

Nickel-aluminium laminates can be used as electrically initiated pyrotechnic initiators. NanoFoil is such material, commercially available.

Palladium-aluminium

Palladium-clad aluminium wires can be used as a fuse wire, known as **Pyrofuze**. The reaction is initiated by heat, typically supplied by electric current pulse. The reaction begins at 600 °C, the melting point of aluminium, and proceeds violently to temperature of 2200–2800 °C. The reaction does not need presence of oxygen, and the wire is consumed.

Pyrofuze comes as a solid wire of different diameters (from 0.002" to 0.02"), braided wire, ribbon, foil, and granules. Palladium, platinum, or palladium alloyed with 5% ruthenium can be used together with aluminium. Pyrofuze bridgewires can be used in squibs and electric matches. Pyrofuze foils can be used for e.g. sealing of various dispensers or fire extinguishing systems. Palladium-magnesium composition can also be used, but is not commercially available or not at least as common.

Others

BNCP

BNCP, (*cis*-**bis-(5-nitrotetrazolato)tetraminecobalt(III) perchlorate**) is another common initiator material. It is relatively insensitive. It undergoes deflagration to detonation transition in a relatively short distance, allowing its use in detonators. Its burning byproducts are of relatively little harm to environment. It can be ignited by a laser diode.

Lead azide

Lead azide ($Pb(N_3)_2$, or PbN_6) is occasionally used in pyrotechnic initiators.

Others

Other materials sensitive to heat can be used as well, e.g. tetrazene explosive, lead mononitro-resorcinates, lead dinitro-resorcinates, and lead trinitro-resorcinates.

Chapter 8

Pyrotechnician

A **pyrotechnician** is an individual responsible for the safe storage, handling, and functioning of pyrotechnics and pyrotechnic devices. Although the term is generally used in reference to individuals who operate pyrotechnics in the entertainment industry, it can include all individuals who regularly handle explosives. For the purposes of disambiguation, however, individuals who handle more powerful materials for commercial, demolition, or military applications are generally referred to as explosive technicians.

Certification

It is becoming more common in different countries and regions for individuals involved with the storage, handling and operation of pyrotechnics to have some form of license or certification. The specific requirements for certification, along with any restrictions or prohibitions, however, can vary wildly from one jurisdiction to the next. Most jurisdictions do require some type of minimum professional fireworks training before being allowed to apply for certification.

Australia

In Australia, individuals using, handling or storing pyrotechnics must receive government certification. All individuals must meet certain minimum requirements, including being at least 21 years of age and having received approved training, including working under the direct supervision of a licensed pyrotechnician, before being issued a license. All pyrotechnicians are required to maintain a log of their experience and to submit this log annually during the license renewal process.

Canada

In Canada, individuals using, handling or storing pyrotechnics must receive government certification, administered by the Explosives Regulatory Division of Natural Resources Canada. All individuals must meet certain minimum requirements, including being at least 18 years of age and having received government training, before being issued a license. All pyrotechnicians, of any classification or certification are required to maintain a log of their experience.

Certification for the use of proximate (indoor) pyrotechnics in Canada is separate from certification for display fireworks, and different government training and certification must be obtained.

The available licenses for the use of proximate pyrotechnics are sub-divided into one of 6 categories.

Theatrical User

The Theatrical User classification is intended for individuals who use pyrotechnics as only a minor part of their profession, and have no need for advancement to higher classes of certification. Individuals may use only a severely restricted list of pyrotechnics, and are also subject to significant restrictions as to their application. Certification is valid for one year.

Assistant

The Assistant classification is considered an entry level class for individuals entering the pyrotechnics profession, or who use pyrotechnics in their profession. Individuals may use a restricted list of pyrotechnics individually, but may fabricate, handle, and set-up a broader list of pyrotechnics typically prohibited to the Assistant under the direct supervision of a higher licensed individual. After five years of verifiable experience with a sufficient assortment of pyrotechnics, Assistant level technicians may apply for advancement to Pyrotechnician certification. Certification is valid for one year.

Pyrotechnician

The Pyrotechnician classification is the primary classification in Canada. Individuals may use any pyrotechnic device or product approved for use in Canada, and may also fabricate, handle, and set-up a special purpose or custom fabricated pyrotechnics typically prohibited while under the direct supervision of a Special Effects Technician. After five years of verifiable experience with a sufficient assortment of pyrotechnics, Pyrotechnician's may apply for advancement to Special Effects Technician certification. Certification is valid for one year.

Special Effects Technician

The Special Effects Technician classification is the most advanced classification in Canada. Individuals may use any pyrotechnic device or product approved for use in Canada, and may also fabricate, handle, and set-up a special purpose or custom fabricated pyrotechnics device typically prohibited. A Special Effects Technician may also apply for special certification to use restricted material, such as detonating cord and exploding bolts. Certification is valid for one year.

Authorities Having Jurisdiction

Authorities Having Jurisdiction (AHD) are individuals certified by the Explosive Regulatory Division to inspect and approve pyrotechnic events, including members of agencies associated with pyrotechnics such as fire departments and police forces. Unlike other certification classes, Authorities Having Jurisdiction are not required to pay a renewal fee, and certification is valid for five years.

Out-of-Country Technicians

Pyrotechnicians based outside of Canada participating in the production of a pyrotechnics special effects event in Canada are required to obtain a Visitor Card at either a Pyrotechnician or Special Effects Technician equivalent level. A certified Canadian technician of the applicable class must also be employed for the production. Visitor Cards are valid for one year.

Alternately, pyrotechnicians based outside of Canada may apply for Canadian certification, provided they meet the minimum requirements and attend the Explosive Regulatory Division certification training.

United States

There is no national certification or licensing requirements for pyrotechnicians in the United States, however, many individual states implement their own certification or licensing programs. Not all states have reciprocity agreements in regards to honouring another states certification, so it is not uncommon for pyrotechnicians to have certifications from multiple states. Certain states require certification to store, handle and operate fireworks but not proximate (indoor) pyrotechnics; other states use the same certification for all pyrotechnics. It is always recommended to confer with local authorities in any jurisdiction to determine local laws and regulations.

Professional pyrotechnic companies typically have licenses issued by the Bureau of Alcohol, Tobacco, Firearms and Explosives with regard to manufacturer and distribution of pyrotechnic materials.

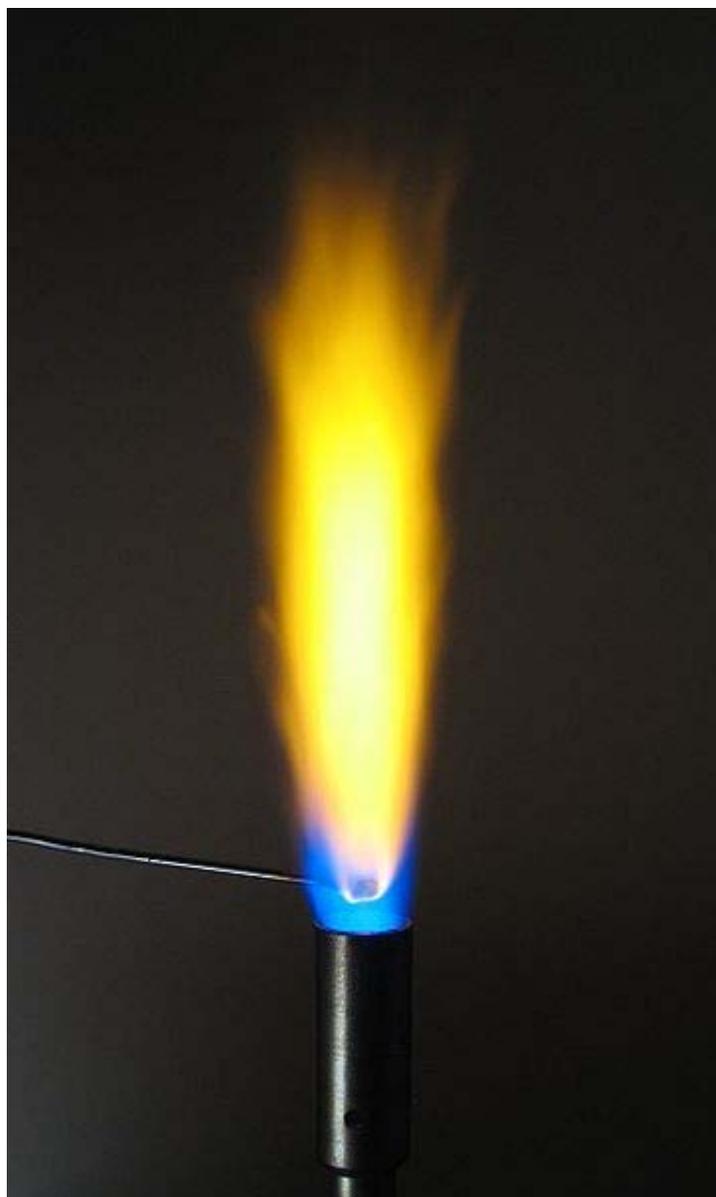# Chapter 9

Pyrotechnic Colorant

The red lithium flame leads to lithium's use in flares and pyrotechnics

Copper compounds glow green or blue-green in a flame.

Calcium compounds glow orange in a flame.

Sodium compounds glow yellow in a flame.

A **pyrotechnic colorant** is a chemical compound which causes a flame to burn with a particular color. These are used to create the colors in pyrotechnic compositions like fireworks and colored fires. The color-producing species are usually created from other chemicals during the reaction. Metal salts are commonly used; elemental metals are used rarely (e.g. copper for blue flames).

The color of the flame is dependent on the metal cation; the anion of the salt has very little direct influence. The anions however influence the flame temperature, both by increasing it (e.g. nitrates, chlorates) and decreasing it (e.g. carbonates, oxalates), indirectly influencing the flame brightness and brilliancy. For temperature-decreasing additives, the limit of colorant may be about 10–20 wt.% of the composition.

Some common examples are:

Color	Compound name	Chemical formula	Notes
Red	Strontium nitrate	$Sr(NO_3)_2$	Common. Used with chlorine donors. Excellent red, especially with metal fuels. Used in many compositions including road flares.
Red	Strontium carbonate	$SrCO_3$	Common. Produces good red. Slows burning of compositions, decomposes yielding carbon dioxide. Fire retardant in gunpowders. Inexpensive, non-hygroscopic, neutralizes acids. Superior over strontium oxalate in absence of magnesium.
Red	Strontium oxalate	SrC_2O_4	Decomposes yielding carbon dioxide and carbon monoxide. In presence of magnesium fuel, carbon monoxide reduces particles of magnesium oxide, yielding gaseous magnesium and eliminating the black body radiation of the MgO particles, resulting in clearer color.
Red	Strontium sulfate	$SrSO_4$	High-temperature oxidizer. Used in strobe mixtures and some metal-based red compositions.
Orange	Calcium carbonate	$CaCO_3$	Produces orange flame. Yields carbon dioxide on decomposition. Often used in toy fireworks as a substitute for strontium.
Orange	Calcium chloride	$CaCl_2$	
Orange	Calcium sulfate	$CaSO_4$	High-temperature oxidizer. Excellent orange source in strobe compositions.
Orange	Hydrated calcium sulfate	$CaSO_4(H_2O)_{x*}$	
Gold/Yellow	Charcoal	C	

	powder		
Gold/Yellow	Iron powder with oxygen based carbon OC12	Fe+C	
Yellow	Sodium bicarbonate	$NaHCO_3$	Compatible with potassium chlorate. Less burning rate decrease than sodium carbonate. Incompatible with magnesium and aluminium, reacts evolving hydrogen gas.
Yellow	Sodium carbonate	Na_2CO_3	Hygroscopic. Significantly decreases burning rate, decomposes evolving carbon dioxide. Strongly alkaline. Very effective colorant, can be used in small amounts. Corrodes magnesium and aluminium, incompatible with them.
Yellow	Sodium chloride	NaCl	Loses hygroscopicity on heating. Corrodes metals.
Yellow	Sodium oxalate	$Na_2C_2O_4$	Non-hygroscopic. Slightly reacts with magnesium, no reaction with aluminium.
Yellow	Sodium nitrate	$NaNO_3$	Also acts as oxidizer. Bright flame, used for illumination.
Yellow	Cryolite	Na_3AlF_6	One of the few sodium salts that is nonhygroscopic and insoluble in water.
Green	Barium chloride	$BaCl_2$	
Green	Barium chlorate	$Ba(ClO_3)_2$	Sensitive to shock and friction. Oxidizer.
Green	Barium carbonate	$BaCO_3$	Pretty color when ammonium perchlorate is used as oxidizer.
Green	Barium nitrate	$Ba(NO_3)_2$	Not too strong effect. With chlorine donors yields green color, without chlorine burns white. In green compositions usually used with perchlorates.
Green	Barium oxalate	BaC_2O_4	

Blue	Copper(I) chloride	CuCl	Richest blue flame. Almost insoluble in water.
Blue	Copper(I) oxide	Cu_2O	
Blue	Copper(II) oxide	CuO	Used with chlorine donors. Excellent in composite stars.
Blue	Copper carbonate	$CuCO_3$	Best when used with ammonium perchlorate.
Blue	Basic copper carbonate	$CuCO_3 \cdot Cu(OH)_2$, $2\ CuCO_3 \cdot Cu(OH)_2$	Occurs naturally as malachite and azurite. Good with ammonium perchlorate and for high-temperature flames with presence of hydrogen chloride. Not easily airborne, less poisonous than Paris Green.
Blue	Copper oxychloride	$3CuO \cdot CuCl_2$	Used in cheap compositions. Not common anymore due to need for mercury(II) chloride to bring out the color.
Blue	Paris Green	$Cu(CH_3COO)_2 . 3Cu(AsO_2)_2$	Copper acetoarsenite, Emerald Green. Toxic. With potassium perchlorate produces the best blue colors. Non-hygroscopic. Fine powder readily becomes airborne; toxic inhalation hazard. Used in majority of Japanese blue compositions as it gives very pretty color.
Blue	Copper arsenite	$CuHAsO_3$	Almost non-hygroscopic. Almost as good colorant as copper acetoarsenite. Toxic. Can be used with chlorate oxidizers.
Blue	Copper sulfate	$CuSO_4 \cdot 5\ H_2O$	Can be used with nitrates and perchlorates. Acidic, incompatible with chlorates. With red phosphorus in presence of moisture liberates heat, may spontaneously ignite. Less expensive than copper acetoarsenite. Anhydrous copper sulfate is hygroscopic, can be used as a desiccant. With ammonium perchlorate produces almost as pretty blue

Blue	Copper metal	Cu	Rarely used, other compounds are easier to work with. Yields pretty blue color in ammonium perchlorate based compositions; but reacts with ammonium perchlorate and liberates ammonia in presence of moisture. The composition must be kept dry.
Purple	Combination of red and blue compounds	Sr+Cu	
Purple	Rubidium compounds	Rb	rarely used
Silver/White	Aluminium powder	Al	
Silver/White	Magnesium powder	Mg	
Silver/White	Titanium powder	Ti	
Silver/White	Antimony (III) sulfide	Sb_2S_3	
Infrared	Caesium nitrate	$CsNO_3$	two powerful spectral lines at 852.113 nm and 894.347 nm
Infrared	Rubidium nitrate	$RbNO_3$	

The * indicates that the compound will burn orange where x=0,2,3,5.

Radiating species

Despite the wide numbers of metal ion donors, they serve to form only a few atomic and molecular species that are useful as light emitters.

In many cases, chlorine donors have to be added in order to achieve sufficiently deep colors, as the desired emitting molecules have to be generated.

Some color emitters are of atomic nature (e.g. lithium, sodium). Presence of chlorine, and the reaction to monochlorides, may actually impair their color purity or intensity.

At high temperatures, the atoms will ionize. The emission spectra of ions are different than of neutral atoms; the ions may emit in undesired spectral ranges. E.g. Ba^+ emits in blue wavelengths. Ionization can be suppressed by addition of an easier-to-ionize metal with weak visible emission of its own, e.g. potassium; the potassium atoms then act as electron donors, neutralizing the barium ions.

The color blue is notoriously difficult to produce in fireworks, as the copper compounds need to be heated at a specific temperature for the optimal shade of blue to be produced. Thus, a deep, rich blue is usually viewed as the mark of an experienced fireworks maker.

Care should be taken to avoid formation of solid particles in the flame zone, whether metal oxides or carbon; incandescent solid particles emit black body radiation that causes "washing out" of the colors. Addition of aluminium raises the flame temperature but also leads to formation of solid incandescent particles of aluminium oxide and molten aluminium. Magnesium has less such effect and is therefore more suitable for colored flames; it is more volatile than aluminium and more likely to be present as vapors than as particulates. Formation of solid particles of magnesium oxide can further be inhibited by presence of carbon monoxide, either by negative oxygen balance of the composition in presence of organic fuels, or by addition of the colorant in the form of an oxalate, which decomposes to carbon dioxide and carbon monoxide; the carbon monoxide reacts with the magnesium oxide particles to gaseous magnesium and gaseous carbon dioxide.

Colour	Emitter	Wavelengths	Notes
Yellow	Sodium (D-line)	589 nm	very strong, overpowers other colors, avoid contamination
Orange	CaCl (molecular bands)	most intense: 591–599 nm and 603–608 nm, and others	
Red	SrCl (molecular bands)	a: 617–623 nm b: 627–635 nm c: 640–646 nm	The SrCl species tends to be oxidized to less desirable SrO; strontium-containing compositions are therefore usually formulated to be oxygen-deficient.
Red	SrOH(?) (molecular bands)	600–613 nm	
Red	Li (atomic spectral lines)		
Green	BaCl (molecular bands)	a: 511–515 nm b: 524–528 nm d: 530–533 nm	Lines of BaOH and BaO are also present, emitting in yellow and yellowish-green (487, 512, 740, 828, and 867 nm for BaOH, 549, 564, 604 and 649 for BaO). The BaOH lines are much stronger than the BaO lines. In absence of chlorine, the BaCl lines are not present and only

the BaOH and BaO lines are visible.

Blue	CuCl (molecular bands)	several intense bands between 403–456 nm, less intense at 460–530 nm	The BaCl species tends to be oxidized to less desirable BaO; barium-containing compositions are therefore usually formulated to be oxygen-deficient. Presence of Ba^+ is undesired, as it emits in a blue region at 455.4 nm. Potassium may be added to suppress barium ionization, as it ionizes easier and acts as an electron donor for the barium ions. Low dissociation energy of copper compounds causes presence of free copper atoms in the flame, weakly emitting in green (lines between 325–522 nm). In presence of chlorine, CuCl is formed, emitting strongly in blue. At higher temperatures CuCl dissociates and lines of atomic copper are present in the spectrum; CuO and CuOH are also formed, emitting molecular bands at green-yellow (535–555 nm) for CuOH and at orange-red (580–655 nm) for CuOH. Adequate control of temperature is therefore required for blue-burning compositions.
Infrared	Carbon particles	black body radiation	For good broadband infrared output, compositions producing lots of heat and carbon particles are required. The burning temperature should be lower than of visible-illuminating compounds. The intensity of the emitted radiation depends on the burn rate. Temperature can be increased by addition of magnesium. A magnesium/Teflon/Viton composition is common for missile decoy flares.
Infrared	CO_2 (molecular bands)	mostly 4300 nm	Produced by carbon-containing fuels.
Infrared	Cs (atomic spectral lines)	two powerful spectral lines at 852.113 nm and 894.347 nm	Used in infrared illumination compositions. Metal is avoided in the compositions to prevent formation of bright, visible-radiating particles.
Infrared	Rb (atomic spectral lines)	spectral lines in near-infrared	Used in infrared illumination compositions, less commonly than cesium.

Chapter 10

Rocket Propellant

Rocket propellant is mass that is stored in some form of propellant tank, prior to being used as the propulsive mass that is ejected from a rocket engine in the form of a fluid jet to produce thrust. A fuel propellant is often burned with an oxidizer propellant to produce large volumes of very hot gas. These gases expand and push on a nozzle, which accelerates them until they rush out of the back of the rocket at extremely high speed, making thrust. Sometimes the propellant is not burned, but can be externally heated for more performance. For smaller attitude control thrusters, a compressed gas escapes the spacecraft through a propelling nozzle.

Chemical rocket propellants are most commonly used, which undergo exothermic chemical reactions which produce hot gas which is used by a rocket for propulsive purposes.

In ion propulsion, the propellant is made of electrically charged atoms (ions), which are electromagnetically pushed out of the back of the spacecraft. Magnetically accelerated ion drives are not usually considered to be rockets however, but a similar class of thrusters use electrical heating and magnetic nozzles.

Overview

The Space Shuttle Atlantis during ascent.

Rockets create thrust by expelling mass backwards in a high speed jet. Chemical rockets, create thrust by reacting propellants within a combustion chamber into a very hot gas at high pressure, which is then expanded and accelerated by passage through a nozzle at the rear of the rocket. The amount of the resulting forward force, known as thrust, that is produced is the mass flow rate of the propellants multiplied by their exhaust velocity (relative to the rocket), as specified by Newton's third law of motion. Thrust is therefore the equal and opposite reaction that moves the rocket, and not by interaction of the exhaust stream with air around the rocket. Equivalently, one can think of a rocket being accelerated upwards by the pressure of the combusting gases against the combustion chamber and nozzle. This operational principle stands in contrast to the commonly-held assumption that a rocket "pushes" against the air behind or below it. Rockets in fact perform better in outer space (where there is nothing behind or beneath them to push against), because there is a reduction in air pressure on the outside of the engine, and because it is possible to fit a longer nozzle without suffering from flow separation.

The maximum velocity that a rocket can attain in the absence of any external forces is primarily a function of its mass ratio and its *exhaust velocity*. The relationship is described by the *rocket equation*: $V_f = V_e \ln(M_0 / M_f)$. The mass ratio is just a way to express what proportion of the rocket is propellant (fuel/oxidizer combination) prior to engine ignition. Typically, a single-stage rocket might have a mass fraction of 90% propellant, 10% structure, and hence a mass ratio of 10:1 . The impulse delivered by the

motor to the rocket vehicle per weight of fuel consumed is often reported as the rocket propellant's *specific impulse*. A propellant with a higher specific impulse is said to be more efficient because more thrust is produced while consuming a given amount of propellant.

Lower stages will usually use high-density (low volume) propellants because of their lighter tankage to propellant weight ratios and because higher performance propellants require higher expansion ratios for maximum performance than can be attained in atmosphere. Thus, the Apollo-Saturn V first stage used kerosene-liquid oxygen rather than the liquid hydrogen-liquid oxygen used on its upper stages Similarly, the Space Shuttle uses high-thrust, high-density solid rocket boosters for its lift-off with the liquid hydrogen-liquid oxygen SSMEs used partly for lift-off but primarily for orbital insertion.

Chemical propellants

There are three main types of propellants: solid, liquid, and hybrid.

Solid propellants

History

The earliest rockets were created hundreds of years ago by the Chinese, and were used primarily for fireworks displays and as weapons. They were fueled with black powder, a type of gunpowder consisting of a mixture of charcoal, sulfur and potassium nitrate (saltpeter). Rocket propellant technology did not advance until the end of the 19th century, by which time smokeless powder had been developed, originally for use in firearms and artillery pieces. Smokeless powders and related compounds have seen use as double-base propellants.

Description

Solid propellants (and almost all rocket propellants) consist of an oxidizer and a fuel. In the case of gunpowder, the fuel is charcoal, the oxidizer is potassium nitrate, and sulfur serves as a catalyst. (Note: sulfur is not a true catalyst in gunpowder as it is consumed to a great extent into a variety of reaction products such as K_2S. The sulfur acts mainly as a sensitizer lowering threshold of ignition.) During the 1950s and 60s researchers in the United States developed what is now the standard high-energy solid rocket fuel, Ammonium Perchlorate Composite Propellant (APCP). This mixture is primarily ammonium perchlorate powder (an oxidizer), combined with fine aluminium powder (a fuel), held together in a base of PBAN or HTPB (rubber-like fuels). The mixture is formed as a liquid, and then cast into the correct shape and cured into a rubbery solid.

Advantages

Solid-fueled rockets are much easier to store and handle than liquid-fueled rockets, which makes them ideal for military applications. In the 1970s and 1980s the U.S. switched

entirely to solid-fueled ICBMs: the LGM-30 Minuteman and LG-118A Peacekeeper (MX). In the 1980s and 1990s, the USSR/Russia also deployed solid-fueled ICBMs (RT-23, RT-2PM, and RT-2UTTH), but retains two liquid-fueled ICBMs (R-36 and UR-100N). All solid-fueled ICBMs on both sides have three initial solid stages and a precision maneuverable liquid-fueled bus used to fine tune the trajectory of the reentry vehicle.

Their simplicity also makes solid rockets a good choice whenever large amounts of thrust are needed and cost is an issue. The Space Shuttle and many other orbital launch vehicles use solid-fueled rockets in their first stages (solid rocket boosters) for this reason.

Disadvantages

Relative to liquid fuel rockets, solid rockets have a number of disadvantages. Solid rockets have a lower specific impulse than liquid-fueled rockets. It is also difficult to build a large mass ratio solid rocket because almost the entire rocket is the combustion chamber, and must be built to withstand the high combustion pressures. If a solid rocket is used to go all the way to orbit, the payload fraction is very small. (For example, the Orbital Sciences Pegasus rocket is an air-launched three-stage solid rocket orbital booster. Launch mass is 23,130 kg, low earth orbit payload is 443 kg, for a payload fraction of 1.9%. Compare to a Delta IV Medium, 249,500 kg, payload 8600 kg, payload fraction 3.4% without air-launch assistance.)

A drawback to solid rockets is that they cannot be throttled in real time, although a predesigned thrust schedule can be created by altering the interior propellant geometry.

Solid rockets can often be shut down before they run out of fuel. Essentially, the rocket is vented or an extinguishant injected so as to terminate the combustion process. In some cases termination destroys the rocket, and then this is typically only done by a Range Safety Officer if the rocket goes awry. The third stages of the Minuteman and MX rockets have precision shutdown ports which, when opened, reduce the chamber pressure so abruptly that the interior flame is blown out. This allows a more precise trajectory which improves targeting accuracy.

Finally, casting very large single-grain rocket motors has proved to be a very tricky business. Defects in the grain can cause explosions during the burn, and these explosions can increase the burning propellant surface enough to cause a runaway pressure increase, until the case fails.

Liquid propellants

History

Though early rocket theorists, such as Konstantin Tsiolkovsky, proposed liquid hydrogen and liquid oxygen as propellants, the first liquid-fueled rocket, launched by Robert Goddard on March 16, 1926, used gasoline and liquid oxygen. Liquid hydrogen was first

used by the engines designed by Pratt and Whitney for the Lockheed CL-400 Suntan reconnaissance aircraft in the mid-1950s. In the mid-1960s, the Centaur and Saturn upper stages were both using liquid hydrogen and liquid oxygen.

The highest specific impulse chemistry ever test-fired in a rocket engine was lithium and fluorine, with hydrogen added to improve the exhaust thermodynamics (making this a tripropellant). The combination delivered 542 seconds (5.32 kN·s/kg, 5320 m/s) specific impulse in a vacuum. The impracticality of this chemistry highlights why exotic propellants are not actually used: to make all three components liquids, the hydrogen must be kept below -252 °C (just 21 K) and the lithium must be kept above 180 °C (453 K). Lithium and fluorine are both extremely corrosive, liquid lithium ignites on contact with air, fluorine ignites on contact with most fuels, and hydrogen, while not hypergolic, is an explosive hazard. Fluorine and the hydrogen fluoride (HF) in the exhaust are very toxic, which damages the environment, makes work around the launch pad difficult, and makes getting a launch license that much more difficult. The rocket exhaust is also ionized, which would interfere with radio communication with the rocket.

Current Types

The most common liquid propellants in use today:

- LOX and kerosene (RP-1). Used for the lower stages of most Russian and Chinese boosters, the first stages of the Saturn V and Atlas V, and all stages of the developmental Falcon 1 and Falcon 9. Very similar to Robert Goddard's first rocket. This combination is widely regarded as the most practical for boosters that lift off at ground level and therefore must operate at full atmospheric pressure.
- LOX and liquid hydrogen, used in the Space Shuttle orbiter, the Centaur upper stage of the Atlas V, Saturn V upper stages, the newer Delta IV rocket, the H-IIA rocket, and most stages of the European Ariane rockets.

- Nitrogen tetroxide (N_2O_4) and hydrazine (N_2H_4), MMH, or UDMH. Used in military, orbital and deep space rockets, because both liquids are storable for long periods at reasonable temperatures and pressures. N_2O_4/UDMH is the main fuel for the Proton rocket. This combination is hypergolic, making for attractively simple ignition sequences. The major inconvenience is that these propellants are highly toxic, hence they require careful handling.

- Monopropellants such as hydrogen peroxide, hydrazine and nitrous oxide are primarily used for attitude control and spacecraft station-keeping where their long-term storability, simplicity of use and ability to provide the tiny impulses needed, outweighs their lower specific impulse as compared to bipropellants. Hydrogen peroxide is also used to drive the turbopumps on the first stage of the Soyuz launch vehicle.

Historical propellants

These include propellants such as syntin, which is an expensive high energy hydrocarbon fuel which was used on Soyuz U2 until 1995.

Advantages

Liquid fueled rockets have higher specific impulse than solid rockets and are capable of being throttled, shut down, and restarted. Only the combustion chamber of a liquid fueled rocket needs to withstand combustion pressures and temperatures and they can be regeneratively cooled by the liquid propellant. On vehicles employing turbopumps, the propellant tanks are at very much less pressure than the combustion chamber, and thus can be built far more lightly than a solid propellant rocket case, permitting a higher mass ratio. For these reasons, most orbital launch vehicles use liquid propellants.

The primary performance advantage of liquid propellants is due to the oxidizer. Several practical liquid oxidizers (liquid oxygen, nitrogen tetroxide, and hydrogen peroxide) are available which have much better specific impulse than the ammonium perchlorate used in most solid rockets, when paired with comparable fuels. These facts have led to the use of hybrid propellants: a storable oxidizer used with a solid fuel, which retain most virtues of both liquids (high ISP) and solids (simplicity).

While liquid propellants are cheaper than solid propellants, for orbital launchers, the cost savings do not, and historically have not mattered; the cost of propellant is a very small portion of the overall cost of the rocket.

Disadvantages

The main difficulties with liquid propellants are also with the oxidizers. These are generally at least moderately difficult to store and handle due to their high reactivity with common materials, may have extreme toxicity (nitric acids), moderately cryogenic (liquid oxygen), or both (liquid fluorine, FLOX- a fluorine/LOX mix). Several exotic oxidizers have been proposed: liquid ozone (O_3), ClF_3, and ClF_5, all of which are unstable, energetic, and toxic.

Liquid fueled rockets also require potentially troublesome valves and seals and thermally stressed combustion chambers, which increase the cost of the rocket. Many employ specially designed turbopumps which raise the cost enormously due to difficult fluid flow patterns that exist within the casings.

Gas propellants

A gas propellant usually involves some sort of compressed gas. However, due to the low density and high weight of the pressure vessel, gases see little current use, but are sometimes used for vernier engines, particularly with inert propellants.

GOX was used as one of the propellant for the Buran program for the orbital manoeuvring system.

Hybrid propellants

A hybrid rocket usually has a solid fuel and a liquid or gas oxidizer. The fluid oxidizer can make it possible to throttle and restart the motor just like a liquid fueled rocket. Hybrid rockets are also cleaner than solid rockets because practical high-performance solid-phase oxidizers all contain chlorine, versus the more benign liquid oxygen or nitrous oxide used in hybrids. Because just one propellant is a fluid, hybrids are simpler than liquid rockets.

Hybrid motors suffer two major drawbacks. The first, shared with solid rocket motors, is that the casing around the fuel grain must be built to withstand full combustion pressure and often extreme temperatures as well. However, modern composite structures handle this problem well, and when used with nitrous oxide and a solid rubber propellent (HTPB), relatively small percentage of fuel is needed anyway, so the combustion chamber is not especially large.

The primary remaining difficulty with hybrids is with mixing the propellants during the combustion process. In solid propellants, the oxidizer and fuel are mixed in a factory in carefully controlled conditions. Liquid propellants are generally mixed by the injector at the top of the combustion chamber, which directs many small swift-moving streams of fuel and oxidizer into one another. Liquid fueled rocket injector design has been studied at great length and still resists reliable performance prediction. In a hybrid motor, the mixing happens at the melting or evaporating surface of the fuel. The mixing is not a well-controlled process and generally quite a lot of propellant is left unburned, which limits the efficiency and thus the exhaust velocity of the motor. Additionally, as the burn continues, the hole down the center of the grain (the 'port') widens and the mixture ratio tends to become more oxidiser rich.

There has been much less development of hybrid motors than solid and liquid motors. For military use, ease of handling and maintenance have driven the use of solid rockets. For orbital work, liquid fuels are more efficient than hybrids and most development has concentrated there. There has recently been an increase in hybrid motor development for nonmilitary suborbital work:

- The Reaction Research Society, although known primarily for their work with liquid rocket propulsion, has a long history of research and development with hybrid rocket propulsion.

- Several universities have recently experimented with hybrid rockets. Brigham Young University, the University of Utah and Utah State University launched a student-designed rocket called Unity IV in 1995 which burned the solid fuel hydroxy-terminated polybutadiene (HTPB) with an oxidizer of gaseous oxygen,

and in 2003 launched a larger version which burned HTPB with nitrous oxide. Stanford University researches nitrous-oxide/paraffin hybrid motors.

- The Rochester Institute of Technology was building a HTPB hybrid rocket to launch small payloads into space and to several near Earth objects. Its first launch was scheduled for Summer 2007.

- Scaled Composites SpaceShipOne, the first private manned spacecraft, is powered by a hybrid rocket burning HTPB with nitrous oxide. The hybrid rocket engine was manufactured by SpaceDev. SpaceDev partially based its motors on experimental data collected from the testing of AMROC's (American Rocket Company) motors at NASA's Stennis Space Center's E1 test stand. Motors ranging from as small as 1000 lbf (4.4 kN) to as large as 250,000 lbf (1.1 MN) thrust were successfully tested. SpaceDev purchased AMROCs assets after the company was shut down for lack of funding.

Inert propellants

Some rocket designs have their propellants obtain their energy from non chemical or even external sources. For example water rockets use the compressed gas, typically air, to force the water out of the rocket.

Solar thermal rockets and Nuclear thermal rockets typically propose to use liquid hydrogen for an I_{sp} (Specific Impulse) of around 600–900 seconds, or in some cases water that is exhausted as steam for an I_{sp} of about 190 seconds.

Additionally for low performance requirements such as attitude jets, inert gases such as nitrogen have been employed.

Mixture ratio

The theoretical exhaust velocity of a given propellant chemistry is a function of the energy released per unit of propellant mass (specific energy). Unburned fuel or oxidizer drags down the specific energy. However, most rockets run fuel-rich.

The usual explanation for fuel-rich mixtures is that fuel-rich mixtures have lower molecular weight exhaust, which by reducing M increases the ratio $\dfrac{\sqrt{T_c}}{M}$ which is approximately equal to the theoretical exhaust velocity. This explanation, though found in some textbooks, is wrong. Fuel-rich mixtures actually have lower theoretical exhaust velocities, because $\sqrt{T_c}$ decreases as fast or faster than M.

The nozzle of the rocket converts the thermal energy of the propellants into directed kinetic energy. This conversion happens in a short time, on the order of one millisecond. During the conversion, energy must transfer very quickly from the rotational and

vibrational states of the exhaust molecules into translation. Molecules with fewer atoms (like CO and H_2) store less energy in vibration and rotation than molecules with more atoms (like CO_2 and H_2O). These smaller molecules transfer more of their rotational and vibrational energy to translation energy than larger molecules, and the resulting improvement in nozzle efficiency is large enough that real rocket engines improve their actual exhaust velocity by running rich mixtures with somewhat lower theoretical exhaust velocities.

The effect of exhaust molecular weight on nozzle efficiency is most important for nozzles operating near sea level. High expansion rockets operating in a vacuum see a much smaller effect, and so are run less rich. The Saturn-II stage (a LOX/LH_2 rocket) varied its mixture ratio during flight to optimize performance.

LOX/hydrocarbon rockets are run only somewhat rich (O/F mass ratio of 3 rather than stoichiometric of 3.4 to 4), because the energy release per unit mass drops off quickly as the mixture ratio deviates from stoichiometric. LOX/LH_2 rockets are run very rich (O/F mass ratio of 4 rather than stoichiometric 8) because hydrogen is so light that the energy release per unit mass of propellant drops very slowly with extra hydrogen. In fact, LOX/LH_2 rockets are generally limited in how rich they run by the performance penalty of the mass of the extra hydrogen tankage, rather than the mass of the hydrogen itself.

Another reason for running rich is that off-stoichiometric mixtures burn cooler than stoichiometric mixtures, which makes engine cooling easier. And as most engines are made of metal or carbon, hot oxidizer-rich exhaust is extremely corrosive, where fuel-rich exhaust is less so. American engines have all been fuel-rich. Some Soviet engines have been oxidizer-rich.

Additionally, there is a difference between mixture ratios for optimum I_{sp} and optimum thrust. During launch, shortly after takeoff, high thrust is at a premium. This can be achieved at some temporary reduction of I_{sp} by increasing the oxidiser ratio initially, and then transitioning to more fuel-rich mixtures. Since engine size is typically scaled for takeoff thrust this permits reduction of the weight of rocket engine, pipes and pumps and the extra propellant use can be more than compensated by increases of acceleration towards the end of the burn by having a reduced dry mass.

Propellant density

Although liquid hydrogen gives a high I_{sp}, its low density is a significant disadvantage: hydrogen occupies about 7x more volume per kilogram than dense fuels such as kerosene. This not only penalises the tankage, but also the pipes and fuel pumps leading from the tank, which need to be 7x bigger and heavier. (The oxidiser side of the engine and tankage is of course unaffected.) This makes the vehicle's dry mass much higher, so the use of liquid hydrogen is not such a big win as might be expected. Indeed, some dense hydrocarbon/LOX propellant combinations have higher performance when the dry mass penalties are included.

Due to lower I_{sp}, dense propellant launch vehicles have a higher takeoff mass, but this does not mean a proportionately high cost; on the contrary, the vehicle may well end up cheaper. Liquid hydrogen is quite an expensive fuel to produce and store, and causes many practical difficulties with design and manufacture of the vehicle.

Because of the higher overall weight, a dense-fueled launch vehicle necessarily requires higher takeoff thrust, but it carries this thrust capability all the way to orbit. This, in combination with the better thrust/weight ratios, means that dense-fueled vehicles reach orbit earlier, thereby minimizing losses due to gravity drag. Thus, the effective delta-v requirement for these vehicles are reduced.

However, liquid hydrogen does give clear advantages when the overall mass needs to be minimised; for example the Saturn V vehicle used it on the upper stages; this reduced weight meant that the dense-fueled first stage could be made significantly smaller, saving quite a lot of money.

Chapter 11
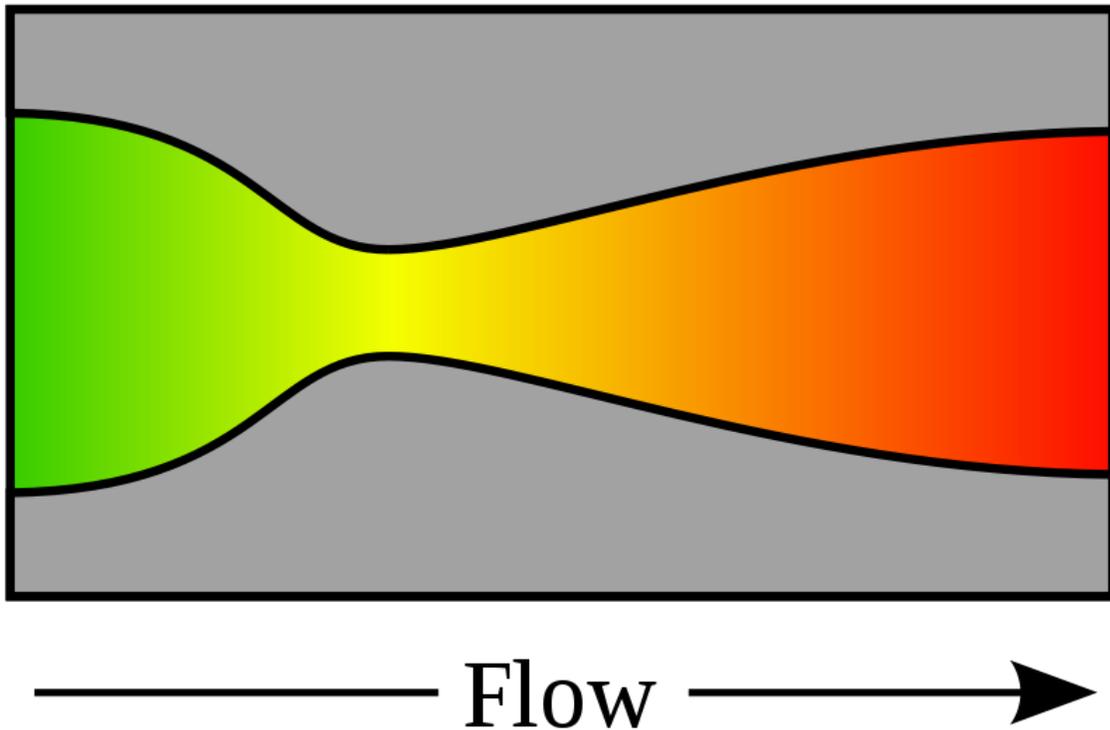
Rocket Engine Nozzle

Figure 1: A de Laval nozzle, showing approximate flow velocity increasing from green to red in the direction of flow

A **rocket engine nozzle** is a propelling nozzle usually of the de Laval type used in a rocket engine to expand and accelerate the combustion gases, from burning propellants, so that the exhaust gases exit the nozzle at hypersonic velocities.

History

The de Laval nozzle was first used in an early rocket engine developed by Robert Goddard, one of the fathers of modern rocketry. Subsequently, almost all rocket engines used this idea, including Walter Thiel's implementation which made possible Germany's V2 rocket.

Atmospheric use

The optimal size of a rocket engine nozzle to be used within the atmosphere is when the exit pressure equals ambient pressure, which decreases with altitude. For rockets travelling from the Earth to orbit, a simple nozzle design is only optimal at one altitude, losing efficiency and wasting fuel at other altitudes.

If the pressure of the jet leaving the nozzle is above ambient pressure then a nozzle is said to be 'underexpanded'; if the jet is below ambient pressure then it is 'overexpanded'.

Slight overexpansion causes a slight reduction in efficiency, but otherwise does little harm. However, if the jet pressure is approximately 40 percent of ambient then 'flow separation' occurs. This can cause jet instabilities that can cause damage to the nozzle or simply cause control difficulties of the vehicle or the engine.

In some cases it is desirable for reliability and safety reasons to ignite a rocket engine on the ground that will be used all the way to orbit. For optimal liftoff performance, the nozzle should be ambient at sea-level; however, if a rocket engine is primarily designed for use at high altitudes and is only providing additional thrust to another "first stage" engine during liftoff in a multi-stage design, then designers will usually opt for an overexpanded (at sea-level) design. This is the technique employed on the Space shuttle's main engines, which spend most of their powered trajectory in near-vacuum while the shuttle's two Solid Rocket Boosters provide the majority of the liftoff thrust.

Vacuum use

For nozzles that are used in vacuum or at very high altitude, it is impossible to match ambient pressure; rather, larger area ratio nozzles are usually more efficient. However, a very long nozzle has significant mass, a drawback in and of itself. A length that optimises overall vehicle performance typically has to be found. Additionally, as the temperature of the gas in the nozzle decreases some components of the exhaust gases (such as water vapour from the combustion process) may condense, or even freeze. This is highly undesirable and needs to be avoided.

Magnetic nozzles have been proposed for some types of propulsion (for example VASIMR), in which the flow of plasma or ions are directed by magnetic fields instead of walls made of solid materials. These can be advantageous since a magnetic field itself cannot melt and the plasma temperatures can reach millions of kelvins. However, there

are often thermal design challenges presented by the coils themselves, particularly if superconducting coils are used to form the throat and expansion fields.

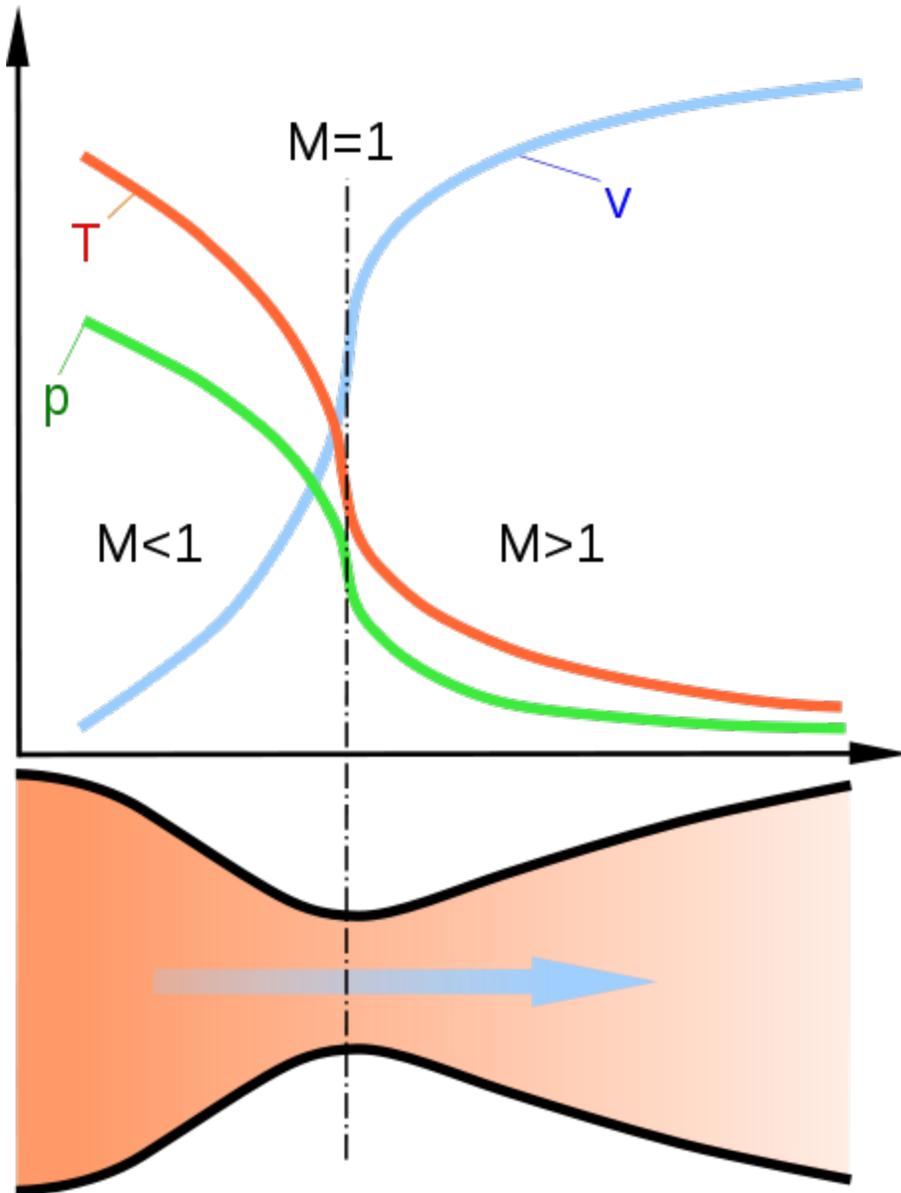## *1-D Analysis of gas flow in rocket engine nozzles*

Diagram of a de Laval nozzle, showing flow velocity (v) increasing in the direction of flow, with decreases in temperature (t) and pressure (p). The Mach number (M) increases from subsonic, to sonic at the throat, to supersonic.

The analysis of gas flow through de Laval nozzles involves a number of concepts and assumptions:

- For simplicity, the combustion gas is assumed to be an ideal gas.

- The gas flow is isentropic (i.e., at constant entropy), frictionless, and adiabatic (i.e., there is little or no heat gained or lost)
- The gas flow is constant (i.e., steady) during the period of the propellant burn.
- The gas flow is along a straight line from gas inlet to exhaust gas exit (i.e., along the nozzle's axis of symmetry)
- The gas flow behavior is compressible since the flow is at very high velocities.

As the combustion gas enters the rocket nozzle, it is traveling at subsonic velocities. As the throat contracts down the gas is forced to accelerate until at the nozzle throat, where the cross-sectional area is the smallest, the linear velocity becomes sonic. From the throat the cross-sectional area then increases, the gas expands and the linear velocity becomes progressively more supersonic.

The linear velocity of the exiting exhaust gases can be calculated using the following equation

$$V_e = \sqrt{\frac{T\,R}{M} \cdot \frac{2\,k}{k-1} \cdot \left[1 - (P_e/P)^{(k-1)/k}\right]}$$

where:

V_e = Exhaust velocity at nozzle exit, m/s

T = absolute temperature of inlet gas, K

R = Universal gas law constant = 8314.5 J/(kmol·K)

M = the gas molecular mass, kg/kmol (also known as the molecular weight)

k = c_p / c_v = isentropic expansion factor

c_p = specific heat of the gas at constant pressure

c_v = specific heat of the gas at constant volume

P_e = absolute pressure of exhaust gas at nozzle exit, Pa

P = absolute pressure of inlet gas, Pa

Some typical values of the exhaust gas velocity V_e for rocket engines burning various propellants are:

- 1.7 to 2.9 km/s (3800 to 6500 mi/h) for liquid monopropellants
- 2.9 to 4.5 km/s (6500 to 10100 mi/h) for liquid bipropellants
- 2.1 to 3.2 km/s (4700 to 7200 mi/h) for solid propellants

As a note of interest, V_e is sometimes referred to as the *ideal exhaust gas velocity* because it based on the assumption that the exhaust gas behaves as an ideal gas.

As an example calculation using the above equation, assume that the propellant combustion gases are: at an absolute pressure entering the nozzle of P = 7.0 MPa and exit the rocket exhaust at an absolute pressure of P_e = 0.1 MPa; at an absolute temperature of

T = 3500 K; with an isentropic expansion factor of k = 1.22 and a molar mass of M = 22 kg/kmol. Using those values in the above equation yields an exhaust velocity V_e = 2802 m/s or 2.80 km/s which is consistent with above typical values.

The technical literature can be very confusing because many authors fail to explain whether they are using the universal gas law constant R which applies to any ideal gas or whether they are using the gas law constant R_s which only applies to a specific individual gas. The relationship between the two constants is $R_s = R/M$.

Specific Impulse

Thrust is the force which moves a rocket through the air, and through space. Thrust is generated by the propulsion system of the rocket through the application of Newton's third law of motion: "For every action there is an equal and opposite reaction". A gas or working fluid is accelerated out the rear of the rocket engine nozzle and the rocket is accelerated in the opposite direction. The thrust of a rocket engine nozzle can be defined as:

$$F = \dot{m}\, V_e + (P_e - P_o)\, A_e$$
$$= \dot{m} \left[V_e + \left(\frac{P_e - P_o}{\dot{m}} \right) A_e \right]$$

and for perfectly expanded nozzles, this reduces to:

$$F = \dot{m}\, V_{eq}$$

The specific impulse, I_{sp}, is the ratio of the amount of thrust produced to the weight flow of the propellants. It is a measure of the fuel efficiency of a rocket engine. It can be obtained from:

$$I_{sp} = \frac{F}{\dot{m}\, g_o} = \frac{\dot{m}\, V_{eq}}{\dot{m}\, g_o} = \frac{V_{eq}}{g_o}$$

where:

F = gross rocket engine thrust, N

$\dot{m}$ = mass flow rate of exhaust gas, kg/s

V_e = exhaust gas velocity at nozzle exit, m/s

P_e = exhaust gas pressure at nozzle exit, Pa

P_o = external ambient pressure, Pa   (also known as free stream pressure)

A_e = cross-sectional area of nozzle exhaust exit, m²

V_{eq} = equivalent (or effective) exhaust gas velocity at nozzle exit, m/s

I_{sp} = specific impulse, s

$$g_o = \text{Gravitational acceleration at sea level on Earth} = 9.807 \text{ m/s}^2$$

In certain cases, where P_e equals P_o, then:

$$I_{sp} = \frac{F}{\dot{m}\, g_o} = \frac{\dot{m}\, V_e}{\dot{m}\, g_o} = \frac{V_e}{g_o}$$

In cases where this may not be the case since for a rocket nozzle P_e is proportional to $\dot{m}$, then it is possible to define a constant quantity which is the vacuum $I_{sp}(vac)$ for any given engine thus:

$$I_{sp}(vac) = \frac{V_e}{g_o} + \frac{P_e A_e}{\dot{m}\, g_o}$$

and hence:

$$F = I_{sp}(vac)\, g_o\, \dot{m} - A_e P_o$$

which is simply the vacuum thrust minus the force of the ambient atmospheric pressure acting over the exit plane.

Essentially then, for rocket nozzles, the ambient pressure acting over the engine largely cancels but effectively acts over the exit plane of the rocket engine in a rearward direction, while the exhaust jet generates forward thrust.
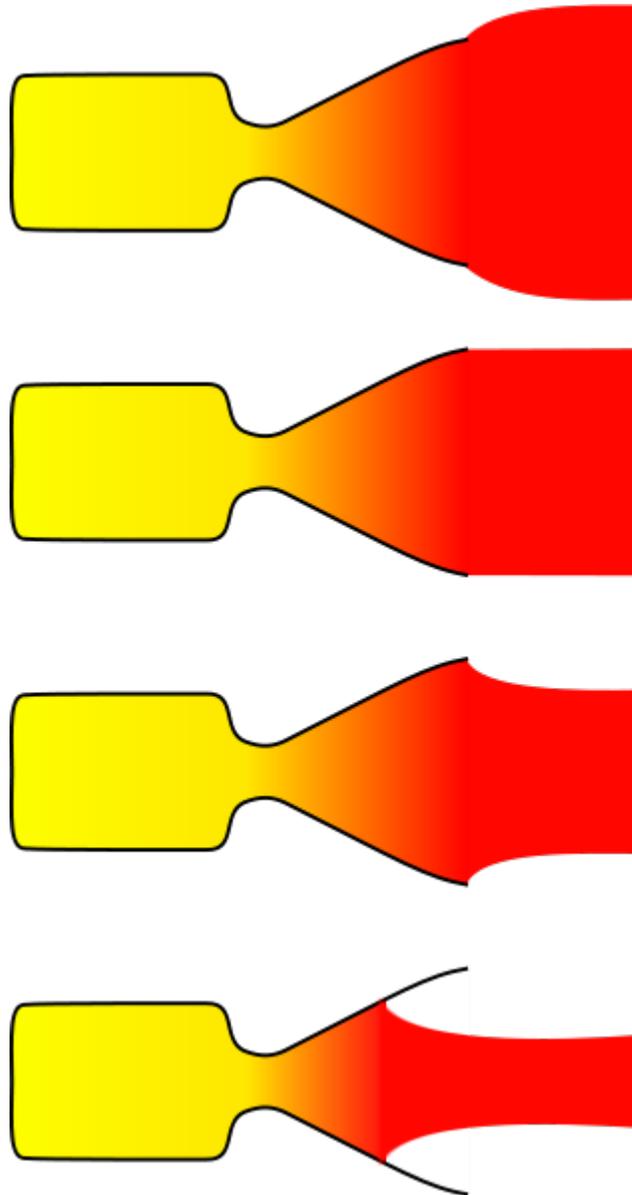
Nozzles can be (top to bottom):
Underexpanded
Ambient
Overexpanded
Grossly overexpanded
If under or overexpanded then loss of efficiency occurs. Grossly overexpanded nozzles have improved efficiency, but the exhaust jet is unstable.

Aerostatic back-pressure and optimum expansion

As the gas travels down the expansion part of the nozzle the pressure and temperature decreases and the speed of the gas increases.

The supersonic nature of the exhaust jet means that the pressure of the exhaust can be significantly different from ambient pressure- the outside air is unable to equalize the pressure upstream due to the very high jet velocity. Therefore, for supersonic nozzles, it is actually possible for the pressure of the gas exiting the nozzle to go significantly below or very greatly above ambient pressure.

If the exit pressure is too low, then the jet can separate from the nozzle. This is often unstable and the jet will generally cause large off-axis thrusts, and may mechanically damage the nozzle.

This separation generally occurs if the exit pressure goes below roughly 30-45% of ambient, but may be delayed to far lower pressures if the nozzle is designed to increase the pressure at the rim, as is achieved with the SSME (1-2 psi at 15 psi ambient).

Other design aspects affect the efficiency of a rocket nozzle; the nozzle's throat be a smooth radius. The angle of the narrowing down to the throat also has an effect on the overall efficiency, but this is small. The exit of the nozzle needs to be as sharp as possible to minimize the chances of separation problems at low exit pressures.

Advanced designs

A number of more sophisticated designs have been proposed and they can be categorised by the method with which they achieve altitude compensation.

Nozzles with an atmospheric boundary include:

- the expansion-deflection nozzle,
- the plug nozzle and
- the aerospike.

Each of these allows the supersonic flow to adapt to the ambient pressure by expanding or contracting, thereby changing the exit ratio so that it is at (or near) optimal exit pressure for the corresponding altitude. The plug and aerospike nozzles are very similar in that they are radial in-flow designs but plug nozzles feature a solid centrebody (sometimes truncated) and aerospike nozzles have a 'base-bleed' of gases to simulate a solid centre-body. ED nozzles are radial out-flow nozzles with the flow deflected by a centre pintle.

Controlled flow-separation nozzles include:

- the expanding nozzle,
- bell nozzles with a removable insert and
- the Stepped nozzles or dual-bell nozzles.

These are generally very similar to bell nozzles but include an insert or mechanism by which the exit area ratio can be increased as ambient pressure is reduced.

Dual-mode nozzles include:

- the dual-expander nozzle and
- the dual-throat nozzle.

These have either two throats or two thrust chambers (with corresponding throats). The central throat is of a standard design and is surrounded by an annular throat which exhausts gases from the same (dual-throat) or a separate (dual-expander) thrust chamber. Both throats would, in either case, discharge into a bell nozzle. At higher altitues where the ambient pressure is lower, the central nozzle would be shut off reducing the throat area and thereby increasing the nozzle area ratio. These designs require additional complexity but an advantage of having two thrust chambers is that they can be configured to burn different propellants or different fuel mixture ratios. Similarly, Aerojet has also designed a nozzle called the 'Thrust Augmented Nozzle' which injects propellant and oxidiser directly into the nozzle section for combustion allowing larger area ratio nozzles to be used deeper in an atmosphere than they would without augmentation due to effects of flow separation. They would again allow multiple propellants to be used (such as RP-1) further increasing thrust.

There is also a SERN (Single Expansion Ramp Nozzle), a linear expansion nozzle where the gas pressure transfers work only on one side and which could be described as a single-sided aerospike nozzle.