



© 1995-2026 by Isidoro Martínez

ENVIRONMENTAL EFFECTS AND HAZARDS IN COMBUSTION

Environmental effects and hazards in combustion	1
Fire safety. Protection and remediation	2
Fire safety education	2
Fuel detection.....	5
Fire detection.....	6
Smoke detectors	6
Water sprinklers	6
Inert atmospheres	7
Fire-breaks and fire extinguishers.....	7
Pollutant emissions	9
Emission quantification.....	10
Fuel tank and crank-case ventilation.....	10
Exhaust emissions and pollution.....	11
Vibrations and noise.....	17
Electromagnetic interferences.....	17
Safety management	17
Risk: a combination of hazard and damage	17
Emergency response	18
Analysis of accidents	18
Prevention of accidents	18
Glossary of terms: accident, exposure, fear.....	19

ENVIRONMENTAL EFFECTS AND HAZARDS IN COMBUSTION

Combustion is a hazard, and, besides the many services it provides to humankind, it may cause nuisance (e.g. noise, smoke), damage to property (deformations, loss of strength, burnings and explosions), and damage to people (injury and loss of life). Damage may be ranked in top-down severity order as: a) loss of life (mortality), b) loss of health (morbidity), c) loss of property and d) loss of activity.

Besides damage caused by the combustion process itself, there is also damage associated to the management of fuels (and oxidisers, if special). Coal handling produces respiratory hazards, and crude-oil derivatives are carcinogenic. Liquefied petroleum gases, LPG, and particularly cryogenic fluids like LNG, may cause severe frostbite and structural damage (carbon- and low-alloy steels show a marked ductile to brittle transition at freezing temperatures).

Damage may be caused to individuals or to the environment in general. A general summary on safety management is included below; here, some techniques to minimise risks associated to combustion are studied.

Combustion is a physico-chemical hazard, and, to minimise its impact, one has to be aware of it, rely on safer fuels (e.g. diesel instead of gasoline, natural gas instead of butane), reduce unnecessary fuel stores, avoid fuel leakages and provide fuel detectors, reduce uncontrolled ignition-sources (sparks and hot spots), decrease the impact of the controlled combustion processes (emissions), and plan for the best

rescue actions in case of uncontrolled combustion (fire detection and fighting). As usual, pyrotechnics hazards (from amusement firecrackers to weaponry) are not considered under the combustion heading.

A quick-summary of hazard types associated to combustion may be:

- Physical hazards: mechanical (explosion), thermal (excessive heat, out-range temperatures), radiation (blinding flare).
- Chemical hazards: oxygen depletion, gas poison, aerosols, liquid poisons, solid poisons.

The effects of combustion on the environmental may be grouped in two categories:

- Sudden uncontrolled events (combustion accidents). This impact is fought with proper prevention (minimising risk and educating people) and proper fire fighting (smoke detectors, automatic fire-sprinklers, portable fire-extinguishers, fire-fighting brigades).
- Continuous degradation, due to pollutant emissions during normal combustion. This impact is fight by developing better fuels (sulfur-free diesel, unleaded gasoline), better combustion processes (fluidised bed, porous media) and post-combustion treatment (catalytic conversion).

Only a descriptive view of the subject is here presented (some theoretical insight can be found on Combustion Kinetics). [Thermal effects on materials](#) in general, which may be originated from a combustion process, are presented aside. We have tried to follow a top-down approach in the analysis of the environmental effects of combustion, i.e. from deadly explosions to inconvenient electromagnetic interferences.

Fire safety. Protection and remediation

Fear of the fire has always frightened humans. Risks must be prevented first (minimising risk), their consequences foreseen (minimising damage), their occurrence appropriately handled (early warning, gateways, fighting), and the consequent damage allocated in justice.

Contrary to common sense, there are many fires that are not fortuitous accidents but directly caused by irresponsible people, from children left playing with matches, to arson. People are the primary cause of all accidents. Again, education on fundamental principles, and not only instructions about particular items, is the best preventive measure.

Fire protection can be achieved by passive means (using fire-resistant materials), or by active means (fire-extinguishers). The most effective protection is based on proper fire safety education.

- Minimising risk: fire safety education, inert atmospheres, smoke detectors and fire-doors.
- Minimising damage: fire-breaks, fire sprinklers and fire extinguishing.

FIRE SAFETY EDUCATION

Education is the best prevention. For every identified risk, plan a fire safety procedure (e.g. get a hose or a water bucket nearby when making an outdoor fire), and rehearse it (e.g. evacuate multi-store buildings once a year, even at a pre-established time; it teaches people and safety personnel a lot). Clean habits already help to prevent fires, since accumulation of waste (packing material, oily rags, rubbish) and even

dust may be a fire hazard (old stores must be kept tidy, too!). Smoking is reported to be a major cause of fire accidents.

Hazard types to humans at normal pressure (for goods there are only two concerns: either destruction by fire, or fire promotion):

- Toxicity of emissions, i.e. poisoning. The main toxic gas in combustion is CO; $x_{\text{CO}} > 1\%$ for 1 minute is mortal (maximum permissible 50 ppm); other toxic gases may be SH₂ ($x_{\text{SH}_2} > 0.1\%$ for 1 minute is mortal), SO₂, CNH, HCl, NO₂, NO, NH₃. As a rule, hydrocarbon vapours in concentration $> 0.1\%$ in volume (1000 ppm) cause eye irritation after some minutes, whereas $> 1\%$ ppm produces unconsciousness after a few minutes. Smoke, i.e. particles and droplets aerosols, cause eyes and nose irritation and orientation lost (panic).
- [Hypoxia](#), i.e. insufficient oxygen ([anoxia](#) is total lack of O₂; [asphyxia](#) really means lack of pulse). Normal air has $x_{\text{O}_2} = 21\%$; above $x_{\text{O}_2} = 17\%$ normal breathing can be sustained (really at $p_{\text{O}_2} > 0.17 \cdot 100 = 17$ kPa for other ambient pressure), but below $x_{\text{O}_2} < 15\%$ muscle fatigue is noticeable, at $x_{\text{O}_2} < 10\%$ reasoning stops, at $x_{\text{O}_2} < 5\%$ consciousness stops. Oxygen in the air (or another gas mixture) can be monitored by electrochemistry (ZrO₂). In normal working conditions, breathable oxygen concentration should not be outside the 19 %..22 % range, to avoid anoxia if $x_{\text{O}_2} < 19\%$ (workers should wear oxygen masks), and to minimize the risk of fire if $x_{\text{O}_2} > 22\%$. In some special cases (e.g. data centres, archives) hypoxia is [maintained](#) on purpose, adding N₂ to keep x_{O_2} say at 15 %, avoiding most common fire hazards while allowing for short-time human visits. The release of any inert gas into a room may be fatal by depriving O₂ for respiration ([inert gas asphyxiation](#)), but the case of CO₂ is special because if $x_{\text{CO}_2} > 5\%$ the release of CO₂ waste from blood to air at the lungs is prevented, and becomes toxic ([hypercarbia](#)); up to $x_{\text{CO}_2} > 1\%$ respiration is normal; up to $x_{\text{CO}_2} > 5\%$ may be beard for one hour or so with respiratory stress, but $> 10\%$ of CO₂ in air is mortal after a minute or so.
- Burning, i.e. dehydration and ablation of tissues, may range from mild skin burns to incineration, usually graded as first-degree burns (skin surface painful and red, a small blister), second-degree burns (large blisters on the skin), third-degree burns (destruction of both epidermis and fatty dermis; dry and painless), and calcination. Burning may be due to hot objects, a very hot environment, or direct flame contact: superficial skin burn (1st and 2nd degree) takes 6 hours at 45 °C but 1 second at 70 °C. Monitored by explosimeters (oxidation in a hot Pt-wire), which usually indicate fuel content relative to the lower ignition limit (LFL or LEL): the atmosphere is safe if $< 10\%$ LEL; in the range 10..20 % one should be on alert; if $> 20\%$ better to leave the room and take measures.
- Suffocation and hyperthermia, i.e. inability to evacuate metabolic heat to the environment, resulting in heat exhaustion and heat stroke. At 40 °C and 100 % RH death follows after a few hours (but a steam-sauna, Turkish bath, at 40 °C for a few minutes may be healthy; at 50 °C and 100 % RH death follows after a few minutes). At 120 °C, even in the driest, death follows after a few minutes (but a dry sauna, Nordic sauna, at 90 °C and less than 10 % RH for some minutes may be healthy).

Each fire is unique, but most domestic and industrial fires (explosions not included) have the following common characteristics:

- $\Delta t_{\text{buildup}}=10\pm 5$ minutes, i.e. a build-up period of some 10 minutes after ignition, while sufficient heat is released for a thermal runaway; suddenly, oxygen is locally depleted and CO and HCN abound. The spreading of fire over a quiescent liquid-fuel pool (e.g. oil spillage) at room temperature is at some 0.1 m/s, and some 0.01 m/s over solid fuels.
- $\Delta t_{\text{max heat}}=30\pm 10$ minutes, i.e. the maximum heating taking place 30±10 minutes after ignition
- $\Delta T_{\text{buildup}}=1100\pm 100$ K, i.e. a maximum heating (maximum temperature relative to the ambient) of 1100±100 K, what may be explained in terms of the fuel/oxidiser characteristics.
- $\Delta T_{\text{residual}}=700\pm 100$ K, i.e. a residual slowly-decreasing heating of $T_{\text{amb}}+700\pm 100$ K, after one and a half or two hours after ignition.

The ISO standard fire-event is just an exponential heating, $T=T_{\text{amb}}+A\log(1+Bt)$, with $A=345$ K and $B=8$ min⁻¹.

There are some basic differences between open and enclosed fires: flame tip temperature, burning rate, pressure jumps, and, most important, the ceiling layer.

Consider the same fuel in air geometry, e.g. a circular oil-pool fire of a 1 m², in calm air, either outdoors, or indoors in the middle of say a 3·3·3 m³ room; if the enclosed fire is close to a wall, significant changes take place. In both cases there is a turbulent flame that completely fills the space above the fuel to some height (nearly independent of pool size for >1 m²), plus some flame tongues or flame tips going further up (some 2..3 m in total). In both cases the bulk region is at a nearly uniform temperature of 1100±100 K, but the temperature at the flame tips is 650±50 K in open fires and 800±50 K in enclosed fires, due to the different heat radiation loss in each case.

Open fires show larger burning rates because of better air supply; the values for a 1 m² kerosene pool being 0.02..0.05 kg/(m²·s) for enclosed fires and some 0.07..0.08 kg/(m²·s) for open fires.

Enclosed fires give way to significant pressure changes in the interior. Depending on openings and ventilation, of course, inside pressure suddenly rises some 0.2..0.8 kPa for a few minutes after fire builds up, due to the initial expansion of hot gases; then the pressure fluctuates around the original ambient pressure. If the fire is extinguished, there is a small underpressure of order 0.1 kPa for a few minutes (depending on ventilation), due to contraction on cooling of the hot gases inside. If the fire goes on and a flashover in the ceiling layer takes place, a sudden pressure increase occurs that may break windows or walls.

The most important difference, however, is that, although in both cases the temperature slightly decreases with height further up the flame tips, and the vertical speed of gases also decrease due to air entrainment (from a maximum of up to 10 m/s), after a few minutes from ignition, enclosed fires build a hot ceiling layer that slowly increase temperature with time, due to the hindered heat losses, until the flashover temperature of 900±50 K (typical autoignition temperature) is reached in the ceiling layer with the sudden burning of all combustible gases generated by pyrolysis and vaporisation of other combustible matter existing in the room.

A two-zone thermal model, a uniform ceiling layer of hot gases floating over a floor layer of fresh gases and a narrow hot plume, exchanging mass and energy, is often used as a first stage in the analysis of enclosed fire development, before incurring on the expense of CFD codes.

FUEL DETECTION

A fire needs a fuel, an oxidiser (that is always available, ambient air), and an ignition source. Because ignition sources are commonly present (cigarettes, heaters, electrostatic sparks), fire safety starts by identifying and detecting fuel sources.

Besides pyrotechnics and explosives, that must be specially treated, fuels may be classified as flammable substances (gaseous fuels and high-vapour-pressure condensed fuels) and combustible substances (low-vapour-pressure condensed fuels).

Non-flammable combustible substances are of secondary concern to fire safety, since they will not be ignited by accidental sparks or distant flames; amongst them, only liquid fuels (particularly gas-oil and kerosene) are of special risk, and the emergency measures should be proportional to spillage and inversely proportional to flash-point temperature. The usual fuel-leakage detection method for combustible substances is visual inspection of liquid-fuel tanks.

Flammable substances must be so labelled, and any uncontrolled treated as an immediate fire hazard with ample ventilation and evacuation. Flammable liquids (gasoline, alcohols, liquefied petroleum gases) and gaseous fuels are an obvious hazard since on a leakage occasion, they form ignitable mixtures with air during the process of mixing (and perhaps after full mixing, in closed spaces). Accidental ignition sources are so common (sharp knocks, electrical contacts, cigarettes, stoves and other hot points), that the risk of ignition is very high.

Fuel-gas leakage detectors are also called explosimetres. They are usually based on the electrical resistance variation of a platinum wire, due to the temperature increase caused by rapid catalytic oxidation of the fuel-air mixture at low temperature in the surface of the catalyst. Controlled combustion of fuels to avoid further damage has been used in old times, not only by burning a downstream field to avoid propagation of an incoming fire, but by purposely burning from time to time the fuel-gas released in mines (the latter documented at least since medieval times, because sometimes it became uncontrolled).

Portable system with field replaceable measuring cells are in the market capable of sensing minute concentrations of natural gas, butane and propane, either along pipes and combustor (gas leak), or in the ambient (explosimetres).

Sometimes, to avoid explosions, it is not enough to have a quantity less than the lower ignition limit in a closed room, since very light fuels like H₂ or very heavy gas fuels as diethyl ether (C₄H₁₀O) will stratify a lot.

Mercaptan odorants are always added to gaseous fuels so that they can be detected by scent before reaching explosive levels.

FIRE DETECTION

Once a fire breaks out, it can be detected by different methods:

- Smoke detectors
- Flame detectors (infrared or visible)
- Heat detectors or, more generally, thermal detectors.

The detector can be used to ring an alarm or directly fight the fire by active means, usually by water sprinklers, using low-melting-point or thermoelastic switchers (e.g. an aluminium rod that expands and breaks a glass stopper), or any other fire-fighting fluid. Some flame detectors and thermal detectors can be found in [Combustion instrumentation](#) or in [Thermal effects on materials](#), aside. For thermal detection, care should be taken not to confuse fire with other inoffensive heating; fire alarms usually require a temperature above 60 °C plus a heating rate above 1 °C/min.

SMOKE DETECTORS

Smoke detectors are used to provide a quick alarm (acoustic at least) once a fire breaks out. They are usually combined with automatic water sprinklers (after a warning period of alert, since fire extinguishers always cause damage, and the smoke detector trigger might be due to a false alarm). Smoke detectors should be located in exposed areas of the room, and not in dead-air corners (a forced air convection is applied in spacecraft racks, for that purpose, and to enhance heat removal).

There are two basic type of smoke detectors:

- Ionization detectors. They contain a very small amount of radioactive material (e.g. americium, a radioactive metallic element produced by bombardment of plutonium with high energy neutrons) that ionizes the air, making an electrical path, where an electric current is established. When smoke enters within the path, the smoke molecules attach themselves to the ions and the electric current changes, triggering the alarm.
- Photo-electric detectors. They contain a light source (usually a small bulb) and a photocell. When smoke enters within the light path, the transmissivity changes, triggering the alarm.

WATER SPRINKLERS

Automatic water sprinklers, connected to a wet-pipe system (only suited for areas not subject to freezing), provide both fire detection and suppression. They were introduced as back as the XIX c., and they are based on an operating element, a low-melting-point or thermoelastic device, that clears the water exit; water pressure pushes the sprinkler cap aside, and water is discharged only through sprinklers that have opened due to exposure to heat, all the others remaining intact. Water sprinklers are very reliable and safe (the chances of a sprinkler accidentally going off are remote) and minimise the water damage associated to fire fighting.

In large systems, the flow of water out of the sprinkler system trips a monitoring device, typically a water flow detector, which activates a central fire alarm.

Dry-pipe systems are essentially the same as wet-pipe systems except that the pipes in the protected area contain pressurized air, allowing for freezing temperatures. When a sprinkler head is activated by a fire, the pressurized air is released and water flow occurs.

A new fire-sprinkler technology is based on delivering water at very high pressure (requires special pumping), producing a fine and high-efficiency water-vapour mist that maximize cooling, extinguishing fires with minimal amounts of water (a few litres for a typical room).

INERT ATMOSPHERES

Many industrial fires take place when handling flammable materials or when welding near combustible materials. Procuring a local inert atmosphere (i.e. depleting oxygen from the air) may be the best fire-prevention action, since it is impossible to get rid of combustible materials, and very difficult to get rid of ignition sources. In most circumstances, an inert atmosphere is one having $x_{O_2} < 5\%$ (not to be confused with an under-lean atmosphere, which is one with less flammable vapours than the lower ignition limit for the fuel).

The two basic inertisation procedures are:

- Nitrogen atmosphere, where the oxygen molar fraction in air $x_{O_2}=0.21$ is reduced below $x_{O_2}=0.08$ by adding nitrogen (nitrogen with 5 % impurities, as obtained with selective permeation membranes, is good enough). Inert atmospheres are routinely used onboard crude-oil tankers, low flash-point chemical cargo ships, and fuel tanks; the largest nitrogen-generator producing $1.7\text{ m}^3/\text{s}$ from air by membrane technology. Besides fire prevention, nitrogen systems are used as super dry ($T_{\text{dew}} < 200\text{ K}$), non-freezing, non-oxidative, non-corrosive atmospheres.
- Burnt atmosphere, where the oxygen molar fraction in air $x_{O_2}=0.21$ is reduced below $x_{O_2}=0.08$ by adding exhaust gases from a combustor (the air/fuel relative ratio cannot be too large; up to $\lambda=2$ is good enough).

For a tank to be really protected with an inert atmosphere, it must always have some overpressure, relative to the surrounding air.

FIRE-BREAKS AND FIRE EXTINGUISHERS

Once a fire is noticed, an early alarm to trained personnel is most of the times better than a personal attempt to extinguish a fire. Small fires may be fought with fire extinguishers, but for large fires the first action must be to isolate the damage with fire-breaks. A fire-break is anything that stops a fire from spreading: a strip of cleared land in a forest, a masonry wall, a fire-retardant door, a hydraulic seal, etc.

Materials are usually termed non-combustible if they cannot combine with oxygen at all or if their flash-point is higher than 1000 K , i.e., if when heated to 1000 K in a furnace for 3 hours, they neither self-inflame, nor can be ignited by a near spark (ISO 1182). But there are several other characteristics that

make a material fire-resistant to different degrees. Fire-resistance tests are performed on building construction elements (ISO-384), vehicles, wires, industrial installations, etc.

Extinguishers must be located near escape routes. Fires and extinguisher are classified according to the material that is on fire (A, solid; B, liquid; C, electrical; D, metal), although many extinguishers are good for several types of fire (and so are labelled; e.g. CO₂, halons, their substitutes (e.g. HFC-227ea, HFC-236fa, FM-200 and Inertgen), and dry-powder (NH₄H₂PO₄, mono-ammonium phosphate, or ammonium dihydrogen phosphate, ADP), are all good for types A, B and C):

- Type-A fires involve ordinary solid combustible substances (coal, wood, cloth, rubber and many plastics), and can be extinguished with a cooling agent (water, foam, earth) to arrest the generation of fuel vapours. Beware of arrested solid fires; their embers remain hot inside for long, and may inflame many hours later by a blow of air. Typical hazards at home are cloth fires by cigarettes, stoves and unsafe playing with lighters and matches. These fires are smoky and cause disorientation and toxic fumes (remember: the air in a fire is cleaner at the floor).
- Type-B fires involve flammable liquids and gases (oil, gasoline, natural gas, GLP, paints, lacquers, grease, solvents), and are extinguished with an air-barrier dry-chemical (CO₂, Inertgen, FM-200) and never with water (the fire would spread), with the advantage that they do not leave a mesh of foam. Typical hazards at home are fires at the kitchen by overheated oil or grease when cooking (covering with a lid is usually enough to stop the fire; do not carry the pan outside or throw water over). Sometimes, liquids are called flammable only if their flash-point is below 48 °C (that of diesel), the rest being called combustible liquids.
- Type-C fires involve electrical potentials (wiring, fuse boxes, energized electrical equipment), and must be extinguished with an electrically insulating air-barrier (e.g. CO₂; water may cause electrocution).
- Type D fires involve metals such as magnesium, aluminium, iron, titanium or sodium; they are very dangerous and should not be handled by untrained personnel.

As for refrigerant fluids, the standard fire-extinguisher fluids during the last half of the 20th century were halogenated hydrocarbons (halons), which had to be substituted in the 1990s by non-ozone-depletion fluids. The most used were Halon 1211 (CF₂ClBr, bromochlorodifluoromethane, a liquefied gas), and Halon 1301 (CF₃Br, bromotrifluoromethane, a compressed gas), which have been substituted by heptafluoropropane (R227, C₃HF₇, also named FM-200).

CO₂ fire extinguishers are loaded with liquid CO₂ (assuming internal temperature below the critical point, $T_{cr}=31\text{ °C}$, $p_{cr}=7.4\text{ MPa}$). When the valve is triggered, liquid CO₂ is expelled from the bottom through a riser pipe and finally expanded at the exit of the high-pressure hose, where the liquid flashes to a mist of dry-ice particles and CO₂-gas, at about -79 °C , which are focused within a long funnel (which becomes very cold and should not be touched). The discharge is clean (the white jet of dry-ice and condensed-water particles leave no visible residue), but the air around may become unbreathable (fatal blood decarboxylation blockage for $x_{CO_2}>9\%$), although the high density of the gas at -79 °C (2.7 kg/m^3) retards natural convection. Inergen (IG-541) is a mixture of 52 % N₂, 40 % Ar and 8 % CO₂, which has substituted CO₂ in fire extinguishers to avoid that problem; when Inergen mixes with air (they are almost

isodense), for a half-and-half mixing the resulting O_2 level is $x_{O_2} < 10\%$, already low to sustain fire propagation (but able to keep human conscience during several minutes), whereas the resulting $x_{CO_2} < 4\%$, low enough to not blocking blood release of CO_2 at the lungs.

Powder fire extinguishers are loaded with $NH_4H_2PO_4$ or $NaHCO_3$ powders and a pressurised CO_2 cartridge. When triggered, the CO_2 gas pushes down and expels the powder as a fine mist that dissociates to CO_2 and H_2O in contact with the fire, and which penetrates everywhere (the mesh they create may outbalance their use in small fires).

Fire engine trucks carry an extensive assortment of tools and equipment: pumps, hoses, water tanks, portable extinguishers, ladders, axles, breathing apparatuses, communication equipment, electric lights and generators, etc. They are used to fight domestic, industrial and forest fires, but the latter usually requires straightforward measures as firebreaks (removing further fuel ingest), spreading chemicals that decrease the flammability of wood, flooding with water, or spreading smothering materials such as dirt or sand.

Pollutant emissions

Life is a polluting process, because life must live at the expense of the environment. The problem is that the amount and concentration of pollutants emitted by human activities has gone too far and seriously menace life, both locally and globally.

The first and traditional approach to fight pollution is to go away or throw it away, e.g. to make a chimney for venting the fireplace, to have out-side-air sealed combustion boilers, to build power stations aside, etc.

The effects on the environment are usually identified with pollutant emission through the tail-pipe of combustors, but handling of fuels, fuel losses at the inlet, and product losses from the combustor shell, are other sources (up to 20 % of the hydrocarbon emissions in a car do not go out along the tail-pipe). Mass losses and energy losses may be a danger to humans, animals, plants and goods: explosion danger (in confined places), open flame danger, toxicity from CO (and other toxic gases in chemical fires), suffocation or anoxia from CO_2 , hyperthermia by heat, respiratory and visual irritation by smoke and noxious gases, etc. Mechanical pollution (noise) and electromagnetic pollution (interferences, EMI), are dealt apart.

Main contaminants, besides the unavoidable CO_2 in carbon-containing fuels that contribute to the greenhouse warming (the legacy left by these emissions would be felt mainly by our offspring), are: VOCs (Volatile Organic Compounds), CO, NO_x , SO_x , and particulate matter (PM, or PM10 to explicitly restrict to sizes $< 10\ \mu m$). Soot is formed in non-premixed flames and on premixed flames for equivalence ratios $\phi > 1.5$. Diesel engines produce more pollutants in the stated order (more PM and less VOC), whereas Otto engines do just in the reverse order. Some 40 % of man-produced VOCs come from transport (not only through the tail-pipe but from reservoirs and at the stations). Sometimes, instead of

VOC, the term HC (hydrocarbons) is used, even splitting between methane and NMHC (non-methane hydrocarbons).

EMISSION QUANTIFICATION

Quantifying emissions is not a trivial issue and several methods can be followed:

- Mass-to-mass emission indices, EI_i , defined as the mass of i -contaminant emitted divided by the mass of fuel burnt. Although a dimensionless ratio, units of g/kg are common. This measure is independent of the application at hand and the dilution applied, thus it does not enter into considerations of the actual effects of the emissions or the real need of the process, but it is the best method from the combustion point-of-view to quantify emissions.
- Mass-to-energy emission ratio, EER_i , defined as the mass of i -contaminant emitted divided by the energy supplied by the fuel burnt. It is intended to weight the burden against the benefit of the combustion process, but great care must be paid to ascertain if the energy supplied is just the heating value of the fuel burnt, or the final energy delivered to the payload (shaft work for combustion engines, or water heated energy for boilers). This ratio serves to compare pollution from other energy sources different to combustion, but with little relevance since the emissions are so different (e.g. nuclear vs. fossil power stations).
- Mass-to-purpose, e.g. mass-to-distance travelled emission ratio, DER_i , defined as the mass of i -contaminant emitted divided by the distance travelled. It is intended to weight the burden against the real benefit of the combustion process, but great care must be paid to measure the benefit; of course, the goodness of transportation is not the power of the engine but the distance the payload travels; but time is also important, and the payload is not fixed beforehand (e.g. distance-emissions ratios are given for a car in a given trajectory, city cycle or highway, irrespective of the number of actual occupants).

To give an idea of the pollution in a major city, the average figures for measured values in Madrid are: 1000 $\mu\text{g}/\text{m}^3$ of CO, 70 $\mu\text{g}/\text{m}^3$ of NO₂, 1000 $\mu\text{g}/\text{m}^3$ of CO, 40 $\mu\text{g}/\text{m}^3$ of PM10, 30 $\mu\text{g}/\text{m}^3$ of O₃ and 20 $\mu\text{g}/\text{m}^3$ of SO₂.

FUEL TANK AND CRANK-CASE VENTILATION

Diesel fuel has a low vapour pressure, but up to 20 % of the hydrocarbon emissions in old gasoline cars did not go out along the tail pipe but directly from the fuel tank, the carburettor, the crank-case, and other fuel leakages (e.g. deterioration of fuel-line joints and tank cap). We leave aside hydrocarbon emissions not directly related to the fuel, as those emitted by tyres, upholstery, carpets, etc.

Fuel tanks are pressurised only for gaseous fuels. Liquid fuels are kept in tanks at ambient pressure, which changes a little with ambient weather; hence, tanks must be open to the atmosphere to avoid pressure build-up and vacuum build up, during filling fuel and fuel withdrawal. But gasoline has a large vapour pressure (a limit of 60 kPa is accepted), and the problem worsen nowadays that bioethanol is added (some 5..20 % of ethanol by volume). Hence, a lot of volatile hydrocarbons would be vented when filling the tank, when the tank warms up, and on other leakage (gasoline permeation through tank walls is about 1 g/day on average, doubling for a 10 °C rise; multilayer high-density poly-ethylene (HDPE) tanks with special vapour-tight films are being used to reduce permeation). Although ethanol has just 8 kPa of

vapour pressure at 25 °C, when added to gasoline increases the mixture vapour pressure linearly with a maximum of some 6 kPa at around 5 % ethanol by volume, slightly decreasing beyond that concentration until at about 50 % ethanol the original vapour pressure of gasoline is recovered, and beyond that the mixture vapour pressure tends towards the pure-ethanol value. Modern gasoline-cars have no fuel-return line, but on traditional installations, part of the fuel supplied to the engine by the fuel pump returned to the tank significantly hotter than the fuel in the tank.

To avoid pollution (and save fuel), nowadays all gasoline tanks are built with an evaporative emissions control system (often known as EVAP), consisting basically in a carbon-activated filter (canister) that adsorbs and stores the organic vapours coming from the tank (until it becomes saturated), while letting air pass through. The adsorber-canister is regenerated during engine operation, by drawing some fresh air through it, pulling the vapour into the engine, where it burns. Besides this on-board fuel-vapour recovery system, some modern fuel-serving stations make use of special hose and nozzle with vapour return to the underground storage tank.

The crank-case (oil box) is also ventilated to the admission pipe, because there is an important fuel loss from the combustion chamber to the oil box through the slipping rings, particularly during cold operation (at starts).

Fuel leakage can be detected by several methods. For condensed fuels the key leakage diagnostic is spillage tracking, whereas for gases, bubbling (usually by applying a soap solution), UV-fluorescence, ultrasonic, and catalytic methods are used.

EXHAUST EMISSIONS AND POLLUTION

The complete combustion of $C_uH_vO_wN_x$ fuels would only yield CO_2 and H_2O as new compounds. Water is thought to be processed globally by the hydrological cycle (although local condensations may be corrosive and be the best culture for moulds and bacteria), but CO_2 is already considered a pollutant due to the overall green-house-effect contribution if non-renewable fuels are used. We intend here to analyse pollutants going out the exhaust pipe of mobile and stationary combustors that, although in concentration much lower than CO_2 and H_2O (typically less than 1 %), have a great impact on the environment. Combustion processes where non-commercial fuels are burn (e.g. wild fires, waste incineration, rocket propulsion) give off many more hazardous contaminants not considered here: halogenated (dioxines, furanes, hydrogen chloride), organometallic and others..

Just in EU, the annual emission of CO_2 is some $3 \cdot 10^{12}$ kg CO_2 (40 % due to electricity generation, 30 % due to transport engines, and the rest to industrial and other activities), and is stabilised (other emissions are slowly declining: $15 \cdot 10^9$ kg VOC , $15 \cdot 10^9$ kg NO_x , $10 \cdot 10^9$ kg SO_2 , etc.). A major milestone in world pollution control was achieved in the Kiotto-1997 protocol, where a target on anthropogenic greenhouse gases emissions of less than 5 % the 1990 world figures was established for 2008.

Environmental pollution locally depends on the amount and type of industrial activities, density and age of vehicle fleet, efficiency in combustion, weather conditions, climatology, etc. In most developed

countries, the transport sector is a major source of air pollution (amongst it, road transport takes more than 80 %), and the dominant source in urban areas. Continuous emissions monitoring (CEM) is mandatory in most major combustors. Exposure to air pollution can cause adverse health effects, most acute in children, asthmatics, and the elderly, and can damage vegetation and materials (notably, the cultural heritage). ICE are responsible for nearly half of the world contamination load. About 1 % of the exhaust gas stream is harmful, and consists of carbon monoxide (CO), oxides of nitrogen (NO_x), volatile organic compounds (VOC, also named hydrocarbons: HC) and particulate matter (PM).

In premixed combustion, emissions depend upon the air-fuel ratio, but unfortunately when the concentration of CO and HC decreases the concentration of NO_x increases, and vice versa. Non-premixed combustion may be much more pollutant: the flame sits near the stoichiometric diffusion-rates and thus its temperature is very high, causing the formation of NO_x, and the pure fuel approaching it gets pyrolysed with large production of soot (that give the characteristic yellow colour to non-premixed flames) and other volatiles.

CO₂

Carbon dioxide (CO₂) is an unavoidable emission in the combustion of carbon-containing fuels. There is little concern with local contamination by CO₂ emissions, being an inert gas like nitrogen. Like nitrogen, it may cause local suffocation; a 9 % CO₂ is fatal to a person after a few minutes, by anoxia, and a 5 % already produces troubles after 1 hour. The main concern of CO₂ emissions is at global scale, with the positive correlation found between anthropogenic CO₂ generation and the increase of CO₂ fraction in air (e.g. from 310 ppm molar in 1950, to 380 ppm molar in 2007), and the foreseeable consequences on climate change due to the associated increase in the global greenhouse effect, which is feared to be highly non-linear, with a small global warming but larger regional changes (desertification, floods, hurricanes, and so on).

There are two ways to decrease CO₂ emissions: to decrease overall emissions by increasing the energy efficiency of the combustor, engine and associated transmissions, and to use low-C fuels (shift from coal with C/H=1.3 and liquid fuels with C/H=0.5, to GLP and, better, to natural gas with C/H=0.25, and eventually to H₂ with C/H=0).

However, the foreseeable reduction in CO₂ emissions seem not enough, and technologies to capture the CO₂ before it goes to the atmosphere must be applied in the near future. Use of CO₂ as by-product to other industries is too small: as a chemical stuff for methanol and urea synthesis, as an inert gas in welding and inertization of large fuel installations (dry stoichiometric exhaust gas from a combustor is the cheapest choice), CO₂ is used to help recover residual crude-oil at some wells, as a refrigerant (including dry ice applications), as a solvent in the cleaning industry, in the preparation of carbonated beverages, etc.

The only way out is then CO₂ capture (or sequestration), and permanent disposal in deep soil reservoirs (deep-sea disposal seems too risky, environmentally). CO₂ capture may be based on different approaches:

- Capture the emitted CO₂ from conventional sources. This is impractical once the CO₂ is diluted in the atmosphere ($x=0.04$ % molar), and seems impractical too in transport, but is being tried in

large coal-fuelled power stations (with $x=0.15..20$ % molar). Physical separation (by membrane technology, cryogenic distillation, or sorption) is presently too expensive, but chemical separation has made good progress in the carbonation-calcination process ($\text{CO}_2(\text{gas mix})+\text{CaO}=\text{CaCO}_3$, followed by $\text{CaCO}_3+\text{heat}=\text{CaO}+\text{CO}_2$).

- Capture the emitted CO_2 in a better way by modifying the combustion process, to be performed with pure oxygen what is known as oxy-combustion, yielding a pure CO_2 exhaust, or a $\text{CO}_2 / \text{H}_2\text{O}$ gas mixture easily separated by water condensation. To avoid too high temperatures, CO_2 is always partially recirculated. To get pure oxygen from air, traditional cryogenic distillation or membrane separation may be used, although new approaches are been tried, as using an intermediate metal that gets oxidised, separated, and then reduced to yield pure O_2 and the regenerated metal
- Fuel decarbonisation before combustion, i.e. capture the carbon (in the form of C, CO, or CO_2). This has no sense for coal, which is some 85 % by weight C, but a possible solution for natural gas (e.g. a reforming stage can be used to decompose $\text{CH}_4=\text{C}+2\text{H}_2$, get rid of the solid C, and change to a hydrogen economy.
- An indirect way out to CO_2 capture is to reforest, for the trees to fix the atmospheric CO_2 into biomass (which can be later used as fuel source or not). Some other large scale ‘enhanced natural ways’ to get rid of CO_2 have been suggested, as promoting carbonation of marine biota by seeding the sea-surface with iron particles, and so on (it is a fact that only a third of the CO_2 emissions accumulate in the atmosphere, the rest being captured by the oceans).

CO

Carbon monoxide (CO) is found in exhaust emissions due to a poor combustion process (i.e. too rich a mixture, unburnt fuel pyrolyses at crevices, or not enough residence time for equilibrium), particularly in the Otto engine at cold starts, idle, and full power conditions. Unburnt pyrolysed fuel would be in negligible amounts if sufficient time for equilibrium at the low exit temperatures were allowed, as in large combustion chambers and large marine engines, where the residence time is near one second (combustion is similar to eating; it takes time for a good digestion, starting by proper food preparation, chewing and so on).

CO is a deadly poison that reduces the ability of the blood to absorb oxygen and, as a result, lowers the blood oxygen content by producing carboxyhemoglobin. Even as low a proportion as 0.5 percent by volume of CO in the air can prove fatal within 1 hour (>50 % carboxyhemoglobin in blood), 0.05 % produces headache after 10 hours (10 % carboxyhemoglobin in blood). In uncontrolled fires, like in a hotel room, typical concentrations of up to 5 % are achieved after the fire runs away of control. Measured in the blood. For clean air standard EU sets a limit of $10 \text{ mg}_{\text{CO}}/\text{m}^3$ in a 8 hours average.

Two types of approaches may be followed to fight CO emissions (besides minimising fuel use): to avoid CO formation inside (e.g. using stratified charging), and to eliminate the CO inside the tailpipe, usually by a catalytic oxidiser (e.g. the three-way catalyser in Otto engines). CO and CO_2 are usually measured by infrared absorption.

NO_x

NO_x stands for all nitrogen oxides, mainly NO and NO₂, but also N₂O, N₂O₂, N₂O₃, N₂O₄ and N₂O₅, and all appear from atmospheric nitrogen during combustion with air (coals and heavy fuel-oils have some intrinsic nitrogen also, up to a few percent by weight). All nitrogen oxides are unstable at ambient conditions when pure, i.e. they dissociate, but their decomposition may be very slow. They are formed at very high temperatures in the presence of air (there is a high peak in the range $\lambda=1..1.1$), and two approaches are followed to avoid their emission: avoidance of high temperature formation (by using very lean mixtures, exhaust gas recirculation, porous burners, catalytic burners, water injection), and catalytic reduction at the exhaust. Notice that the peak in NO_x production practically coincides with the range of maximum combustion efficiency (minimum entropy production), so that it might be said the NO_x emission is a sign of good combustion, contrary to unburnt emissions.

The most polluting of NO_x-components is nitrogen dioxide, NO₂, a brown gas at normal conditions (but readily condensable, $T_b=21$ °C). When heating an ampoule containing NO₂ from above, some dinitrogen tetroxide N₂O₄ ($2\text{NO}_2=\text{N}_2\text{O}_4(\text{g})+57$ kJ/mol) is exothermically formed; N₂O₄ is a colourless heavier gas that appears at the bottom (because of buoyancy), although the reaction would be more displaced to the left in equilibrium at high temperature (but kinetics dominates). A third gas appears when heating at 600 °C, nitrogen oxide, NO ($\text{N}_2\text{O}_4=2\text{NO}+\text{O}_2$, also transparent. Nitrogen oxide, NO, is a colourless gas that in the presence of atmospheric oxygen, rapidly converts to yellow NO₂; NO concentration can be measured by chemiluminescence with ozone: $\text{NO}+\text{O}_3=\text{NO}_2+\text{O}_2+h\nu$. NO₂ smells pungently and causes pronounced irritation of the respiratory system if > 10 ppm, and is fatal if >100 ppm after minutes; due to the fact that it destroys the lung tissue, for clean air standard EU sets a limit of 40 $\mu\text{gNO}_2/\text{m}^3$. When NO₂ or N₂O₄ are cooled, a blue liquid condensate first develops (a strong mixture of N₂O₄ in NO₂), and after further cooling, a blue solid appears, mainly consisting of N₂O₃. N₂O is a powerful greenhouse gas. Atmospheric ozone, O₃, is another pollutant (contrary to stratospheric ozone), and, although not directly emitted in combustors, it is formed by reaction with air of NO_x emissions. Nitrogen oxides also combine with water vapour to form acid mists (pH<5.6 at 288 K) that give way to acid rain, damaging forest, lakes and rivers ecosystems, one of the key reactions being $\text{NO}(\text{g}) + (3/4)\text{O}_2(\text{g}) + (1/2)\text{H}_2\text{O} = \text{H}^+(\text{aq}) + \text{NO}_3^-(\text{aq})$.

Two types of approaches may be followed to fight NO_x emissions (besides minimising fuel use): to avoid NO_x formation inside by avoiding high temperatures (e.g. using lean mixtures, using exhaust recirculation, using water-emulsified fuel), and to eliminate the NO_x inside the tailpipe, usually by a catalytic reductor (e.g. the tree-way catalyser in Otto engines, the urea catalyser in Diesel engines). NO_x concentration may be measured by chemiluminescence or by infrared absorption. Some amount of exhaust gas recirculation (EGR), typically in the range 10..20 % (but up to 50 % for small loads) is currently applied in all kind of new engines (Diesel and Otto).

VOC

Volatile organic compounds, coming from unburnt fuel and pyrolysed fuel, are a group of chemicals with $T_b<250$ °C that includes important air pollutants like benzene, 1,3 butadiene, and acrylic aldehyde (CH₂CHCHO, deadly if >10 ppm), that is the cause of the bad smell from tail-pipes. From uncontrolled

fires, with typical solid substances as wood, wool, plastics and flesh, very toxic substances are released, as hydrogen cyanide (HCN, deadly if >0.3 %, and found up to 0.1 % in typical home fires), ammonia (NH₃, deadly if >0.3 % in half an hour), hydrogen sulphide in rubber and flesh burning (H₂S, deadly if >0.1 %), and phosgene from PVC burning (COCl₂, deadly if >0.1 ppm). For clean air standard EU sets a limit of 5 µgC₆H₆/m³.

VOC is a *cul de sac*, comprising all chemical emissions except the singled-out H₂O, CO₂, CO and NO_x; and the expected trend is to go on with the singularisation of emitted substances, since there have widely different effects on the environment. In that move, separate analyses have been already applied to natural gas combustion, classifying its VOC (or gaseous HC) as methane and non-methane (MHC and NMHC). Other approaches split further the bunch of substances identifying e.g. polycyclic aromatic hydrocarbons (PAH), BTEX (benzene, toluene, ethylbenzene and xylene), and others, as the more dangerous to health.

VOC (and CO) emissions should be very low for premixed combustion with excess air (even with stoichiometric air), but Otto engines are the major source of them because of the small residence time (some milliseconds for combustion, against near one second in premixed industrial burners), and the associated small size of the combustion chamber (limited to say half a litre per cylinder for this fact). The most pollutant are the small two-stroke Otto engines used in motorcycles and gardening, because the fresh mixture is directly thrown to the exhaust to sweep the burnt gases in the cylinder. By the way, for reciprocating engines, VOC are not only due to the fuel but to the lubrication oil that seep through the segments and gets burnt (in the small two-stroke engines oil is add directly to the fuel).

Two types of approaches may be followed to fight VOC emissions (besides minimising fuel use): to avoid VOC formation inside (e.g. using stratified charging), and to eliminate the VOC inside the tailpipe, usually by a catalytic oxidiser (e.g. the tree-way catalyser in Otto engines). VOC may be measured by flame ionisation or by infrared absorption.

PM

Particulate matter (PM, or PM₁₀ to explicitly restrict to sizes <10 µm) is harmful to the respiratory system for sizes smaller than say 10 µm (larger particles do not follow the air stream and get stuck at the nose and trachea), but the worst are sizes <2 µm. Particulate matter consists of soot from all kind of hydrocarbon combustion (mainly in non-premixed flames), and fly ash from coal and waste combustion and incineration. Premixed combustion starts producing soot for air-to-fuel relative ratios $\lambda < 0.5$ or 0.6, depending on the fuel.

Particulate matter was also characteristic of diesel engines at low loads (e.g. during acceleration), due to very inefficient burning of fuel drops on cold surfaces, with a dense dark smoke at the exhaust. Remedies have been the elevation in fuel-injection pressure (up to 200 MPa), preheating of air, and exhaust filtering. Nowadays, a non-visible-smoke exhaust is mandatory in practically all types of engines (even for ships). Tobacco smoke, incense burning, charcoal grills and the like, are well-known sources of particulate matter associated to combustion (as well as some related processes as deep frying), but emphasis here is on engineering applications.

Finer particles, of sizes smaller than 2.5 µm (named PM2.5), are even worse than PM10; they are issued from combustor exhaust, but also form by atmospheric reactions of NO_x and SO₂ emissions (forming nitrates and sulphates).

Two types of approaches may be followed to fight PM emissions (besides minimising fuel use): to avoid PM formation inside (e.g. using homogeneous mixture compression and suitable injection rates), and to eliminate the PM at the exhaust by an appropriate filter, that should be periodically regenerated (e.g. by passing hot gases rich in oxygen, as done in Diesel engines). PM and smoke are distinguished by the measuring method: PM is measured by weighting a filter, and smoke by light absorption. For clean air standard EU sets a limit of 20 µg/m³ for sizes <10 µm.

SO₂

Sulfur dioxide (SO₂) emissions mainly depends on type of fuel and not on combustion details, and the trend has been to get off the market sulfur-containing fuels (by desulfurising those that need it), or implementing desulfurising agents in fluidised-bed combustion (e.g. adding lime for CaO+SO₂+2H₂=CaSO₃·2H₂O, or limestone), or in the exhaust (deSO_x dry or wet scrubbers). Nowadays only very large marine engines and large power stations still burn sulfur-containing fuels (residual fuel oil and coal, respectively), causing severe local and global pollution (acid rain); even in 2005 the IMO-MARPOL limit on marine fuel is 4.5 % in sulfur (down to 1.5 % in special areas like in EU seas). Power plants alone contribute to 2/3 of SO₂ global generation in 2000 (and 1/4 of NO_x and 1/3 of mercury, from the fuel). SO₂ has been shown to have detrimental effects on the selective reduction of NO_x with ammonia (SCR and SNCR), by formation of the highly corrosive ammonium bisulphate, although the dirty exhaust associated to the combustion of sulfur-containing fuels usually prevents the use of catalysers.

Emission regulations

In the European Union, exhaust emission limits and their testing are regulated: 1992 Euro I (adoption of catalytic converters), 1997 Euro II, 2000 Euro III and 2005 Euro IV. Table 1 presents the typical emission rates of new (2000) cars, as per-distance travelled. Table 2 compares these internal combustion engines with other power-producing devices, in a per-shaft-energy basis. Notice that a typical car running at 100 km/h demands a propulsive power of some 20 kW, consuming thence 1 kWh of work every 5 km or so.

In the USA, the Environmental Protection Agency (EPA) is the organism in charge of protecting human health and safeguarding the natural environment, and thus responsible for emission control.

Table 1. Typical emission rates of new (2000) cars ^a.

	Otto	Otto (tree-way cat.)	Diesel	Diesel
	Exhaust manifold (wet basis)*	Emissions	Exhaust manifold (wet basis) ^b	Emissions
CO ₂	8..10 %	>120 g/km	4 %	>100 g/km
CO	0.1..1 %	>0.2 g/km	0.1 %	>0.05 g/km
VOC	0.5..1 %	>0.03 g/km	0.5 %	>0.03 g/km

NO _x	NO: 100..1000 ppm NO ₂ : 10..30 ppm	>0.01 g/km	NO: 100..1000 ppm NO ₂ : 10..30 ppm	>0.2 g/km
PM	<0.001 g/m ³	<0.001 g/km	>0.01 g/m ³	>0.01 g/km

^aStationary engines have tighter emission regulations (e.g. CO<700 ppm, NO_x<250 ppm, or NO_x<400 ppm for biogas engines).

^bWater molar fraction in Otto engine exhaust is some 15 %, and in Diesel engines some 7 %.

Table 2. Typical emission rates and fuel consumption of different power engines, in g/kWh ^a.

	Coal Steam Power Plant	Diesel ICE Euro III ^b	Diesel ICE with catalyst	Gas Turbine Oil-fired	Gas Turbine NG-fired ^c	Phosphoric Acid Fuel Cell NG-fuelled
CO ₂	800	500	600	800	600	450
CO		5	10			
VOC		0.8	2			
NO _x	1	5	0.4	0.7	1	0.004
PM		0.1	0.1			0
SO ₂	3	0	0.05	0.08		0
Fuel-in	>400	>170	>170	>200	>200	>120

^aNotice that specific fuel consumption is the inverse of specific energy output (e.g. 200 g/kWh = 18 MJ/kg).

^bMarine diesel (>150 kW engines) NO_x 2000-regulation <10 g/kWh (up to 17 g/kWh for very low engines, below 200 rpm).

^cGas Turbine NO_x 2000-regulation <5 ppm in the exhaust.

VIBRATIONS AND NOISE

Combustion generates acoustic waves due to shear flows and turbulent fluctuations. This aerodynamic noise, besides the possible mechanical noise associated to oscillating or vibrating solid parts in combustors, is a source of environmental pollution.

In reciprocating engines in particular, exhaust gases leave the cylinder under high pressure that, if allowed to escape to the atmosphere directly, would create an unbearable loud noise. That is why muffler silencers are installed in all exhaust pipes for sound attenuation.

ELECTROMAGNETIC INTERFERENCES

In spite of the undeniable fact that combustion pollution is mainly due to tail-pipe chemical emission (CO, NO_x, VOC and PM), the electromagnetic contamination due to operation of electrical and electronic devices in reciprocating engines keeps increasing since the old days (1897) when the magneto substituted the open-flame hot-tube ignition system in Otto engines.

SAFETY MANAGEMENT

Risk: a combination of hazard and damage

Humankind has always evolved in a risky environment, plenty of possible sources of injury (hazard), and different levels of possible impact (damage). We cannot envisage life without risks (it might turn that risk is a native ingredient in life evolution), but we must be aware of risks and try its optimum management, accepting minor risks and injuries as natural events (e.g. freely using glassware, cutlery, matches..., but restricting the use of powerful machinery, or flammable materials and explosives).

The basic rule in risk management is that "the higher the possible damage, the lower the acceptable hazards", always realizing that we cannot devote our life to risk prevention (e.g. most minor accidents and

unsafe exposures are recoverable, and bald remedies requiring a century are useless). Galen, in the 2nd century, already said that doses alone make the difference between medicine and poison.

Emergency response

A quick-list of actions to do after an accident occurs may be (intervention protocol:

1. What happened? Keep calm, to best identify the accident for proper acting and for reporting (identify the type of damage and its extent).
2. Ask for help? Do not panic but hurry up; alert the closest knowledgeable people. An early alert to professional teams is key to control large emergencies.
3. Isolate damage! Has it ended? Avoid escalation in damage; isolate causes and damage extension: close valves, put further risks away (including children).
4. Injuries? Keep priorities: is life threatening? Do not think about property until life and health is safe.
5. Rescue. Keep priorities (benefit/cost) on what can be rescue. Organise actions to minimise overall cost, accident and countermeasures; sometimes fighting accidents cause increased damage.
6. Remediation. Many times, damage costs increase with time due to lack of benefit of use, so that quick temporal repairs are often applied (they should not contribute to enlarge risks).
7. Be better prepared for emergencies. Individuals cannot be on permanent watch, but society must keep watch teams alert all the time (e.g. policemen, firemen). Both, society and individuals must keep proportional emergency stores (e.g. first aid box), and rehearse emergency procedures (e.g. evacuation rules).

Analysis of accidents

1. What happened. Identification of the accident: what happened, when and where.
2. How it happened. Immediate cause of the accident (first explanation).
3. Why it happened. Immediate responsibility: first explanation of why it happened (had proper prevention measures been taken?).
4. How it was fought. Damage control, rescue and remediation.
5. Who pays. Responsibilities.
6. Rules updating. Risk acceptance is a subjective measure, and people may change priorities with experience.

Prevention of accidents

Individuals and society accept risks in accordance to the benefit the risky activity brings or may bring, as when settling by river banks that might flood, under roofs that might fall over, when travelling in sophisticated vehicles, or when using powerful tools.

There is, however, a demand on risk management, usually delegated on social authorities, to control that risks have been evaluated, and procedures have been adopted in developed societies to guarantee a safe, efficient and respectful development of human activities at reasonable risk.

Risk management can be split in several stages:

1. Hazard identification and labelling (the first part of risk management). Hazards must be categorised and regulated during production, transport and use.

2. Consequences identification (i.e. possible damage prediction, the second part of risk management).
3. Risk assessment (e.g. evaluating risk by comparison with other better-known risks). Known risks are less feared of (fear might increase risk).
4. Acceptability identification (avoiding risks disproportionate to benefits, and minimising acceptable risks).
5. Distribution of risk according to profiteers.
6. Prepare intervention protocols to fight in case of accidents (if they can, they will). It is very important to have an early detection, early alert, early containment and early fight, but above all to avoid escalation by improper action (quick-response systems may become unstable).
7. Distribute damage. Prepare intervention protocols to repair possible damage. Insurance companies aim at reducing the financial risk of individuals by spreading financial loss to a community.

Glossary of terms: accident, exposure, fear...

Accident	<p>Unexpected undesirable sudden event that cause direct damage.</p> <p>If damage is not undesirable, but intentional, it is an incident (minor offence), aggression or attack.</p> <p>If damage is not sudden, but progressive, it is wear or illness.</p> <p>If damage is not direct, but indirect, it is side-effects or after-effects.</p> <p>Severe accidents (that affects a lot of people and cause great damage) are termed disasters or catastrophes.</p>
Damage	<p>Actual harm caused to people, property or the environment.</p> <p>Damage usually refers to a sudden event; if more progressive, it is said spoil.</p> <p>Sudden damage to the human body is specifically termed injury.</p>
Defence	<p>Protection against threat or attack from enemy circumstances (e.g. weather) or people (from thieves to sabotage and military attack).</p> <p>Defence and protection against accidents is usually split in prevention (before) and response (after).</p>
Danger	Imminent or probable risk, i.e. threatening circumstances.
Explosion	Sudden conversion of potential energy (mechanical or chemical) into kinetic energy of a high-pressure gas released (pre-existing or being produced), with the production of a bang noise, and some mechanical work (forcing to move or shattering nearby objects).
Exposure	Cumulative amount of hazardous substance or electromagnetic radiation, received by living or non-living systems.
Fear	Subjective feeling of insecurity or risk (real or imaginary). Perceived risk may be more frightening than real danger (a USA poll amongst risk experts rated the three most-risky activities from a given set of 30 as: driving, smoking and alcohol drinking; the same poll amongst college students yielded: nuclear power, handguns and smoking).
Injury	Physical damage or hurt. Also moral harm (from injustice).
Hazard	<p>Potential source of damage (threat). Hazards may be physical, chemical, nuclear or biological, and they are inherent to the materials, conditions, processes and activities involved. Spoil.</p> <p>Hazard types:</p> <ul style="list-style-type: none"> • Physical hazards: mechanical (chock, explosion, vibration and noise, particulates), electrical (chock), thermal (fire, chock, out-range), radiation (ionising, UV, flare, IR, MW, RW). • Chemical hazards: oxygen depletion, gas poison, aerosols, liquid poisons, solid poisons. • Biological hazards: infection by bacteria, by viruses, by prions. • Ergonomic and psychological hazards: bad posture, bad planning, bad timing, changing

	interfaces (e.g. multitasking, dealing with the public), etc.
Risk	<p>Product of probability by consequences of a hazardous event.</p> <p>Risk likelihood may be imminent or remote, events per time (e.g. 10 deaths per year), fractions of event cases (e.g. 1 per million).</p> <p>Risk possible consequences may be on health (deaths, injuries, exposure), property (ruin, spillage), or the environment (pollution, evacuation).</p>
Spoil	<p>Degradation of usefulness by exposure to harmful environments.</p> <p>Environmental effects may be physical (wear, temperature, weather), chemical (reactions), biological (viruses, bacteria) or radiological (ultraviolet, nuclear).</p> <p>Sudden spoil and accumulated spoil are named damage.</p>

[\(Back to Combustion\)](#)