CHAPTER 3

APPLICATIONS OF LEAD

Examples of lead use have been known for thousands of years. The Romans used lead on a large-scale for plumbing, tank lining and domestic articles such as cooking pots and tableware, and also in glasses and glazes on pottery. Lead use has continued to grow and, in recent times, has risen from 4 million tonnes per annum in the 1960s to 6 million tonnes in the 1990s, due primarily to an increase in demand for lead-acid batteries.

Present uses of lead and lead compounds are:

LEAD METAL

Lead-acid storage batteries

The major use worldwide, primarily as a starter battery in motor vehicles, but also as traction batteries for zero-emission electric vehicles and to provide emergency backup power supply, mostly for computer and telecommunication systems. Good rates of recycling are already achieved for starter batteries, though they could be improved upon in some countries; very high recycling rates are achieved for traction and backup batteries. Alternatives are under development for some applications, though at present these could not replace lead at comparable cost, or for technical reasons.

Constructional uses: pipe and sheet

Lead piping is now a minor application, as it is no longer used for domestic water supplies because of concerns that lead slowly dissolves in soft water and may pose a risk to health, and because of improvements in alternative materials. However, much lead piping remains in place. New lead pipes are used in the chemical industry.

Lead sheet is widely used on roofs for flashings and weatherproofings, and is often used for complete roofs on both historic and modern buildings.

Cable sheathing

Lead sheaths are used to protect underwater and some underground power cables. This is now a minor application of lead.

Radiation screening

Lead is the most effective of the commonly available materials for screening from X-rays and some other types of radiation. It is widely used in hospitals as part of X-ray equipment, and also in nuclear power stations.

Miscellaneous products

Lead is widely used in shot and other munitions. Some alternatives are available, and are used in situations where lead poses a particular risk to wildlife, especially to birds, as a result of ingestion. Lead is also used extensively in weighting applications.

Lead alloys

Lead-tin solder is widely used, particularly by the electronics industry. Very minor applications are in bearings and ornamental ware (pewter) - though alternative materials are now generally used. Small additions of lead are made to some steels, brasses and bronzes to improve machinability.

COMPOUNDS OF LEAD

Batteries

This is a major use of lead oxide. Lead dioxide is pasted on to the battery grids, and is the active material in the electrochemical reaction.

Pigments and other paint additives

Lead compounds were widely used until a few decades ago. They have been replaced in certain applications following concerns about potential impacts to human health. Leaded paints are still used in specialised outdoor applications as coatings for commercial vehicles and other industrial applications because of excellent rust-proofing properties. Lead dryers are still used in alkyd-based air-drying paints as very efficient and cost effective through-dryers.

Glasses and glazes

Lead additions improve the appearance and cutting properties of crystal glass. Small additions are also made to optical and electrical glass. The major application of leaded glass is in television screens and computer monitors, to protect viewers from the harmful X-rays generated by these appliances. Lead-containing glazes are used for some pottery, tiles and tableware.

Functional ceramics

Lead titanates/zirconates are used in the electronics industry in various functions.

Additions to PVC

Small additions of organic lead compounds to some grades of PVC improve durability and heat resistance, both in manufacture and in service. This is a significant market for lead compounds.

Leaded petrol

Lead compounds were universally added to petrol to improve its efficiency at low cost. This has been the major source of lead emissions to the environment. It is now being phased out almost universally because of concerns about health impacts.

3.1 HISTORICAL OVERVIEW

Lead has been extracted and used since the earliest periods of history. The oldest known lead article is a metal figure, found in Egypt, believed to date from 4000BC. Other finds from ancient periods have been principally statuettes and figures.

Though lead was well known, the amount used was very small until the time of the Roman Empire. Earlier, it appears that lead was often an unwanted by-product of silver extraction (as the two metals frequently occur together). Being neither strong nor shiny, lead was much less prized than copper, iron or the precious metals. However, the demand for piped water by the Romans resulted in its large scale use for piping, lining of tanks, aqueducts and so on. Lead and lead-rich pewter was also used for domestic articles such as kettles, cooking pots and tableware. Other uses of lead included ornaments, coffins, alloying additions in bronzes used for statues, tankards and some coins; lead tablets were sometimes used for inscriptions; and lead weights. The use of lead for munitions has been known since ancient times.

The bright colours of many lead compounds have been exploited since very early times, for paints and pigments; black, white, yellow and red coloured compounds were also widely used as cosmetics. Lead-rich glazes were used on ceramics by the ancient Egyptians and others; leaded glasses were also known in the ancient world, and used because of their ease of melting and strong colours.

Even though harmful effects of lead were recognised, or at least suspected, lead and its compounds were also considered therapeutic for a variety of ailments, and ointments were believed to work better if stored in lead containers.

3.2 USES OF LEAD METAL

3.2.1 LEAD-ACID BATTERIES

By far the greatest use of lead worldwide is in lead-acid batteries of which more than 70% are recycled. The principle was discovered in 1850 by Siemens, and patented and first put to practical use by Planté in 1859; lead-acid batteries are now used in motor vehicles, electric powered vehicles, and also in some situations such as computer and telecommunication systems, and smaller numbers in other installations including hospitals, which require instant emergency back up power in case of power failure.

Batteries have been the greatest consumer of lead since the 1960s, but their importance has risen hugely: in 1960 batteries accounted for 28% of lead use worldwide, whereas in 1999 74% of lead consumed was for this application.

(ILZSG 2001a) (Note, this is in countries which are members of the International Lead Zinc Study Group which account for around 80% of world consumption of lead.) In Western Europe, 57% of the lead consumed is used in batteries (1999 data, based on total consumption of refined lead, and consumption of lead for batteries, in most of the countries in Western Europe, which account for 95% of total consumption.) In the USA, over 80% of lead is used in batteries (1999 data). (Calculations are based on lead statistics, ILZSG 2001a)

The demand for lead-acid batteries, both for automotive applications and for stationary output, is continuing to increase.

Principle

The simplest form of a lead-acid battery would consist of two electrodes immersed in a tank of dilute sulphuric acid. The electrodes are:

1) an electrode made of grey metallic lead (negative terminal)

2) an electrode made of various lead oxides (positive terminal)

If these two electrodes are connected by an electrical conductor, then an electric current will flow through the conductor - powering any electrical appliance in the circuit - as chemical reactions occur simultaneously at both electrodes:

1) $Pb \Rightarrow Pb^{2+} + 2e^-$
$Pb^{2+} + SO_4^{2-} \Rightarrow PbSO_4$

(electrons generated at the negative electrode)

2) $PbO_2 + 4H^+ + 2e^- \Rightarrow Pb^{2+} + 2H_2O$
$Pb^{2+} + SO_4^{2-} \Rightarrow PbSO_4$

(electrons consumed at the positive electrode)

This cell produces a voltage of 2V.

As current flows, both electrodes react with the sulphuric acid, to deposit plates of lead sulphate. The reaction continues until the electrical connection is broken, either one or both electrodes are used up, the acid is all used up, or until the accumulated lead sulphate blocks further reaction.

The discharged battery can be re-charged by connecting to a direct current power supply. The plate connected to a positive terminal will undergo the reverse of reaction (1), and turn back into lead metal; while the other will revert to lead dioxide, by the reverse of reaction (2).

Design of modern lead-acid batteries
The commonest type of lead-acid battery consists of the following components:

- a grid of lead alloy, which forms the negative terminal, according to reaction (1)
- the spaces in the grid, which are filled with a mixture of powdered lead and lead oxide, forming the positive electrical terminal, according to reaction (2)
- an electrolyte (solution which conducts electricity) of sulphuric acid, in which the whole grid is immersed
- separators (made of insulating material) and electrical connections, including the terminals.
- the case, normally a heavy duty polypropylene box.

To be ready for use, the newly built battery is “formatted” by charging with electricity, so building up the lead dioxide for the positive terminal.

Small alloying additions are made to the lead, in order to improve its strength, lifetime (by lowering its corrosion rate) and in the case of batteries for vehicles, resistance to fatigue, caused by vibrations and jolts.

Historically, the usual alloy was basically lead - antimony (0.75 - 5% antimony), which is much stronger than pure lead. Minor additions of other elements, such as copper, tin, arsenic and selenium can also be made to improve grain refinement, ease of casting and impart age-hardening characteristics.

For starter batteries, the more modern sealed maintenance-free batteries use alloys based on the lead - calcium - (tin) system, containing up to 0.1% calcium, and from 0 to 0.5% tin. The tin is added to improve corrosion resistance. These systems are beginning to predominate, particularly in the larger, more mature markets (in the USA and Europe).

Applications

1. The SLI (starting, lighting, ignition) battery used in all motor vehicles.
2. The traction battery, used to power vehicles such as golf carts and airport vehicles, and some indoor vehicles such as fork lift trucks, where quietness and lack of emissions (from the vehicle itself - though of course there are emissions from the power stations which generate the electricity to charge up the battery) are important, and journey distances are short.
3. Backup power supplies in case of power failure. Most are used for computer systems (59% in 1996), and telecommunications (21% in 1996), with 6-7% each for industrial/utility customers, medical (e.g. for hospitals), and military/government users. (Frost and Sullivan, 1996) They can provide instant supply, either alone, or for the brief interval between power cut and a diesel generator starting to supply power.

Lifetime

Car batteries typically have a lifetime of approximately 4 years in Europe. Batteries for stationary power supply have longer lifetimes, up to 10 years.

Advantages of the lead-acid battery

This is the most economical form of electricity storage. The technology is well-established, and its capabilities and limitations are well known.

Disadvantages

Lead-acid batteries are heavy and bulky, and store a limited amount of energy. The average weight of a European car battery is 13 kg, with a lead content of 7.6 kg.

Recyclability

Lead-acid batteries are highly suitable for recycling. The EU Directive on batteries obliges Member States to implement systems to achieve high recovery rates. Some states have special collection procedures, and collection rates of over 90% are achieved in many countries. (Refer to Chapter 5, Recycling)

Alternatives

There are several other systems which can store electricity. All are more expensive than lead-acid batteries.

Nickel-cadmium batteries are commercially available for some applications. These batteries are more compact than lead-acid, but could not at present replace them in all applications, especially in cars. Also, cadmium is another toxic element and environmental benefits of switching to this system would be questionable.

Other systems are used in very limited applications, or are still at the research stage.

Emerging/projected applications of lead-acid storage batteries

1. *Electric powered vehicles*

The lead-acid battery is one of a number of technologies which are currently being developed for this application.

Electric powered vehicles are more expensive than ordinary motor vehicles, and have limited journey lengths between re-charging. However, this technology has not had as many decades for development as the traditional motor vehicle technology, and there could be a substantial improvement in prices and performances.

The Advanced Lead-Acid Battery Consortium has demonstrated that advanced lead-acid batteries are capable of routinely powering a car for over 100km per charge in urban driving, can have a dependable lifetime of 500 cycles, and can be quickly changed in a matter of minutes. Considerable research and development effort is going into improving performance, with short term aims of extending lifetimes to 1000 cycles, and journey lengths to 150km.

Present incentives to pursue alternative vehicle technologies are to improve air quality in the urban environment, to reduce carbon dioxide emissions and to reduce overall fuel consumption. At present some such vehicles are used in California, in an attempt to reduce the smog problems caused by air pollution; some are in use in Europe, and look set to increase in numbers.

Alternatives include nickel-cadmium, nickel-metal hydride, lithium-ion, and polymer-based battery systems, and completely different technologies such as fuel cells, liquid gas (which is a cleaner fuel for the conventional motor vehicle) and hybrids which use a combination of these.

2. *Power supply to remote areas*

Diesel generators provide the usual electricity supply in areas not connected to a grid. They have a number of problems: transport of diesel can be difficult; the fuel can be expensive; the generators pollute the air and are noisy; regular maintenance is required. They can also be an expensive way of meeting very small electricity demands.

Solar panels, wind and small hydroelectric generators, with electricity stored in batteries for when there is no sunlight or wind or water, avoid all of these problems. Once installed, there are no transport problems, no pollution and very little maintenance is needed. A highly successful project has been reported in Alaska. (Demarest, et al, June 1997) Investment in this application is in place in Peru; Asia is seen as a very large potential market.

Though lead-acid batteries are by no means the only option, they are the cheapest available batteries.

3. *Storage of electricity at power stations*

Banks of batteries at power stations can store electricity produced at times of ow demand, and provide extra supply at peak demand. There is currently an example in the USA, and a system installed in 1995 in Puerto Rico is reported to have improved the reliability of electricity supply to the island. (Taylor et al 1995)

3.2.2 GENERAL CONSTRUCTIONAL USES OF LEAD - SHEET AND PIPE

After batteries, the next most important metallic use of lead is for the manufacture of lead sheet and pipe. Lead sheet is widely used in the building, construction and chemical industries, where the versatility of both the material and its applications have created the worldwide annual demand of some 265,000 tonnes (1999). Lead pipe was once a significant product but is now produced only in very small quantities, exclusively for use by the chemical industry.

The UK produces more of these products than any other country (in 1999, 97,700 tonnes), almost 30% of total UK lead consumption. The next largest producers are Belgium and Germany, each using around 30,000 tonnes per year and accounting for 50% and 11% of their total lead consumption, respectively.

Lead sheet

Most lead sheet is used in the building and construction industry, with the highest demand being in the UK, mainly due to the style of buildings, climatic conditions and its traditional usage. Across Europe traditional applications are typically for flashings and weatherings. Some 85% of lead sheet demand is for these types of application, with lead's durability and malleability providing unique properties to weather seal buildings where chimney stacks, windows and abutments are adjacent to roof lines and vertical walls. This is the main application area as it provides a completely watertight seal preventing rainwater ingress and so avoids adverse internal building environments. The material is extremely easy to install, providing basic skill and design techniques are adopted, and once installed it is resistant to wind lift due to its high weight per square metre.

Other important uses of lead sheet are for complete roofing systems and for vertical cladding of walls. Architects have long recognised the unique properties of lead sheet, using it on many cathedrals and historic buildings across Europe. Prominent building designs using lead sheet are also visible in new construction projects and are not solely a feature of this traditional approach. Though more expensive initially than alternatives, its long life - over 100 years is quite feasible for correctly installed lead - and low maintenance requirement, can make the long term costs comparable with, or even lower than, some cheaper alternatives, as other (non-metallic) materials need replacement after about 20 to 50 years. The grey colour of the natural material provides a unique aesthetic appeal, toning in well with a variety of colour schemes and other building materials.

A life cycle analysis performed in the Netherlands (Roorda and van der Ven, 1999) of lead and two alternative polymeric materials for flashings, found that lead compared favourably with the alternatives. This study included the impacts of production of the materials, effects of their use, and eventual disposal. Lead is generally recycled, rather than disposed of. However, it must be noted that this study assumed:

a) the polymeric materials would need replacing during an estimated 70 year lifetime of a building, but the lead would not. If the polymeric materials proved to be able to last without replacement, then the total impacts of the lead and polymeric alternatives are roughly equivalent.

b) the lead comes entirely from secondary sources. This is valid in most countries which produce all their lead from scrap, but in some countries, small amounts are produced from primary lead. Primary production entails considerably more energy consumption, there is greater potential for pollution, and this causes depletion of a non-renewable mineral resource, so the total impacts of the use of lead would be greater than calculated.

c) this study did not include zinc or copper, which are also durable roofing materials, and are more widely used in other countries.

It was noted that lead sheet possessed superior qualities due to its longevity, its recyclable nature, and low energy requirement for conversion. The study concluded that 'the environmental impact of lead sheet is more favourable than that of the alternatives. The main reason is the product lifetime of the alternative materials is expected to be shorter than that of lead' and that 'corrosion products from lead sheet have a negligible impact on the aquatic ecosystem, based on present toxicological data. In fact lead is one of the substances which reaches target levels on water quality in the Netherlands'.

Lead sheet is used to a lesser degree for radiation shielding, noise attenuation and damp proofing. Inside buildings, layers of lead incorporated into walls can be used as part of a system for sound insulation, particularly where space constraints do not allow thicker walls of cheaper materials. The softness and formability of lead allow it to be shaped exactly as required, so an integral sound barrier can be constructed.

Layers of lead sheet can be used to provide watertight linings for tanks and vessels. This application is occasionally used in the building industry, where complete integrity and lack of maintenance are required. However, it is more commonly used by the chemical industry for the lining of tanks and other vessels exposed to corrosive contents such as sulphuric acid, because of its good corrosion resistance compared with other materials.

The pattern of use of lead sheet is considerably different in North America. There is no tradition of using lead sheet in roofing, but it is used in small amounts in building construction, for example to provide maintenance free waterproofing membranes and occasionally for more prestigious projects. The use of lead in radiation shielding is relatively large (27% of sheet consumption in the USA), and it is also used by the chemical industry. Japan has a different pattern of lead sheet use again, using most (70%) for radiation shielding, and the remainder for sound insulation.

Alternative materials - Many alternatives are suggested as providing equivalent characteristics to lead. However, this is not found to be the case when all factors are taken into account.

Flashings, weatherproofings etc. - aluminium, lead-clad steel, rubber backed metal could be used, though they may not be as durable for all applications. (Danish Ministry of Environment 1998)

Roofing - many alternatives exist, including lead-clad sheet and galvanised (zinc coated) steel sheet. Zinc and copper are traditionally used in some countries, and have some of the advantages of lead for this purpose. However, concerns over human and environmental exposure to these materials have also been raised. Many non-metallic materials are in common use. Most alternatives, particularly non-metallic materials, require more maintenance, have much shorter lifetimes than lead and consume more energy during manufacture and recycling.

Listed buildings would require approval for replacement of lead roofs by alternatives.

Lead pipe

Though lead has been used for piping since pre-Roman times, new lead pipe has not been used for domestic water supplies for over 30 years in most countries, and is now a very minor application. Its use has been discontinued because other materials (eg copper and PVC) are cheaper and easier to install. Lead from old pipes can dissolve slowly in soft water, and can thus contribute to human lead intake, with potential adverse impacts on health. (This is discussed in more detail in Chapters 6 and 7.) Considerable amounts of lead pipework are still in service, particularly connecting the street mains supply with individual houses.

Lead piping is still used in chemical plant because of its excellent corrosion resistance. It is particularly useful in some acid plants, particularly for sulphuric acid.

Alternatives - For domestic water supplies - copper and plastic piping are now used. For chemical plants, the alternatives are not necessarily obvious as it depends on the design and usage requirements. Stainless steel or other corrosion resistant alloys could be considered in certain cases but these would be more expensive.

Leaded window cames

Traditionally, these consist of H-shaped extruded sections of lead which hold together small pieces of glass which make up a window. Such cames have been used for stained-glass windows in churches and cathedrals. The modern equivalent of this 'H' section is a flat self-adhesive extruded lead tape which is applied to glass windows. This is a cheaper alternative and is very effective in providing the appearance of the traditional lead came.

Alternatives - For this application, no viable alternative exists at present (Danish Ministry for the Environment and Energy, 1998).

Suitability of lead sheet, pipe and other articles for recycling

Recycling rates are very high. Lead from these sources is frequently 'clean and soft' (free from major impurities) and therefore extremely suitable for recycling into similar products. The speed and efficiency of recycling are high, with the whole process of collection through to re-processing and reforming often completed in just a matter of days, making lead a fine example of sustainability and conservation.

3.2.3 SHEATHING FOR ELECTRICAL CABLE

Lead is used as a sheathing material for power cables in several areas, e.g. the petrochemical industry or undersea (for example to supply electricity to islands) and for underground high voltage cables. Alloys are usually designed to provide specific mechanical properties.

The largest consumers of lead cable sheathing in 1999 were France (13,000t), UK (9,600t), Italy (3,300t), India (3,000t) and South East Asia (7,7000t). Most countries in Western Europe use between 1 and 3% of their lead for this purpose.

Lead sheathed electrical cables consist of the following major components:

- electrical conductors to carry the electrical current;
- electrical insulation (usually PVC for low voltage power cables, cross linked polyethylene and paper for medium and high voltage power cables) to protect users and prevent current leakage;
- impermeable protective sheathing, to protect the cable from moisture and corrosion;
- sometimes an additional layer of armouring used to protect the cable from mechanical damage;
- external oversheathing for corrosion protection in general and to protect the cable during installation.

Lead is used as the impermeable sheath in these applications as:

- it is completely impervious to water;
- it has very good corrosion resistance in a variety of media, including marine environments;
- it can be extruded in very long lengths, and also easily jointed by soldering ;
- it is pliable, so can be coiled and uncoiled, without being damaged, during cable preparation, transport and application;
- it can be applied to the cable core at temperatures which do not damage vital cable components.

Concerns about lead used in this application relate to possible corrosion. However, since an external oversheath is always used over the lead, the influence of cable lead sheaths on the environment is regarded as relatively low. This applies also for cables which are not removed at the end of their useful lives, but left in the soil or on the seabed.

Alternative materials - As an impermeable sheathing, aluminium sheaths or foils can be used as substitutes in some cases, provided that mechanical or electrical requirements specifically meet the properties of a lead sheath. Thus the use of lead sheathing in some applications has been reduced significantly over the last few years.

At present no alternative has been found for undersea cables, (Danish lead study) as other metallic materials e.g. aluminium, stainless steel, do not have the same resistance to corrosion by salt water. Similarly, lead exhibits resistance to corrosion by oils and is thus used in underground cables by the petrochemical industry. Moreover, due to the lower resistivity of aluminium, eddy currents in aluminium sheaths can be as much as six times greater, compared with lead sheaths. This can reduce the high voltage transmission overall yield by 2 or 3%. Consequently a greater electrical energy loss occurs with subsequently more generation required and thus greater release of pollutants into the environment. Additionally, no equivalent alternative material is known, for lead compounds used as a stabilising element in EPR insulations.

Suitability for recycling **-** Old cable sheaths can be recycled, and sometimes this is done, primarily to obtain the copper. The main difficulty is that it is often not economic to recover them, particularly from the sea bed, and they are often left in place at the end of their useful life. (Refer to Chapter 5.)

3.2.4 RADIATION SHIELDING

Throughout the world, lead is the major shielding material used for most screening purposes.

Metallic lead is widely used to provide protection from certain types of radiation, most commonly gamma and X-rays. As described in Chapter 2, the high density and atomic number of lead make it a very effective screening material. Lead finds applications in containers for radioactive materials, and as a component of linings for rooms containing X-ray equipment, such as in hospitals and dental surgeries. Significant quantities of lead are also used in the nuclear power industry.

When exposed to neutrons (a different type of radioactivity typically generated at nuclear power stations and research facilities) lead has the additional advantage of having extremely low levels of absorption. This means that lead, unlike many other elements, does not itself become radioactive to any significant degree, even after prolonged bombardment. Thus it can be used as a durable shielding material. For such applications, pure, unalloyed lead should be used to ensure minimum neutron absorption. (To absorb neutrons, different shielding materials are used; for example, several metres thickness of concrete).

Alternative materials would be either:

- less dense materials with weaker screening properties, so greater thickness would be needed to provide the equivalent levels of protection.
- materials of similar or greater density. However there are few of these, and candidates are either precious metals (gold, platinum), or refractory metals, such as tungsten and tantalum, which are difficult to produce and shape and thus are very expensive.

In short, although lead is by no means the only material which can provide screening against radiation, its very high screening ability, combined with malleability and relative low cost, makes it a particularly suitable candidate for many applications. Stability on exposure to neutrons makes it particularly suitable for use in power stations and for the containment of radioactive waste. One special application has been the use of lead-containing concrete to build the sarcophagus around the damaged Chernobyl nuclear reactor.

In some situations, copper and steel (which have fairly high densities) are used in radiation shielding, and cadmium for shielding from neutrons. It has been suggested that concrete or barium could replace lead (Danish Ministry of the Environment and Energy, 1998), though it is conceded that possible technical problems have not been studied. In summary, replacements for lead are largely impractical and certainly more expensive.

3.2.5 LEAD SHOT, WEIGHTS AND MISCELLANEOUS PRODUCTS

Lead shot

Lead shot remains a minor lead product, accounting for 1-3% of lead consumption in most countries. Italy is exceptional, in that almost 9% of its consumption, 24,000 tonnes, is used for this purpose. Fine lead shot is used for alloying additions to steel, brass and other alloys. Larger shot is used for shotgun cartridges.

Munitions

Lead has been used in the manufacture of bullets, canon balls and the like for many centuries. It is a favoured choice because its high density means that leaden projectiles have greater momentum, and so greater destructive power and longer range, than similar missiles of less dense materials. Lead also has the advantages that it is relatively cheap, very easy to form, and causes minimal abrasion to the gun barrel.

Alternatives - Steel shot is used in some countries, but can cause a number of problems. The shot can become lodged in trees and damage wood saws, can ricochet back towards the hunter from stones etc, and also reduces the lifetime of the gun barrel. Bismuth and tin are also used as shot material, and are commercially available (J. L. Caillerie, Metaleurop, personal communication).

Suitability for recycling - In principle, lead shot can be collected from indoor and outdoor firing ranges, and once collected, could easily be re-melted.

Lead weights

Lead has been used for many centuries for weighting purposes. Apart from its high density, which enables smaller volumes to be used to provide desired weights, the main advantage of lead is its durability. This is particularly relevant in aqueous and marine environments, such as weights for fishing lines and anchors, because iron - itself fairly dense - rapidly corrodes in such environments, unless large additions of alloying materials are used or the weight is covered with a protective coating. Small lead weights are now banned for hunting and fishing in certain areas because of the risk of birds ingesting them. Larger weights are still permitted, as are other uses such as in diving belts.

Lead weights are also found in many other applications including wheel balances on motor cars, curtain weights and yacht keels.

Alternatives - Alternatives are available, though they do not always give the same performance.

For fishing tackle - a number of alternatives exist, including zinc, bismuth-tin and other tin based alloys, and plastic coated iron.

For commercial fishing - iron and stainless steel weights can be used, but there is no immediate alternative to lead for nets. Various manufacturers claim to have developed alternatives but have not marketed them (Danish Ministry of the Environment 1998).

For yacht keels - iron is widely used and is cheaper than lead. However, lead has the advantages that it is more plastic than iron, and may deform rather than fracture in the case of an impact (J. L. Caillerie, Metaleurop, personal communication), though lead also has much lower strength than iron and may break more easily, depending upon the circumstances of the impact. It has also been shown that yachts with lead keels can sail more quickly than those using iron (Danish Ministry of the Environment 1998).

Suitability for recycling - As with other metallic applications, lead weights can easily be recycled. In practice, the degree of recycling depends on the ease with which the weights can be collected. For weights used by the fishing industry, it would be feasible for “used” weights to be returned to the supplier, as these items are regularly replaced. Recycling would never be complete, as considerable loss of material occurs in the water as a result of abrasion and damage to fishing equipment. Wheel balance weights used in vehicles are generally removed from end-of-life vehicles when the tyres are removed, and sent for recycling. Weights which are not removed generally enter the non-ferrous fraction of vehicle shredder material and are recovered along with other non-ferrous metals.

MISCELLANEOUS APPLICATIONS OF LEAD

Figures, ornaments
These are a very minor use of lead. Many alternatives exist, such as plastic, tin and other metals. The use of lead in "toys" is tightly controlled by toy safety regulations.

Security seals
A very minor use of lead. It could be replaced by aluminium or plastic.

Capsules for wine bottles
Following a 1990 European directive, lead capsules are no longer permitted and tin, plastic or aluminium are used instead.

Lead powder
This is incorporated into several products: a minor constituent in some plastics for protective clothing to screen from radiation; and some paints which protect steel from corrosion.

Suitability for recycling - Smaller miscellaneous items could be re-melted if collected. Some probably find their way to scrap merchants, though small items are generally disposed of in the municipal waste stream.

3.3 USES OF ALLOYS CONTAINING LEAD

Lead can be added to a variety of other metals to improve the properties of the resulting alloy for a particular application. The largest consumers of lead for alloys (excluding batteries) are the USA (34,800t), the UK (16,800t) and Japan (11,600t) (1997 data, ILZSG 1999). Other countries in Europe use much smaller amounts of lead for this purpose.

3.3.1 TIN-LEAD ALLOYS

Solders
Soldering is one of a number of ways of joining materials. While it does not generally give the same strength as welding or mechanical joining, soldering has the advantages that it is easy to apply, does not require very high temperatures, and a completely sealed joint is possible.

Tin-lead solders (a type of soft solder) are the most widely used, because their low melting temperatures and good flow characteristics make them highly suitable for many different applications. They are also cheaper than alternative solder alloys.

Solders are used in many applications, but the largest is in the electronics industry, which consumes approximately 60,000t of leaded solder per year (ILZSG 1999).

Tin-lead alloys have low melting temperatures - a eutectic (an alloy containing two or more constituents, which has a minimum melting temperature at an exact composition) mixture of 38% lead and 62% tin melts completely at 183°C (which is below the melting temperature of either tin or lead.) This liquid can penetrate minute openings, and is suitable for soldering components easily damaged by heat.

Alloys containing between 19 and 97% tin melt over a temperature range, starting at 183°C (for example, 70% lead and 30% tin melts between 183°C and 255°C.) In the melting range, the solder is "pasty", and can be moulded into a desired shape, which renders it useful for making "wiped joints" on lead pipes and cables, and for filling holes in car bodywork. Lead-rich solders retain solidity to higher temperatures and are suitable for applications requiring joint strength at slightly elevated temperatures such as in car radiators. These applications are dying out.

For joining materials which are particularly sensitive to heat, fusible alloys can be used. These contain lead, but also additional alloying elements such as tin, cadmium, and bismuth to further reduce melting temperature (for example, "Wood's metal", consisting of 50% bismuth, 25% lead, and 12.5% each of cadmium and tin, melts at 73°C.) These are rarely used and cadmium-containing alloys would not be preferred because of the potential toxicity of that metal.

Alternatives - A great deal of work is in progress to find suitable lead-free alternatives. Some are already used commercially and utilise mainly tin, silver and copper. Other approaches include the use of conductive glue (particularly for lightbulbs and electronic equipment), although technology is still at the evaluation stage. Welding or brazing can be used where the application would not be damaged by the higher temperatures involved.

There is no single replacement suitable for the diverse range of applications of lead-tin solder; alternatives are generally specific to a certain application. It is not known whether these alternatives could be satisfactory for all applications. (Danish Ministry of the Environment 1998)

Suitability for recycling - As solder is only used in small amounts in an article, the recycling of solder alone is not possible (though residues from *solder production* can easily be recycled). If the whole article undergoes recycling, the solder is recovered from the non-ferrous metal fraction along with copper, tin and precious metals.

Some recovery of solder from electronic products is already performed in Europe (ILZSG, 1998); substantial recovery may be required by law in the future. (See Chapter 5, Recycling)

The presence of alternative solder materials could complicate non-ferrous metal recovery operations. The mixture of metals obtained from the scrap is treated to separate it into different fractions (iron-rich, copper-rich and so on); these fractions then undergo further treatments to remove impurities and to recover valuable minor constituents. The whole process involves many stages. Additions of different solders could introduce large quantities of materials which are difficult to separate (for example, bismuth, which is difficult to remove from lead) and extra purification steps may be necessary. This would increase costs, may increase the amount of waste generated, and could make the process of non-ferrous metal recycling from waste electronic equipment uneconomic.

Terne plate

This is a thin layer of lead-tin alloy bonded on to steel sheet. The product has the corrosion resistance of lead, combined with the mechanical strength and durability of steel. Vehicle petrol tanks are often lined with such a lead alloy to give corrosion resistance.

SOME MINOR USES OF LEAD-CONTAINING ALLOYS

Bearing materials

Bearings are used to provide low-friction interfaces between moving parts. In general, bearing materials contain a soft component, so that any misalignments do not cause very high local pressures.

One group of such bearing materials is lead-tin based alloys. Such bearings can withstand light loads, but have poorer fatigue resistance than tin-based bearings and other alternatives. Lead based bearings have the advantage of good lubrication, however their chief advantage is their low cost. (Rollason, 1973)

Other bearing materials include bronzes, which may contain up to 20% lead. These are used for some heavy-duty applications. (Blaskett and Boxall, 1990) An aluminium-lead alloy is also used.

Alternative materials - At present the number of lead based bearings used is very small compared with other alloys based on tin and copper and standard bearings which use hardened steel components.

Alternatives for applications which currently use leaded bearings may need to solve lubrication problems, and a change of design may be necessary. (Danish Ministry of the Environment 1998)

Pewter

Pewter is a tin based alloy, which can contain up to 50% lead. It was widely used for centuries for ornamental purposes and tableware. It is soft, easy to cast and shape, has a dull metallic lustre, and does not tarnish under normal circumstances.

Pewter can also be made from tin with only very small additions of copper and antimony to improve strength. The non-leaded pewter is shiny and harder. Leaded pewter is no longer manufactured in significant amounts, though some old pewter articles, such as tankards and ornaments, have traditional appeal and are still in use.

Leaded tableware has the potential to contaminate food and drink, particularly when used for acidic beverages such as wines or fruit juices. This is discussed in Chapters 6 and 7.

3.3.2 LEADED BRONZES, STEELS AND ALUMINIUM ALLOYS

Small additions of lead in bronze and other copper alloys found at archaeological sites, are believed to have been added as a diluent to the more precious copper, and/or to reduce the melting temperature.

Some modern copper, aluminium and steel alloys use small additions of lead to improve machinability.

Some aluminium alloys are formulated with a lead addition of less than 4% for improved machinability. These are mainly used by smaller specialised companies for ‘niche’ machined products for the automotive industry. The market share of these products is estimated at 0.3% (maximum) of the aluminium used in automotive applications, with a decreasing trend with time.

The current European standard for aluminium casting alloys (EN 1706, 1676) includes a few alloys with a lead content of up to 0.35%. The lead content in the majority of the casting alloys is significantly lower, typically 0.1%. Lead is not an alloying element for casting alloys or for the majority of wrought alloys but is a tolerated impurity. Higher lead content cannot be accepted because it would reduce quality of the final product. Lead is not necessary to reach specific properties of the alloys mentioned above.

The term “machining” of metal covers several operations, including drilling, boring and turning, but generally involves cutting the material towards the desired final shape and size. Machining of ductile materials can be difficult, because a thick swarf (strip of material which is removed from the main body) builds up, obstructing and putting pressure on the cutting tool. “Free machining” steels contain small additions of lead (up to 0.35% by weight) which form insoluble globules of metal in the steel. These make the swarf break off into small pieces during machining. Lead additions are reported to improve machinability by 30%, allowing higher cutting speeds and longer tool life, and so increased production rates; this also improves the surface finish of the machined material, and the machining consumes less energy and is quieter. (EUROFER statement, 1998)

European leaded steel production figures are quoted as well over 1 million tonnes per year, containing 2000 tonnes of lead (late 1990s), with British Steel alone producing half a million tonnes in 1997. (EUROFER, 1998)

Small additions of lead (1.5 - 3.5%) are added to some bronzes for the same reason.

Such additions generally have detrimental effects on the strength and ductility of the material. However with small, well controlled additions, this effect can be small.

Alternatives - The steel industry has investigated a number of potential alternatives over a period of more than 15 years.

Calcium-treated carbon and low alloy engineering steels can have improved machinability; they are widely available in Europe, and are being investigated in Japan as alternatives to some leaded steel automotive components. However, calcium additions are not beneficial in all grades of steel (low carbon free-cutting steels).

Bismuth enhances the machinability of steel. However, it has a significant adverse effect on the ductility of steel at hot-rolling temperatures. Its cost is almost ten times that of lead and it arises as a by-product of lead extraction. Current annual world production of bismuth, at a little over 5,000 tonnes, would not suffice if lead in free-machining steels were to be replaced by bismuth.

Resulphurised steel gives good machinability under certain machining conditions. This could potentially replace some, but not the majority of, applications of leaded steel.

Other elemental enhancers of steel machining include tellurium and boron, but their applicability is also limited. Selenium has been discounted for a number of reasons, including its toxicity.

It is concluded that, at present, no viable alternative to lead exists as a steel machinability enhancer. Though the environmental impact of leaded steel is negligible, the search for a replacement for lead is likely to continue.

Recovery of lead

Fumes generated by electric arc furnace steelmaking plants, which may use some leaded steel scrap in their charge, typically contain 1-4% lead and 15-30% zinc. These fumes are collected in high-efficiency bag-house dust extraction systems, which have to meet stringent air quality standards. The collected dust may be enriched by recycling, the zinc and lead-rich product being sent to smelters for recovery.

Fume generated at the point of steel leading, captured in dedicated extraction systems, may contain lead at levels greater than 50%. These are also recovered by smelting.

Compounds of lead

These cover lead used in glasses, glazes, pigments and other paint additives, stabilisers in PVC and petrol additives.

All the above - excluding petrol additives and lead oxide used in lead-acid batteries - have made up 9-10% of worldwide lead consumption since 1960. The total used in 1997 was half a million tonnes. (ILZSG, 1999b)

The most commercially important applications are as additives to glass for cathode ray tubes, and additives in PVC.

3.4 LEADED GLASSES AND CERAMICS

Lead oxide has been added to glasses and glazes since ancient times.

The main advantage to early glass-makers would have been the large reduction in melting temperature. Additions of lead compounds to silica-based glasses can reduce the softening temperature considerably (e.g. 20-30% PbO glass has a softening temperature of approximately 660-670°C, compared to pure silica, which softens at around 1600-1670°C. However, addition of alkali has a similar (though not quite so strong) fluxing effect, and a "typical" soda-lime glass (based on silica, with a total alkali content of about 30%) softens at around 700°C. (Bansal et al, 1986)

Additions of lead oxide also change other properties of the glass. Leaded glass has an increased refractive index giving it a more attractive appearance in crystal and making it suitable for certain optical glasses. The application of lead glass for radiation shielding, including TV-tubes, is based on the much higher absorption coefficient of leaded glass to X-rays.

The relatively low specific electrical conductivity and dielectric losses are the basic properties for the important application of lead glass in many electrical and electronic devices.

3.4.1 LEAD CRYSTAL AND OPTICAL GLASS

Additions of lead oxide to glass have a number of advantages. Most importantly, it increases the refractive index of the glass, making it more sparkling in appearance. It also decreases the melting temperature of the glass, and makes the glass softer and easier to cut.

Full crystal glass normally contains 24-36% lead oxide; cheaper "semi-crystal" glass contains about 14-24% PbO. Smaller additions of lead are made to some optical glass, such as binoculars and telescopes, and to ophthalmic glass for spectacles.

Alternatives - Additions of some other oxides, such as barium or zinc, can give similar optical properties to glass. (Danish Ministry of the Environment and Energy, 1998)

Much research has concentrated on reducing the rate of lead leaching from the product, for example, by composition control or surface treatment. However, some crystal manufacturers are working to reduce lead contents of their products. One UK company developed a lead-free product for the Californian market where there is great concern about leaded products. This glass, which contained some alternative additives including barium, was found to have equally good optical properties. It also did not give problems in manufacture, because the glass had similar melting behaviour and could easily be cut. The full scale manufacture of this glass was not pursued for economic reasons - chiefly the higher cost of the alternative raw materials. (M. Marshall, British Glass, personal communication, 1999)

As lead oxide imparts excellent optical properties to the glass, at reasonable cost, it is not expected to be replaced without strong economic or legal incentives.

It should be noted that some of the alternatives, particularly barium, can be toxic themselves. Also, many special glasses contain small amounts of other additives, some of which (arsenic, selenium) are also potentially toxic. There is relatively little data on the toxicity, and therefore the health and environmental impacts, of many of the alternatives.

Current EU regulations define qualities of lead crystal glasses in terms of their lead contents: lead-free glass could not be sold as “full lead crystal”.
(Information from M. Marshall and J. Stockdale, British Glass, personal communication)

Recyclability

Lead crystal items generally have high value and will last indefinitely. They are usually kept, or perhaps sold as antiques, and only disposed of when broken.

No scheme is in place for collecting these items, and for the small number involved, it would not be economic. Also, as these glasses span a wide composition range - both of lead and also of other additives - adding large amounts of glass to the recycling process could affect product quality and melting behaviour. However, some leaded glass could be processed in some lead furnaces in Europe. (A. Bush, personal communication)

These glasses are not wanted in the normal waste stream of recycled container glass, because lead would act as an unwanted contaminant.

A large amount of waste generated in the factory, by cutting etc., is recycled in-house. Some of the lead dissolved into etching and polishing solutions is recovered by the glass industry, or returned to smelters for lead recovery.

3.4.2 RADIATION SHIELDING GLASS, CATHODE RAY AND FLUORESCENT TUBES, ELECTRICAL GLASS

This is the largest current application for lead compounds.

The high density and good optical properties of leaded glass make it useful for these applications.

A television set or computer monitor incorporates a cathode ray tube, which produces X-rays when switched on. Thus, a high density glass is needed to protect the viewer. The visible front screen (panel) does not contain any lead in order to avoid the browning-effect that occurs when leaded glass is exposed to x-rays. The radiation shielding is accomplished by using barium in combination with a high wall thickness. The rear part of the picture tube, the funnel, contains around 22% of lead oxide. A substitution of lead by barium for the funnel is not possible due to the requirement of low wall thickness, especially in the yoke-area, in combination with high radiation protection.

Leaded glass is also used in hospitals, laboratories and nuclear power stations, for viewing X-ray equipment and radioactive materials from behind a safe screen.

Alternatives - Lead additions give excellent shielding properties to glass. No economically viable alternatives exist for current lead glass applications (M. Marshall and J. Stockdale, British Glass, personal communication). Some research indicates that it could be possible to replace the lead in cathode ray tubes with alternatives such as barium, strontium and zirconium, (which also shield from X-rays, though not as strongly) though no such glass is commercially available. (Danish Ministry of the Environment and Energy, 1998) Any alternative would certainly be much more expensive to produce, and it is questionable whether these materials could be supplied in sufficient quantities to meet demand.

It has been suggested that lead in fluorescent tubes could be replaced by strontium and barium, though the manufacturing process would be more difficult. (Danish Ministry of the Environment and Energy, 1998) Again, manufacture of alternatives would be far more expensive.

Recyclability - It is technically possible to recycle TV screens, or to recover the lead from them. This is currently not being done in Europe to any significant degree because of the lack of economic incentive. This situation may change with future EU legislation. However, some of these items are recycled in the USA (see Chapter 5). Leaded glass should not be recycled with ordinary bottle glass, as this would cause contamination.

3.4.3 CERAMIC GLAZES AND ENAMELS

There is an extremely long history of the use of lead compounds for glazing. Lead is still used in a wide range of glaze formulations for items such as tableware, wall and floor tiles, porcelain and some sanitary ware (toilets, washbasins etc). Lead compounds are also added to some enamels used on metals and glasses.

Lead compounds have the advantages that they have relatively low melting temperatures, good compatibility with substrate material, a wide temperature range for softening, good electrical properties, and give a hardwearing and impervious finish. They show good chemical durability under a range of both acidic and alkaline conditions (which occur in dishwashers). Lead compounds also have a relatively low cost.

Alternatives - There are alternative glazing systems available, though they may not perform so well under all conditions for all products. The ceramics industry in general is aiming towards voluntarily phasing out the use of leaded glazes in the long term, not because they consider there is any problem with the product, but primarily to avoid the need for leach tests on the products, and particular workplace health and safety procedures, which are legally required if lead is used. (J. Cope, Wedgewood Ceramics, personal communication)

Recyclability - Glazes and enamels are not suitable for recycling, as they represent a very small proportion of the final product and would be difficult to separate from the substrate.

3.4.4 ELECTRICAL CERAMICS

Some lead-containing ceramics, namely lead zirconate/lead titanate, have piezo-electric and other useful properties. They find applications as spark generators, sensors, electrical filters etc.

3.5 LEADED PIGMENTS AND PAINTS

Many compounds of lead are strongly coloured and highly durable, so they have a long history of application in paints, pigments, and even cosmetics (see Annex). Some lead compounds are also added to paints as drying agents. These are very efficient through-dryers in alkyd-based air-drying paints. Typical lead contents are 0.1-0.5% in paints ready for use. Lead compounds were widely used before 1950; there was then a rapid move to alternatives so that they were virtually eliminated by 1960 in sectors such as household paints.

At present, the use of lead compounds has significantly been reduced, though they are still used for a few specific applications.

The main compounds of interest are:

Powdered lead metal
This used to be added to some paints for heavy duty corrosion protection.

White lead

White lead or basic lead carbonate, is an intimate mixture of lead carbonate, lead hydroxide, and sometimes lead oxide, and has an "ideal" composition $PbCO_3.2Pb(OH)_2$. White lead can be formulated into paint which is very easy to work with. The product is very durable and has good external weathering properties. This was one of the major bases for white paint although its use was largely phased out in the 1950s. The only remaining and legally permitted uses are for certain historic buildings and in artists' colours for restoration work.

Oxides of lead

There are four forms of lead oxide:

- Litharge, PbO, has two forms with different crystal structures: red and yellow
- Lead dioxide, PbO_2, which is brown
- Minium, or "Red lead", Pb_3O_4, has a composition between the above.

The main present uses of lead oxides are in additives to glass and PVC, described separately; a mixture of litharge and lead dioxide is used in lead-acid batteries, as described earlier.

Red lead was historically used in paints because of its colour and as an anti-corrosive pigment in rust inhibiting primers used for the protection of steelwork. Its use today is very small.

Other compounds

Calcium plumbate used as a pigment in paints is very effective on galvanised steel, as it gives good corrosion resistance.

A quite important compound technically is basic lead silicate, used in cathodic electrodeposition primers for motor vehicles to improve throwing power and corrosion resistance. Non-lead systems with satisfactory performance are now available, but leaded systems are still in the large majority.

Lead is present as a naturally occurring impurity in a large number of pigments and fillers. Examples of raw materials used in the paint sector with impurities of lead are: talc, calcium carbonate, china clay, iron oxide black, perylene reds, anthraquinone reds, quinacridone reds and violets, phtlalocyanine blues and aluminium pastes.

Lead chromate pigments

Chrome yellows and molybdate oranges are part of a whole group of inorganic pigments still in modern use. Chrome yellows and molybdate oranges are not single compounds but are solid solutions of lead chromate and lead sulphate, with the addition in the case of the oranges of lead molybdate, the colour properties depending on the proportions of each constituent and on the crystal form.

Lead chromate yellow and molybdate oranges/reds are, from a technical point of view, among the best and cheapest pigments for paints and plastics where opaque, bright end-colour is required.

They can, in many applications, be substituted by opaque organic pigments in mixture with other inorganic types, but at high cost and often with loss of brightness, opacity, flow, gloss or other technical properties.

The use of lead in lead chromate pigments represents approximately 1% of total worldwide use of lead. The global market of lead chromate pigments will be around 90,000 tonnes a year. Based on an average content of 60% of lead, the total lead consumption due to lead chromate pigments is around 55,000 tonnes a year. Market studies made in 1980/81 indicated a steep decline in the lead chromate market in the USA and Europe, to be followed by a flattening and subsequent modest increase in the later 1980s. Present indications now support this view. The recent market development shows a yearly decline of about 3-5% in Western Europe, and a decline of about 5-10% in the USA. For the former Eastern Europe and for Far-East countries the market-size will also vary depending on general industrial growth.

***Alternatives* -** For rust-proofing primers, alternatives exist, such as paints containing compounds of zinc, although it appears that they are not so effective as lead, and more frequent repainting can be needed. (Danish Ministry of the Environment, 1998)

Although there are alternatives to lead for pigments, there is no replacement for some of the colours at comparable cost and with similar durability. For applications using coloured compounds, the final choice of paint depends on the precise colour required, and costs (Danish Ministry of the Environment, 1998).

Recyclability - Red-lead rust-proofing primer could, in principle, be recovered from steel structures by sand blasting, if present in large enough amounts, and if there was a large enough economic or other incentive to do so. In practice most of the lead is captured in steelworks flue dust when lead-painted steel is recycled.

3.6 PVC STABILISERS

This is the second most important application for compounds of lead (after cathode ray tubes). (European Council of Vinyl Manufacturers, 1997)

All thermoplastics (plastics which soften on heating) require small amounts of additives, called stabilisers, to prevent the material degrading rapidly during manufacture, or in service.

All lead stabilisers are based primarily on nine basic lead compounds, which are all of low water solubility. A typical formulated lead stabiliser system comprises:

- lead compounds - two or more
- lubricant system - a combination of say stearic acid, calcium stearate and esters such as glycerol esters of fatty acids
- phenolic antioxidant system, to deal with oxygen attack on the carbon backbone
- organic costabilisers - often polyhydric molecules.

For PVC, lead salts are the most cost-effective stabilisers, and used for around three quarters of PVC applications. They are principally used in rigid PVC products, for example building profiles such as window frames, guttering, pipes and other products used outside. The incorporation of lead compounds can give excellent stability to heat and UV light, good electrical and mechanical properties, and good processing behaviour to the plastic. Flexible PVC cable used for insulation of electric wires is almost entirely made from PVC stabilised with lead. In this application, the lead stabiliser improves the dielectric properties of the insulation and is an efficient stabiliser, especially if the cable is exposed to higher temperatures.

The amount of formulated lead stabilisers used in Europe in 1998 was 112,383 tonnes, of which 98.55% was used in three main applications:

- pipes 35,902 tonnes (approx 13,000 tonnes of lead metal)
- cables 20,418 tonnes (approx 12,000 tonnes of lead metal)
- profiles 54,427 tonnes (approx 25,000 tonnes of lead metal).

(European Stabilisers Producers Association). Lead contents of PVC are in the range: 0.5 - 2.5 % lead.

***Alternatives* -** Lead based stabilisers are technically very effective, and it takes the plastics industry a long time to develop alternatives which have equivalent performance at comparable cost. However, PVC manufacturers in several countries in Europe have begun to develop and produce PVC stabilised with alternative systems. This is chiefly for marketing reasons. Substitution in window profiles began in Austria, spread to other countries in the European Union, and is currently at about 15%. Alternatives for insulated cable are now produced in France, Italy and Scandinavia, following marketing pressure from Sweden, and substitution for this product is estimated at 25-30% in the EU, though mainly for less demanding applications. Substitution for pipes is low, because this is a much more demanding application. (Donnelly, P., 1999)

Several alternative stabilising systems are in use:

Organo-tin compounds have been used commercially for over 40 years. They can give good heat stability and outdoor weathering properties. These grades of PVC are commonly used for rigid bottles and sheet. Organo-tin compounds are the next most widely used stabilisers after lead, but there is also concern about potential risks: Sweden plans to phase out the more hazardous organotin stabilisers by 2000, a position paper in Holland states that organotin levels should not rise above 1995 levels, and in Germany, discussions between the industry and authorities are taking place, since finding low levels of organotin stabilisers in sewage sludge. (Donnelly, P., 1999)

Calcium-zinc stabilisers impart good electrical and mechanical properties to the material, and also good weathering properties for outdoor applications. This system is considered non-toxic, and so is used for drinking water bottles, food packaging, and toys. Pipes for potable water in France and Belgium also use these stabilisers for the same reason. Calcium-zinc stabilisers are more expensive than other options, but research and development work is underway to increase their use in other applications.

Cadmium-based stabilisers also impart good properties to PVC, but these are being phased out for environmental reasons.

Electrical cable can be insulated by cross-linked polyethylene, as an alternative to PVC, but this is very little used at present. It is more expensive than PVC.

Recycling and end-of-life

There is no current practice to extract lead from PVC residues. However, PVC pipes are recycled and in Holland 85% of what is available is recycled back to pipe. Germany has a window profile recycling plant. New windows are made from this material which incorporates a surface layer of virgin material to ensure the colour properties are correct. However, manufacturers are generally reluctant to use recycled material in view of problems of unknown feedstock, possible contamination, collection problems, and small price difference between virgin and recycled PVC.

PVC has a reasonably high calorific value, and can be disposed of by incineration; however, if lead stabilisers are used, these would add to the lead content of the incinerator ash. However, the voluntary commitment of the PVC industry is developing the use of alternatives to lead stabilisers (ECVM 2001). The presence of lead in this ash causes disposal problems. There is the potential for volatile lead oxide or chloride to escape as a gas, causing contamination of the environment (though in a well run incinerator, these should be collected in gas cleaning apparatus). Emissions are discussed more fully in Chapter 6.

3.7 PETROL ADDITIVES

Since the 1920s, organic compounds of lead - tetraethyl lead and tetramethyl lead - have been added to petrol as an inexpensive way to improve performance.

However, these have drastically been reduced in recent years, particularly in the USA and Western Europe, and now account for only 1% of lead consumption. For comparison, in 1960 leaded gasoline accounted for over 9% of lead used, and in 1972 its use peaked at approximately 11% of total lead use. (Roskill Information Services, 1975)

How lead additions work

Petrol, or gasoline, consists of a mixture of volatile hydrocarbons, suitable for use within a spark-ignited internal combustion engine, and having an octane number of at least 60. (Irwin et al, 1997)

The octane number is a measure of the burn rate of the fuel, and is defined as lying between 0 and 100. Petrol of higher octane number burns well and smoothly; low octane number petrol can cause "knocking" during combustion, giving poorer performance and causing some engine damage. The addition of the lead compounds to petrol increases the octane number. For petrols used in the EU, the increase is typically from octane number 89 to 97.

The addition of lead to petrol from the 1920s was hailed as a great success at the time, as it allowed good performance from fuel, without the need for sophisticated refining, which would make the fuel much more expensive. An additional benefit was that metallic lead deposited on the valve seats can act as a lubricant.

Amid mounting concern that the lead dispersed in the environment was causing damage to human health and the environment, a series of regulations and directives have been adopted in Europe since the 1980s, in order to phase out the use of leaded petrol. The maximum lead content of petrol has been reduced from 0.4g/l to 0.15g/l, (following the Lead In Petrol Directive 85/210/EEC) and further regulations on air quality - which limit the amount of lead in air - came into force in 2000, with an attainment date of 2005. Virtually all western European countries have now phased out the use of lead in gasoline.

However, in some countries in eastern Europe, higher levels of lead are permitted, up to 0.4g/l. In most of the newly independent states and the Russian Federation, permitted lead levels are 0.15-0.37g/l. Various strategies for reduction of lead in petrol have been made in these countries, though it is expected that some will have difficulty in achieving these targets.

Use of petrol is increasing in many other parts of the world, in particular the rapidly expanding economies in Asia. Higher lead levels are permitted in some countries, (though in China, the authorities have recently restricted the use of leaded petrol in Beijing).

In the USA, phasing out of leaded petrol began in the 1970s. This was instigated by the demand for catalytic converters, in order to reduce photochemical smog problems in the cities - catalytic converters are "poisoned" by the use of lead-containing petrol.

The phasing out of leaded petrol is described in more detail in chapter 8: Emissions and Controls.

Alternatives - Unleaded petrol is widely available in Western Europe as leaded petrol is being phased out. Modern vehicles operate on it without problems.

Older vehicles, designed to use high-octane rating leaded fuel, can have problems operating on unleaded petrol if the octane level of the unleaded fuel is too low. The production of high octane unleaded fuel requires either a more exact refining procedure (difficult in countries which do not have modern refineries, though this is not a great problem in western Europe), or addition of aromatic compounds, such as benzene, to the fuel. Some of these compounds are carcinogenic and can cause other problems to human health and the environment.

Some older vehicles with soft valve seats would not operate so well on unleaded petrol, because they require the lubricating effect the lead has on the valves.