WATER AND WASTE PIPES

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Pressure water pipes

In water distribution pipes the water is under pressure and the pipe material has to take up the share stresses in the pipe wall originating from the internal water pressure without breaking. Concrete is a cheap material, but it must be reinforced to be used for pressure pipes. For very large pipe diameters concrete reinforced with steel bars can be economical as pipe material. Asbestos is no longer allowed to be used in Sweden, but earlier some asbestos cement pipes, there the cement is reinforced with asbestos fibres, has been laid.

Table 1. Main and distribution pipes for wate in Sweden, per cent of pipe material and tota length (VAV 1990).

Pipe material	%	km
Cast iron	57	34 270
Steel (galvanised)	7	4 433
PVC	21	13 030
Polyethylene	10	6 248
Other (for ex. concrete)	5	3 156
Total:	100	61 135

Cast iron is the most commonly used material for main water pipes in Sweden. Table 1 shows per cent of pipe material and total length for main and distribution pipes (VAV 1990[1]). Cast iron pipes are economical to produce and are able to withstand the pull stresses from the internal pressure. Cast iron water pipes have been used since 1455 when a cast iron water pipeline was built at the castle of Dillenburg in Germany. However, before the 19th century most water pipelines was built of wood logs with o bored hole in the middle. In 1750 there were about 50 km wooden water pipelines in London. Cast iron pipes were commonly used first in the middle of the 19th century. Thomas Simpson at Chelsea Waterworks invented the cast iron pipes with socket around 1785. Casting in vertical mould was introduced 1846 and the use of bitumen as corrosive protection was introduced 1848. In the water and sewage network plan for Stockholm in the middle of the 19th century cast iron pipes was chosen as material for the water pipelines. In 1922 the centrifugally casted pipe was introduced at Stanton Ironwork Co. The pipe is produced by pouring the melted iron into a rotating pipe, where the iron due to centrifugal force is distributed on the pipe wall and solidifies as a pipe. The pipe is pulled out from the mould pipe, which can be reused for casting the next pipe. Earlier, a new sand mould had to be made for each casted pipe.

Cast iron exists in two forms, grey and ductile cast iron. In 1970 the ductile cast iron was introduced, where alloying elements was added to make the iron less brittle. It is also called nodular cast iron since the shape of the graphite inclusions in the iron is changed to a nodular form (see figure 1). The nodular shape of the graphite inclusions decreases the risk of getting

[1] VAV, Swedish Water and Wastewater Works Association (1990) Driftstörningar på Vattenledningsnät i 11 Svenska kommuner år 1986.

cracks in the material. Pipes with smaller wall thickness could be used, and grey cast iron pipes were no longer laid. However, since most of the water distribution network was laid before 1970, where is more km grey cast iron than ductile.

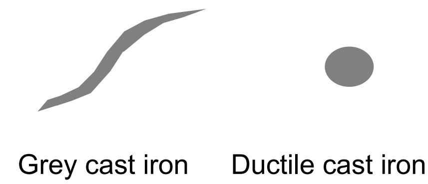


Figure 1. The difference of the shape of graphite inclusions in grey cast iron compared to ductile cast iron makes grey cast iron more brittle.

Steel pipes can also resist the internal force and has been used for smaller galvanised service pipes connecting the main pipe with the houses. Steel pipes are due to a large volume decrease of the steel at solidification not casted. At larger dimensions, the cast iron pipes are therefore less complicated to manufacture and thus less expensive. In cast iron the volume of the precipitated graphite inclusion compensate for the volume decrease of the iron.

In later years plastic pipes of PVC or polyethylene have became popular materials. PVC is harder than PEL was introduced as material for water pipes in the dimensions 40 - 400 mm. In the middle of 1960's PVC pipes have taken half of the market from the cast iron pipes. PVC pipes are cheap and can be an economic alternative if there is no pipe damages. A survey (VAV 1990) of damages to different pipe materials shown that damages per kilometre and year was 1.0 for PVC, 0.3 for polyethylene, 0.4 for ductile cast iron, 1.9 for grey cast iron 1.4 for galvanised steel and 3.3 for other steel. Table 2 shows the per cent of damage causes for different pipe materials. More than half of the specified damages to grey cast iron were breaks caused by uneven setting in the soil. The less brittle ductile cast iron show less breaks and most of the damages were caused by corrosion. For steel pipes almost all damages were caused by corrosion. For PVC most of the specified damages were caused by material defects and for polyethylene by default work.

Table 2. Per cent of damage causes for pipes depending on pipe material (VAV 1990).

	PVC	Galvan. steel	Other steel	Grey cast iron	Ductile cast iron	Poly-ethylene	Other materials
Uneven setting	11%	2%	3%	20%	18%	7%	10%
Material defects	30%			1%			
Corrosion		89%	94%	16%	60%	7%	10%
Default work	4%			1%	18%	43%	
Other	4%			1%	4%	14%	
Unspecified	51%	9%	3%	61%		29%	80%

However, the cost for pipes is only a small part, about 15-20%, of the cost of laying a water pipeline. The cost for excavating is much higher than the pipe cost. Both cast iron and steel pipes corrode and if the pipeline may have to be replaced due to corrosion or other damages, the cheapest material alternative may be the most expensive. Use of stainless steel pipes or a pipe with plastic coating may decrease the risk for getting corrosion damage. Stainless steel is alloyed with 18% chromium and 9% nickel, which make the steel corrosion resistant. The material cost of a stainless steel pipe or a pipe with plastic coating is twice the cost for a ductile cast iron pipe. If the cost for excavating and replacing a corroded or broken pipeline can be saved by using a stainless steel pipe, stainless can be a more economic alternative than cast iron. To reduce corrosion cast iron pipes are today often made with a cement layer on the inside and bitumen layer on the outside. The pipe can also be galvanised inside the bitumen layer. For more corrosive soil cast iron pipes with a plastic outer layer can be used, but the price is higher and at the same level as for stainless steel pipes.

Corrosion of metal pipes is an electrochemical process with an anode reaction there metal is oxidised, which must correspond to an equal cathode reaction, there often oxygen is reduced.

Anode: $Fe \rightarrow Fe^{2+} + 2e^{-}$ Cathode: $\frac{1}{2}O_2 + H_2O + 2e^{-} \rightarrow 2OH^{-}$

In aerobic condition is iron dissolved as trivalent ions and in anaerobic conditions as divalent ions. However trivalent iron is precipitated as iron hydroxide, which together with soil particles creates a crust on the surface. In well-aerated oxygen rich soil is the corrosion initially high due to rich supply of oxygen The corrosion is, however stifled by precipitation a crust of iron hydroxides close to the pipe surface, and the corrosion rates decreases with time. In water logged soil is the corrosion rate initially low due to less oxygen supply but the corrosion rate is not enhanced by formation of corrosion products. On pipes just above the groundwater level corrosion by the action of aeration cells may occur due to good oxygen supply combined with a fairly low resistivity. If one part of the pipeline is situated in well-aerated soil and another in poor-aerated soil,. oxygen reduced on the part in the well-aerated soil can thus cause corrosion on the part in the poor-aerated soil.

Figure 2 shows the corrosivity of the soil types; humus, sand, clay and chalk. Peat is regarded as the most corrosive soil followed by clay. Degradation of the organic material produces humic acids, which makes peat acid. In acidic conditions hydrogen evolution can replace oxygen reduction as cathode reaction ($H_2O + 2e^{-} \rightarrow 2OH^{-} + H_2$) and dissolved metal ions can form complexes with the humic acid. Soils with severe corrosion problems are soils with good electric conductivity, such as clay. A good conductivity allows the anodic process on a small spot to correspond to a cathodic process on a large part of the pipeline, causing a rapid attack, which gives a hole in the pipeline. Measuring the soil resistivity is a way to estimate the corrosivity of the soil. (see figure 3). Water logged soils are more corrosive than dry soils.

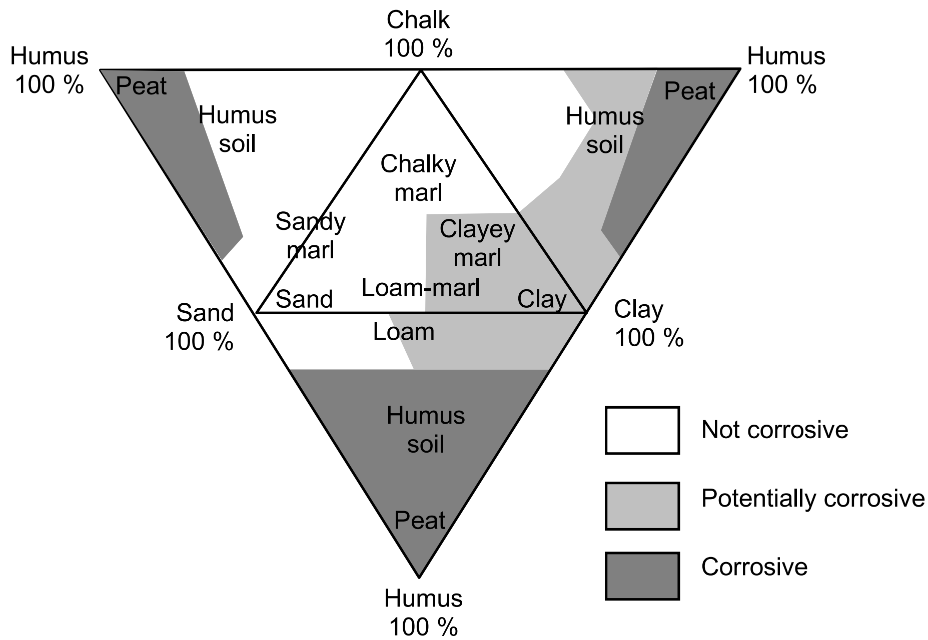


Figure 2. Corrosivity of different soil types humus, sand, clay and chalk[2].

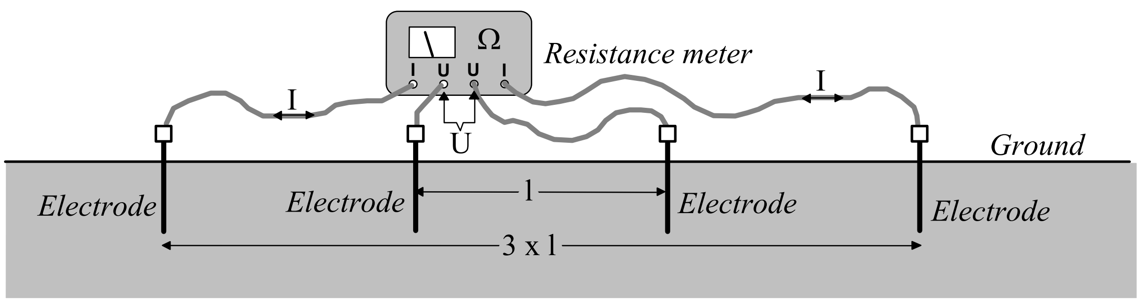


Figure 3. Soil resistance meter with 4 electrodes. A current is flowing between the two outer electrodes while the potential drop is measured between the two inner electrodes and the resistance is calculated by ohms law.

Damages caused by corrosion of steel and cast iron pipes can be counteracted with cathodic protection. Cathodic protection can be achieved in two ways, with sacrificial anodes of a less noble material or with protective current (see figure 4). The protective current moves the anodic process from the pipeline to the counter electrode.

[2] von Baeckmann and Schwenk (1971) Handbook of cathodic protection, Portcullis press

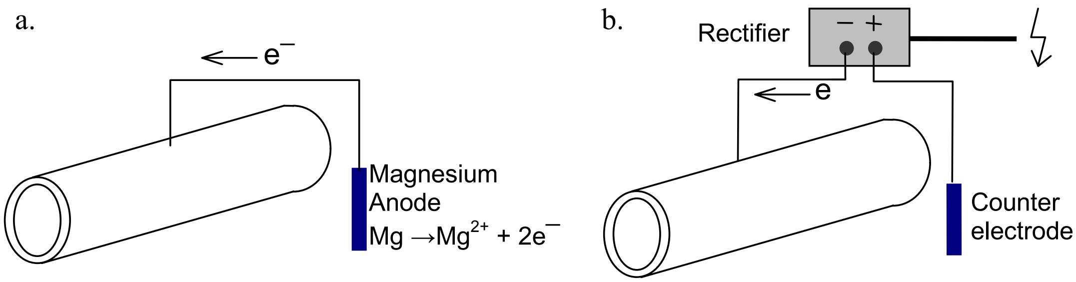


Figure 4. Sketch of cathodic protection with (a) sacrificial anode and (b) protective current.

Sacrificial anodes have to be replaced when they have been consumed by corrosion. The counter electrode for the protective current can be either permanent, that is of corrosion resistant material, or of iron scrap that must be replaced when the iron is consumed. The effect of cathodic protection is best in corrosive soils with good electric conductivity. Using sacrificial anodes makes a rectifier unnecessary, but more anodes are needed to get the same protective effect. However, cathodic protection may cause increased corrosion on other metal constructions, such as telephone cables, in the soil when the current going from the anode passes other metal constructions, on the way to the pipeline (see figure 5). The risk of getting corrosion on other constructions in the soil is higher using protective current than using sacrificial anodes. Other metal constructions in the soil have therefore to be connected to the cathodic protection. An investigation on what other things there are in the soil must be done before installing a cathodic protection system.

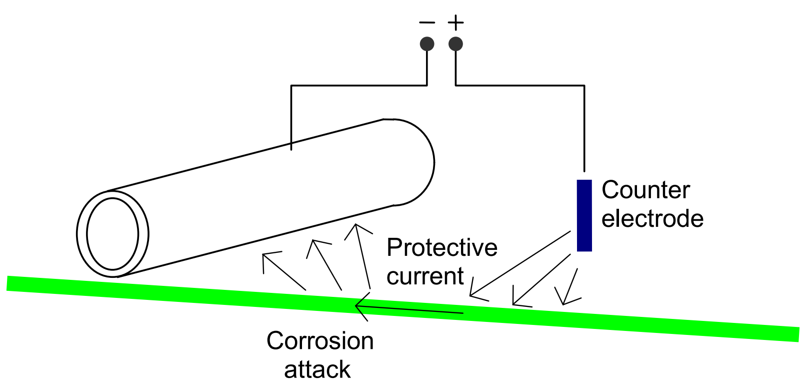


Figure 5. Cathodic protection may create corrosion on other metal constructions in the soil.

Cast iron pipes are slipped into each other and the joint is insulated with a rubber ring. For installing cathodic protection there must be metallic contact between the pipes. To get metallic contact each joint between the individual pipes has to be excavated and cables is installed from one pipe to the next (see figure 6). If sacrificial anodes are used, each second joint can be excavated and a sacrificial anode is connected by cables to both pipes. To build a pipeline steel pipes can be welded together. Cathodic protection is therefore used on most steel pipelines for gas and oil, but not so much on cast iron water pipes.

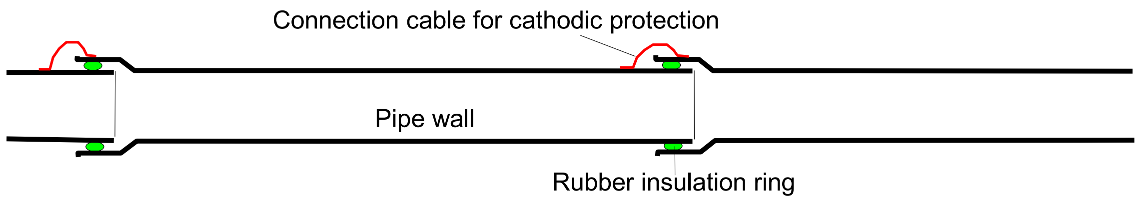
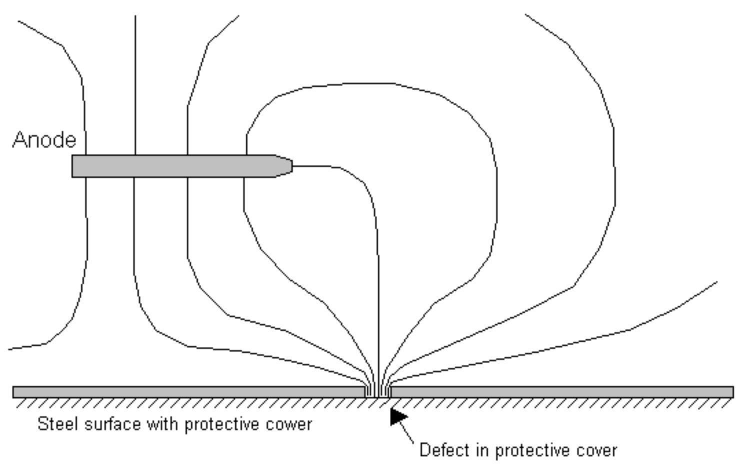


Figure 6. Sketch of a cast iron pipeline with joints insulated with rubber rings and where the pipes are connected to each other with cables.

Cathodic protection is regarded to be very efficient in corrosive soil with high electric conductivity, since the current is concentrated to defects in a protective layer on the surface (see figure 7). A single anode can protect a larger surface area if the surface has a protective cover. However, the risk of getting corrosion is not eliminated, only less probable. Due to loosening of the protective layer a crevice is created there the protective current may not reach the bottom of the crevice and corrosion may occur. Other causes to corrosion are that the soil gets dry and the electric conductivity becomes too low to transport the protective current.

a.



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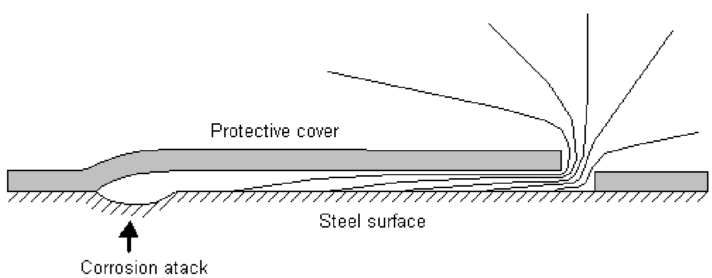

Figure 7. (a) Cathodic protection of a defect in a protective cover. (b) A corrosion attack due to non-successful protection in a crevice caused by loosening of the protective cover.

Internal water pipe corrosion

To avoid corrosion in water pipe either oxygen or salinity can be eliminated. In pipes with low oxygen content such as central heating systems, there the water is circulated, there is no corrosion problems using iron pipes. After that the oxygen in the water has been consumed by the cathodic reaction, the corrosion process stops. In fresh water pipes there the oxygen supply is better the corrosion ought to be prevented by deposition of iron hydroxide. However cathodic and anodic reactions on different parts of the surface and tubercular corrosion can occur (see figure 8). The high dissolution of iron inside the tubercular consumes oxygen and the iron can be dissolved as divalent ions. The tubercular is covered by a crust there the divalent ions are oxidised to trivalent by oxygen in the water and precipitates as iron hydroxide. The cathode reaction, oxygen reduction, occurs at the surface surrounding the tubercles. The salinity of the water transports the corrosion current and decreasing the salinity prevents corrosion. In nuclear power plants corrosion is prevented by use of total desalination, there the water is distilled and ion exchangers remove the remaining salinity.

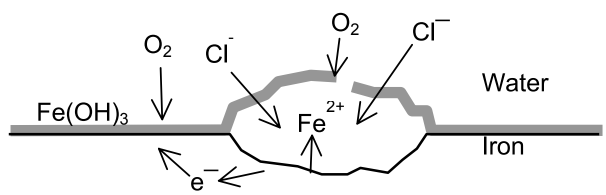

Figure 8. Tubercular corrosion on iron pipes

Figure 9 shows different forms of corrosion on copper, which is an often-used material for water pipes in buildings. If the water has too high velocity erosion corrosion may occur. To avoid this the diameter of the pipe shall be chosen from the expected water flow. The risk of getting erosion corrosion increases with decreasing pH-level. If there is a high sulphate content in the water basic copper sulphate is precipitated, which can grow through the pipe wall creating pit holes. Basic copper carbonate is deposited as a protective layer on the copper surface. To avoid pitting corrosion the carbonate content in the water shall be higher than the sulphate content. A high carbonate content is also good for iron pipes, which are protected by deposition of iron carbonate.

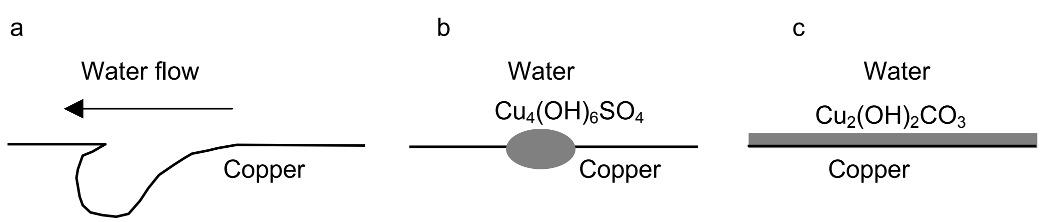

Figure 9. Different types of corrosion on copper; a, erosion corrosion caused by a too high water velocity, b, pitting corrosion due to precipitation of basic copper sulphate and c, protection by deposition of basic copper carbonate.

To minimize corrosion problems the water should have a pH-level of 8 – 8.5, a bicarbonate content of 15 – 30 mg/l and no chloride and sulphate (see table 3). An other corrosion problem with copper is cuprosolvency, which means that copper is dissolved in the water. By raising the pH-level of the water the dissolution of copper is counteracted by precipitation of copper oxide or basic copper carbonate on the copper surface.

Table 3. The composition of ideal water for minimizing corrosion problems.

pH-level	8 – 8.5
Alkalinity (HCO_3^-)	40 – 100 mg/l
Hardness (Ca^{2+})	15 – 30 mg/l
Chloride (Cl^-)	as small as possible
Sulphate (SO_4^{2-})	as small as possible

Gravity wastewater pipes

Most sewer pipes are gravity pipes, there the wastewater is flowing without internal pressure in the pipe. There are no shear stresses in the pipe wall, but the pipe wall has to resist the pressure stresses originating from the external soil pressure. In 1986 87 % of wastewater pipes was made of concrete material, which is able to resist pressure stresses. In sewage pipes there the wastewater is pumped the choice of materials is the same as for water distribution pipes.

In the middle of the 19th century sewage network was built in most cities together with water pipe network. In Stockholm a plan for sewage and water pipe network was set up in 1866. Before sewage pipelines was built sewage, garbage and horse dung was flushed with rainwater in an open channel ”rännsten” in the middle of the street. Without water pipe network the water flow was depending on rainfall and therefore to irregular for the sewage system. Concrete was invented 1845 by Isaac Johnson who burnt a mixture of clay and chalk. For the first sewer network pottery pipes of burnt clay was used for the smallest dimension and larger pipes was built of cutted stone. Concrete was first used for the larger dimensions and pottery pipes for the smaller and for more aggressive sewage water. Pottery pipes was manufactured up to 1969 when they were replaced by plastic pipes. In 1967 Concrete was used for 94 % of new laid pipes and pottery pipes for 2%.

Polyvinyl chloride PVC and polythene has also been used for sewer pipes. Low-density polyethylene PEL was introduced for smaller pipes (<100 mm) in the 1950´s. For larger dimension high-density polyethylene PEH and medium density polyethylene PEM were introduced. In new network concrete is about 34 %, PVC 34% and PEH 11 %. In sewer pipes at larger dimension is a PEL pipe deformed by the soil pressure and is unable to keep the circular shape (see figure 10). In a compact soil is the deformation of the pipe prevented by the soil and a pipe with smaller wall thickness can be used.

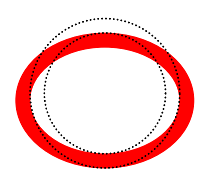

Figure 10. Deformation of a polyethylene pipe due to external soil pressure.

There are normally no corrosion problems for concrete and plastic pipes. However acids can dissolve concrete. The degree of dissolution depends on the amount of acid, and weak acids, as carbonic acid can therefore be a grater risk then a strong acid. Concrete consists of a ballast of gravel surrounded by calcium carbonate that binds the concrete. The acid dissolves the calcium carbonate and a layer created there the concrete is soft without its original strength. If concrete is exposed to sulphate, sulphate and calcium can form ettringite, tricalcium sulfoaluminate a voluminous product that gives a swelling attack on concrete.

$$3Ca(OH)_2 + 2SO_4^{2-} + 2Al(OH)_4^{-} \rightarrow Ca_3(SO_4)_2(Al(OH)_4)_2 + 6OH^{-}$$

To avoid sulphate attack sulphate resistance concrete with a tricalcium aluminte content lower than 3 %, shall be used than the sulphate content is higher than 4000 mg/kg in soil or higher than 400 mg/l in water.

Sulphate attack also occurs if hydrogen sulphide is produced in the pipes. If part of the pipeline is totally full with water anaerobic conditions will be created and hydrogen sulphide is produced. Then the sewage water reaches a part of the pipeline, which is partly full the hydrogen sulphide will leave the water and be deposited on the pipe wall above the water line, there it will be oxidised to sulphuric acid. The acid and the sulphate will produce a severe attack on the concrete. To avoid anaerobic conditions and hydrogen sulphide formation oxidation agents such as nitrate and air can be added at crucial points in the sewer network. Hydrogen sulphide can also be produced inside biofilms on the pipe surface (see figure 11). If the oxygen content is less than 0.1 mg/l hydrogen sulphide can be dissolved in the water. Then the oxygen content is higher than 1 mg/l there is no hydrogen sulphide in the water. Biofilms has to be removed to avoid sulphuric acid attack on concrete pipes.

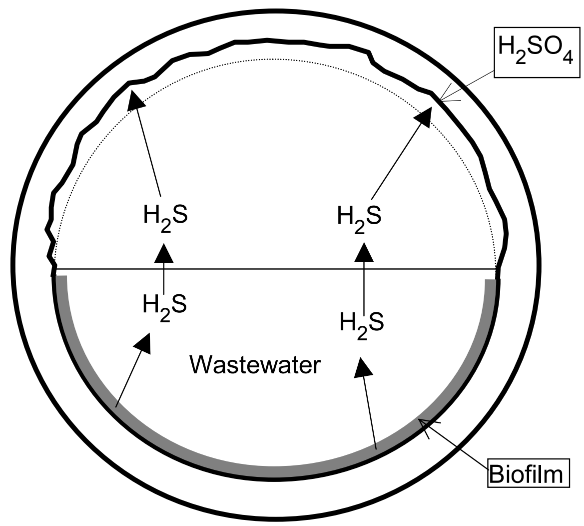

Figure 11. Sulphuric acid attack on concrete pipe. Hydrogen sulphide from the biofilm is deposited on the concrete surface above the water level, there it is oxidised to sulphuric acid causing severe damage.

For sewage pipes in buildings, cast iron is the dominating material. The corrosion occurs as graphitic corrosion, there the iron in the pipe wall is converted into iron oxide. A structure of iron oxide reinforced by graphite is created, which has a lower strength than the original material. The pipe looks intact but it can be easily broken. The corrosion rate is highest in the bottom of horizontal pipes. In vertical pipes is the corrosion equally distributed around the pipe circumference. The pipes have a life length of about 40 years. Replacement of sewage pipes is the most expensive maintenance cost for buildings.

Municipal waste pipes

Pipelines can also be used for municipal waste collection. Vacuum system for transport of solid waste was started to be built in the 70´ies. The largest system in Stockholm with 8000 connected apartments in Husby and Akalla with 6.5 km pipes, 600 waste shafts and 3000 tonne annually collected waste was built 1973. Figure 12 shows a sketch of a pipeline system for vacuum transport of solid waste. The waste is transported to the waste terminal in an air stream with a velocity higher than 10 m/s. The waste shafts in the houses are connected to the transport pipe through valves there the waste is gathered. To collect the waste the air inlet valve is opened and the air blower in the terminal is started. The waste inlet valves are opened sequentially to drop the waste into the air stream. In the terminal the waste is separated by a cyclone and compressed into a container. For small pipe systems a vehicle with a terminal can be used, which is connected to the pipe system then waste is to be collected. The transport pipes are of special hard steel able to sustain the wear from the internal waste stream. Most damages to the pipes are caused by the wear, especially at pipe bends there the waste stream change direction. If a hole in the pipe gives a too large leakage of air into the pipe, the air stream is after the hole too slow to transport the waste to the terminal.

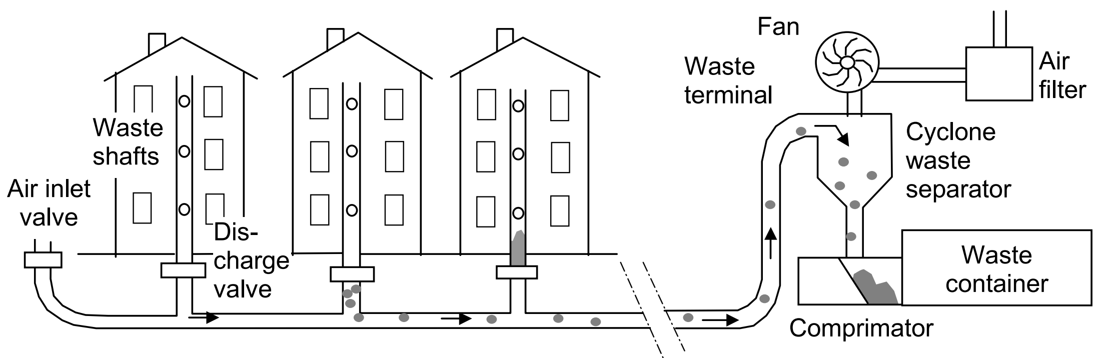

Figure 12. A sketch of a pipeline system for vacuum transport of municipal solid waste.

Most vacuum systems are built for one waste fraction. Using separate shafts and separate waste containers for different waste fractions, vacuum system can also be used for collection of sorted waste. With systems for two fractions, organic compost able waste is separated from other waste. Separated organic waste has a higher density, which requires an transport air stream with a velocity of 25 m/s. Systems have also been built for the three fractions with organic waste, paper and other waste. The system uses the same pipeline, but depending on the type of waste that is collected, the waste stream is directed to different waste containers. Different waste fractions can also as in Borås, Sweden, be transported in plastic bags of different colours, which afterwards are sorted automatically with help of optical sensors. In that case special bags of thicker material must be used, that not are torn to pieces during the transport.

Renovation

When the pipeline has to be renovated it can be excavated and replaced with a new pipeline. However, since excavation is a large part of the cost renovation methods, which minimise excavation, has been developed. The cost for excavation and rebuilding the street after maintenance, can be up to 80 –85 % the cost of repairing a pipeline. New pipes with a smaller diameter can be welded together and dragged into the old pipeline. Since polyethylene is a flexible material the pipes can be welded together on the ground and bended down into the pipeline through the excavated pit (see figure 13). Stainless steel pipes are less flexible and must be welded together in the excavated pit. All service connections to the pipeline have to be opened and the joint between the connections and the new pipe must be insulated. It can be done either by excavating the connections or by drilling holes from the inside.

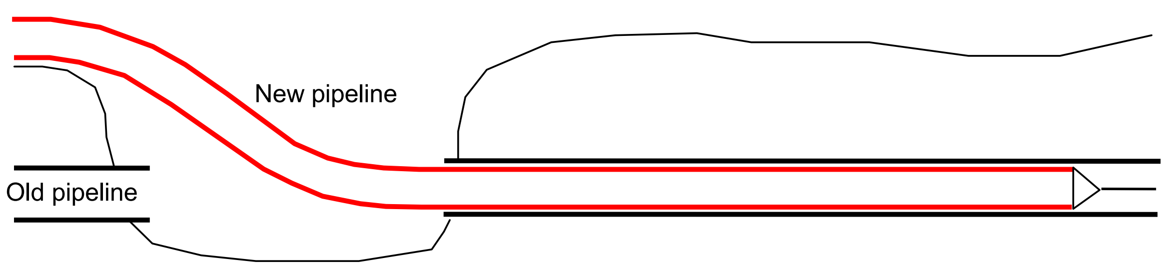

Figure 13. Sketch of a method where polyethylene pipes are welded together and dragged into a pipeline.

To avoid excavation, which is causing a high cost when laying a pipeline, methods for drilling holes have been developed. With controlled long hole drilling pipelines with a diameter of 150 - 600 mm can be laid. The drilling is done with a dirigible drilling head in wanted direction and depth. The navigation is controlled from the surface with a special localisation instrument. Then the drilling is finished an expansion tool and the pipeline is mounted on the drilling rod, and pulled back through the drilled hole.

If a water pipeline is not too much destroyed by corrosion lining the inside of the pipe with cement can prolong the lifetime. A plastic lining can be made on the inside of a pipeline. Figure 14 shows a method there a stocking is turned inside out into a wastewater pipeline with pressurised air. The stocking is impregnated with plastic material, which is annealed with UV light. With this method pipelines with sharper bends can be renovated than if a new pipe is dragged into the pipeline. Holes for the service connections can be drilled from the inside. Since the stocking can be inserted from ordinary manhole no excavating is necessary.

To build new pipeline with a smaller diameter inside an old pipeline decreases the capacity of the pipeline. If the new pipeline must have a larger capacity the diameter must be larger. For that purpose the old pipeline can be broken with a special torpedo and a new pipeline with a larger diameter can be pulled and/or pushed after the torpedo (see figure 15). The torpedo may have a hydraulic hammer to increase the cutting power and a cutting edge for use in steel pipes. All sorts of pipes including concrete, cast iron and steel can be broken. The new pipeline can have a dimension, which is 50% larger than the old, thus increasing the area with 125% and the capacity with 200%. All service connections have to be separated from the old pipeline before breaking it and afterwards connected to the new pipeline. Breaking with a torpedo is not possible if the pipeline is laying in a narrow rock trench or if other pipes that may be destroyed by the torpedo are too close to the pipeline.

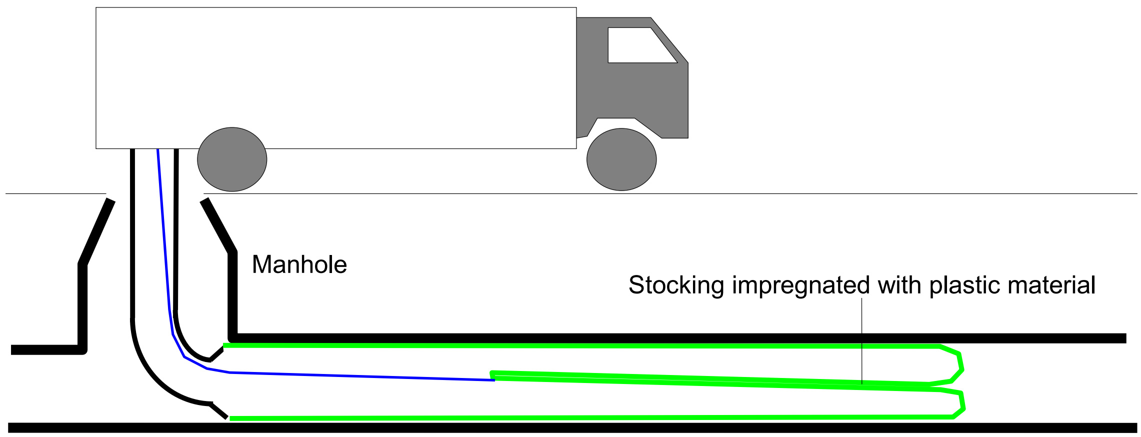

Figure 14. Sketch of a method of lining a pipeline with a stocking, which with pressurised air, is turned inside out into the pipeline.

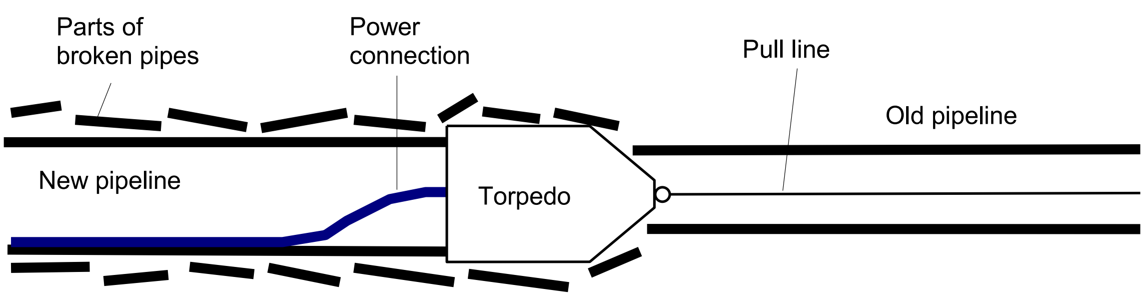

Figure 15. Sketch of a method for replacing an old pipeline with a new by breaking the old pipeline with a torpedo.

To make renovations without excavation possible the pipeline can be installed inside a larger pipeline. In Ärvinge in Stockholm with deep clay soil large concrete pipes were pushed into the clay from excavated shafts to other shafts. The clay inside the pipes was removed and water pipes, sewer pipes and other infrastructure such as electric cables and telephone cables were installed in the pipe.