Pipe material selection in drinking water systems - a conference summary

A. Elfström Broo*, B. Berghult* and T. Hedberg**

*VBB VIAKAB, PO Box 2203, SE-40314, Göteborg, Sweden
**WET, Chalmers University of Technology, 41296 Göteborg, Sweden

Abstract A review is made of the oral presentations held at the conference "Pipe Material Selection in Drinking Water Distribution Systems – Sustainable Drinking Water Distribution Management", held in Göteborg, Sweden on 5–6 September 2000. The topics discussed were: processes in the distribution network (microbiological activity and corrosion), water treatment and corrosion control, pipe material selection and structural design, and also the standardisation work within the European Union.

Keywords Corrosion; distribution; drinking water; microbiological activity; pipe material selection; review

Introduction

Pipe material selection in drinking water systems must be seen from a holistic view. The water leaving the water works normally fulfils the requirements needed for public consumption. Even so it affects the corrosion processes and the microbiological activity in the distribution network. These processes are uncontrolled and will in turn affect the water quality at the consumer’s tap and also the quality of the wastewater.

Several measures have been taken over the years in order to minimise the effect on drinking water quality by the transportation. Most of these measures are related to the water treatment process and consist of the addition of disinfectants for microbiological control and pH, alkalinity and hardness adjustments for corrosion control. In some countries complementary corrosion control actions are taken in the form of inhibitor additions. Since the networks consist of different materials and differ also with respect to hydraulic properties, dimensions, age and quality, the effect of the measures taken vary considerably.

Although the pipes are successively replaced, historically, few overlapping corrosion control strategies for material selection have been applied. Instead the networks still consist of several materials with different corrosion properties and, thereby, different demands on water quality. Recently also new demands have been put on the drinking water quality according to the ideas of a sustainable society.

A sustainable water and wastewater system needs to meet stringent demands on hygiene, environment, the use of resources, economy, functionality and comfort. The system must also be adapted to local situations. Both the conventional system for urban areas and systems for rural areas can be improved. However, the recycling of water and valuable substances in the new sustainable society needs a holistic view of thinking, which covers the system all the way from the raw water source to the discharge of treated wastewater and sludge (Figure 1).

On a European level, new Drinking Water Directives (DWD) are now available for implementation in the member states. New standards for construction products in contact with drinking water are also in progress.

Thus the ultimate goal is to secure the supply of a drinking water that not only is safe for drinking and other applications in the household, but also matches the high demands of the sustainable society.
In order to achieve this situation two sub-goals may be set:

- Through a safe and stable water treatment, water should be produced that fulfils all applicable requirements.
- The water should be transported in a distribution system without water quality deterioration.

Looking at today’s sanitary system, the development of the water treatment process is probably the sub-goal that will be the easiest to fulfil. Research is continually producing new and important knowledge on how to develop the processes at the water works, and the work has been ongoing for several years.

The water quality changes due to transportation have for some time been looked upon as a question of water treatment to meet the aesthetic and hygienic requirements. By adjusting the water quality in order to minimise the corrosion and microbiological processes in the network as discussed above, acceptable levels of water quality deterioration have, in most cases, been reached. However, the increasing requirements on water quality have made water treatment insufficient as a means of solving the transportation problems. The distribution network with all different pipe materials is, thus, the limiting factor for further water quality improvements making the distribution sub-goal far from fulfilled.

Exchanging the distribution systems is a process taking considerable time. Questions have also risen concerning which pipe materials should be used in order to minimise forthcoming problems with corrosion and microbiological activity. Thus, in the foreseeable future increased knowledge is required both for optimisation of the water quality with respect to corrosion and microbiological control over complex distribution systems, and for the corrosion and microbiological properties of the pipe materials used. However, it is always desirable to have as few different pipe materials as possible in the same distribution system.

The present paper contains a review of the presentations held at the conference “Pipe Material Selection in Drinking Water Systems – Sustainable Drinking Water Distribution Management” held in Göteborg in September 2000. The conference was intended to highlight the different areas of drinking water management and was divided into the following topics:

- processes in the distribution network:
Processes in the distribution network
Traditionally until the last few decades, the drinking water distribution systems were made of inorganic materials. Thus, the public systems mainly consisted of grey cast-iron and steel, with or without inside bituminous coating or cement mortar lining, and cementitious materials. For the domestic piping systems galvanised steel and copper were the dominating pipe materials, but there was still a considerable amount of lead pipes used in some countries.

Today there is a trend to replace the inorganic materials, especially in the public distribution systems, with plastic materials. One reason for the change in material selection is the impact of corrosion of the inorganic pipe materials both on the drinking water quality and the lifetime of the pipes. A second reason is the laying techniques, making the installation work easier and more economical.

Microbiological activity
Microbiological activity takes place both on inorganic and organic pipe materials. Beside its deteriorating effect on the water quality, it may cause secondary effects as microbiologically induced corrosion on both inorganic and organic pipe materials. In the drinking water treatment process it is desirable to produce biologically stable water, i.e. water in which bacterial regrowth is strictly limited by extremely low concentrations of growth-promoting substances (Stenström and Långmark, 2001).

There are several ways of measuring the microbiological activity in the distribution systems. One way used by Stenström and Långmark is to apply a continuously flowing system of drinking water to pipes of different materials and count the colony-forming units (CFU). Copper pipes had the lowest number of colony forming units (CFU/cm²) but supported very slow growing bacteria, representing one species. Bitumen-coated pipes showed the highest number of heterotrophic bacteria, including both fast and slow growing populations. Two plastic materials, PVC (polyvinylchloride) and PE (polyethylene), were investigated and showed colony-forming units with values between that for the copper and bitumen-coated pipes. For the plastic materials, low numbers of fast growing bacteria were found but the PE supported an elevated population of slow growing bacteria compared to the other materials.

For the plastic materials, PVC and PE, similar results were found in another investigation using a different method (van der Kooij and Veenendaal, 2001). This method is aimed to assess the microbial growth supporting potential for synthetic materials in contact with drinking water. By determining both the biofilm formation potential and the suspended biomass production as ATP (adenosinetriphosphate, units of pg ATP/cm²), a value of the biomass production potential (BPP) for a material is obtained. The method revealed that PVC had a lower BPP compared to PE. It is however stressed that more work has to be done before criteria can be defined for different materials in terms of biofilm formation potential and biomass production potential.

Internal corrosion
The water distribution systems are continuously exposed to corrosion processes. Whether the material is organic or inorganic these processes may cause drinking water deterioration
as well as pipe degradation. The corrosion processes on inorganic pipe materials have been investigated for a number of years while the research on organic pipe materials for natural reasons have been less intensive. The papers presented at the conference reflected this situation, where most presentations concerned the traditional pipe materials: iron, copper and cement-based.

The surface complexation model for iron corrosion in drinking water has been improved by including the effect of natural organic matter (NOM) (Elfström Broo et al., 2001a). At low pH-values the corrosion rate increases due to NOM, while the opposite effect is found at high pH-values. The lowest corrosion is found at low pH-values for both high and low alkalinity waters, but generally a higher alkalinity is favourable. Another important parameter is the redox potential. At low redox potentials, high iron concentrations are to be expected. Further research is needed to evaluate the effect of this parameter.

Another factor influencing the scale formation and thus the corrosion rate of iron is the flow rate (Osterhus, 2001; Hem et al., 2001). The corrosion rate in corrosion controlled water was found to be considerably lower at higher flow rates compared to lower ones. The effect is explained by formation of a more crystalline and protective layer consisting of calcium and iron carbonates at higher flow rates.

For cement-based materials good performance is obtained if the water has an alkalinity sufficiently high to form protective calcium carbonate precipitates at the cement surface (Wagner, 2000a). Deterioration of the cement takes place if an excess of carbon dioxide is present to dissolve already precipitated calcium carbonate and causes leakage of the alkaline parts of the cement. In waters with low alkalinity and calcium content the latter process will proceed, which leads to water quality deterioration with very high pH-values and degradation of the cementitious material.

For the domestic copper pipe systems considerable research has been performed over the years with respect to the water quality impact on the corrosion and metal-release of copper. In the Netherlands, a model for predicting the copper concentration in drinking water after 24 hours of stagnation has been developed. The water quality parameters included in the model are the pH, the content of total inorganic carbon and the content of sulphate (Slaats et al., 2001). By increasing the pH and decreasing the total inorganic carbon content and sulphate concentration the copper content in stagnant waters decreases.

It is also reported that the presence of sulphate, hydrogen carbonate and phosphate ions can influence the type of solids formed in systems containing cupric ion or cupric hydroxide solids (Edwards et al., 2001). If only hydrogen carbonate is present, basic copper carbonate, malachite, is formed. In the presence of sulphate or phosphate, it is possible to form more soluble basic cupric sulphate, brochantite, or cupric phosphate. This prevents the formation of less soluble cupric oxide, tenorite, or malachite. These effects are assumed to be dependent on the concentration of the anions. Low concentrations of sulphate hasten the formation of tenorite whereas higher sulphate concentrations result in the formation of the more soluble basic cupric sulphate. Thus, a short time reduction in the copper by-product release can be obtained by increasing the sulphate or phosphate concentration, but on a long-term basis higher copper concentrations may result.

As for iron, the water flow rate is important for the corrosion of copper (Osterhus, 2001). The decrease in copper release due to increasing the pH was found to be more pronounced at high flow rates compared to low flow rates. By decreasing the pH and increasing the flow rate, a change in mechanism is observed.

Besides pH, total carbonate and sulphate content the amount of natural organic matter is an important factor for both the copper release and the corrosion rate (Berghult et al., 2001). The copper content in stagnant water increases with increasing content of NOM. This increase is explained by the complexing properties of NOM.
Stainless steel has been used for domestic installations in Germany and Japan for some years and its use has increased rapidly in hard water areas in Denmark the last few years. The corrosion and heavy metal release of the stainless steel grade EN 1.4401 was examined in different Swedish drinking waters (Elfström et al., 2001b). Only very small effects on different drinking water quality were observed. Higher corrosion rates were found in waters with high total carbonate content together with a high NOM content. Heavy metal release in stagnant water was found to be well below the regulation limits. A somewhat elevated nickel release was observed shortly after installation, but diminished after a few months. No local corrosion attacks were observed within the test period (9–12 months). The results imply that stainless steel EN 1.4401 may be an alternative for indoor installations.

External corrosion and protection
Although internal corrosion is serious as it causes water quality deterioration and pipe clogging, external corrosion may determine the lifetime of the pipes as it often results in pipe breaks.

External corrosion statistics for water pipelines have been collected for a number of years in Sweden. It is concluded that external corrosion on metallic materials is mainly caused by corrosive soil, such as marine clays containing chloride or organic clays containing sulphides and/or sulphates (Camitz, 2001). Plastic material failures due to corrosion are naturally less important but material failures and deficiencies in the laying procedure are more common. Counteracting measures may be cathodic protection or introduction of improved protective coatings. Good experience of non-coated stainless steel pipes, grade AISI 316, in soil with no or low chloride concentration is reported from the Swedish town of Karlskoga.

A procedure for calculating the replacement rates for ferrous mains has been presented (Oliphant, 2000). A random set of pipe samples was chosen by dividing the system into categories, such as diameter, soil type, etc. Pipe samples representing each of these categories were then randomly chosen from the system. Collected data were used to calculate the weighted average pipe wall thickness, based on pipe length, and the weighted average age of the system. The procedure was used to estimate the rate of replacement required to maintain the status of the system.

Water treatment and corrosion control
There is a long history of corrosion control actions in drinking water distribution. The measures taken vary from country to country and are dependent on both raw water quality and water treatment process. Traditional chemical water treatment does not necessarily lead to less corrosion in the distribution system (Hedberg, 2001). On the contrary, it may increase corrosion. The progress in corrosion control is strongly related to the knowledge about the corrosion processes.

For corrosion control measures in Sweden three main factors are decisive: the regulating guidelines, the raw water quality and the choice of water treatment process (Berghult et al., 2001). The latter factor is often based on economical considerations. Most water works do not have a sufficient follow-up programme after a water quality change has been performed and thus, there is a loss of valuable information. For waters with low NOM content changing the inorganic water quality parameters can often make an improvement.

In Norway, the typical drinking water has a low pH-value, low calcium content, low alkalinity and a high NOM content. There are two main different strategies for corrosion control: alkalinity, hardness and pH increase, and addition of sodium silicate inhibitors. The former action reduces the copper corrosion. Neither the addition of a sodium silicate...
inhibitor (Osterhus, 2001), nor water supersaturated with respect to calcium carbonate (Hem, 2001) had any effect on the corrosion beside the effect of increasing the pH. The pH, alkalinity and calcium content increase reduced-iron corrosion and it was concluded that the reduction in iron corrosion caused by silicate addition was due to a formation of iron silicate. The highest reduction in iron corrosion was obtained with the calcium carbonate supersaturated water.

In the US more than 53% of the water works use phosphate inhibitors for copper corrosion control. Polyphosphate or orthophosphate in moderate concentrations (≈ 1mg/L) generally decreases the copper release. Orthophosphate reduces the solubility of copper solids in equilibrium with water, presumably by formation of a cupric phosphate scale (Edwards et al., 2000). In waters with higher alkalinity and low pH values the formation of cupric phosphate scale interferes with the formation of the less soluble malachite, leading to a reduction of the copper release over a short term but a higher release over the long term. Orthophosphate was found to be more efficient compared to polyphosphate.

In the Netherlands, about 45% of the drinking water is softened or de-acidified to reduce the copper content in the water. Two new treatment methods: reversed osmosis (RO) and addition of a carbonate-activated silicate have been investigated for their impact on copper by-product release (Slaats et al., 2001). The RO treatment was shown to decrease the copper by-product release, but less than expected. This is explained by a reduction in NOM content due to the treatment. NOM is assumed to inhibit copper corrosion, which is in contrast to some other studies. The RO treatment also decreases the total inorganic carbon content and the sulphate content. The carbonate-activated silicate inhibitor was found to be an effective inhibitor, but not as good as phosphate.

Pipe material selection and structural design
Selecting a pipe material demands several considerations. The new pipe material should ideally be inert in relation to both internal and external corrosion, and thus have an eternal life. In order to make the decision of which pipe material to use, all facts about the pipe material have to be known, i.e. the corrosion properties, the microbiological properties, the physical and mechanical properties and also factors such as environmental impact and the relation to other pipe materials present in the distribution system.

The effect of succession order of the pipe materials in the distribution network may be illustrated by applying different service pipe materials to the indoor copper piping (Berghult et al., 2001). It was experimentally shown that the copper content in stagnant water is extremely dependent on the preceding pipe material. The release of alkali from cement-based pipes and the corrosion process of metallic materials increases the pH. This effect will decrease the copper content. Furthermore, oxygen is consumed due to the corrosion process and the released metal ions will occupy the complexing sites of the natural organic matter. These two effects will further decrease the copper content. Thus, when plastic materials are used in replacement of the traditionally used materials, the copper content will appear to increase.

In Denmark, the major part of the water supply comes from hard water areas. The distribution systems mainly consist of iron pipes with only minor problems with internal corrosion (Nielsen, 2001). The domestic pipe systems consist of galvanised steel, copper, stainless steel and PEX (crosslinked polyethylene). For galvanised steel and copper the permitted metal levels are frequently exceeded, while stainless steel (AISI 316) performs well in waters with low levels of chloride. The trend in Denmark today is towards plastic materials such as medium- or high-density polyethylene (PEM, PEH) for water mains and the use of PEX and stainless steel is expected to increase for domestic installations.

In Germany, steel and ductile iron pipes in the public distribution networks have an inter-
nal cement mortar lining while the outside is protected by PE sheets or cement mortar coating (Wagner, 2000b). Alternative materials are plastic materials, PVC and PE pipes. For domestic installations galvanised steel and copper dominate. Improvements of the pipe materials together with recommendations concerning solders and alloys have led to a reduction in damage caused by corrosion and in the heavy metal release into the water. Plastic materials such as PEX, PP, PB and PVC and also stainless steel are also now being used.

In France, as in other European countries, there is a trend to replace the traditional inorganic pipe materials with different plastic materials, both in the public and the domestic networks (Rigal and Baron, 2001). The main reason for the replacement is to avoid the degradation of the drinking water quality caused by corrosion. For the public distribution systems and the service pipes, the plastic materials PVC and PEH are used. For the domestic distribution systems the same plastic materials are used, and also PEX and PB.

In the work towards a sustainable society Stockholm City has adopted a long-term goal that products and goods must not be harmful to health or the environment. In the building project Hammarby Sjöstad, the material selection for buildings and the water distribution system is emphasised (Hådell, 2000).

Life Cycle Assessment (LCA) as a tool for describing the environmental consequences of different materials and products were discussed. The largest environmental impact for water system pipe materials comes from trench excavation, thereafter from the leakage from the water pipes (Svensson, 2000). Hereafter comes the lifetime of the pipe, the ability to recycle or reuse the material and then the choice of pipe material. The impact of the latter is relatively small. However, when comparing different pipe materials, the most important factor is the weight. Thus, materials with low weight, like plastic materials, have lower environmental consequences compared to cast iron and copper. Stainless steel materials can be of interest, but depend very much on the alloy content.

Structural design for drinking water pipes is complex and different pipe materials need different design considerations (Björklund, 2001). No CEN standards within the EU countries are available today. For ductile iron the structural design is not the limiting factor due to the material’s strength. Glass fibre reinforced pipes demands careful installation to ensure long life. PVC and PE are pipes that can withstand rough handling and do no need careful installation to have a long life.

**Standardisation work within the European Union**

On the European level efforts are made to standardise both the drinking water directives (DWD) and the approval system for construction products in contact with drinking water (CPDW).

The drinking water directives are applied at the consumer’s tap, i.e. the changes in drinking water quality due to distribution are included. These directives (98/83/EC) are ready for implementation in the member states. The national regulations concerning both drinking water and sludge quality differ considerably between the different states. Furthermore, water containing the maximum levels allowed in the drinking water directives of, for example, heavy metals, will cause a sewage sludge that dramatically exceeds the sludge directives for agricultural use. Thus, a harmonisation is needed. In addition, a comprehensive guide for corrosion control would be desirable (Hedberg, 2001).

Concerning construction products in contact with drinking water a Regulators Group (RG-CPWD) is preparing a European Acceptance Scheme (EAS). The Regulators Group consists of representatives from the European Commission, the member states, the European Standardisation Organisation (CEN) and different organisations representing branches with an interest in the subject. A ‘positive list’ for different construction products in contact with drinking water is also under preparation. The implementation of standard-
ised test methods is an important work carried out by CEN. The ultimate objective is to implement the EAS by the end of 2004. From a Swedish point of view there should not be any legal problems with the implementation and there are several advantages with such a voluntary system, the most important being the concern about peoples health (Chaboussant and Jönsson, 2000).

The new directives for drinking water and the approval system for construction products in contact with drinking water will have consequences on the management of the sanitary systems. The holistic way of thinking is essential and also the sharing of responsibilities between the different actors and authorities involved since the systems are complex. Also the consumer will need a set of rules, and a code for good practice, similar to the one in use for food. New scientific data and sharing of existing data is needed for the implementation of directives and the approval system. This is relevant in the field of toxicology and microbiology, as well as in the field of corrosion, corrosion control and degradation of and dissolution of additives from non-metallic materials (Hedberg, 2001; Rapinat, 2000).

Conclusions
Generally, there is a trend to replace the traditional inorganic pipe materials with organic materials. The use of stainless steel is also increasing, especially for indoor applications. Iron pipes with interior cement mortar lining and exterior plastic protection are still installed and also other cement-based materials.

Lead and asbestos cement-based materials are outlined and will be replaced. There is, however, an ongoing discussion about the exchange rate and its economical consequences. Rubber materials should not be used for microbiological reasons. Some materials, such as unprotected, galvanised and bitumen-coated iron are no longer the choice for new installations. Concerning copper piping, there is a discussion about the environmental impact in relation to the sustainable society.

Several different plastic materials are used both for replacement and new installations in the public network as well as in the domestic, e.g. PVC, PEH, PEM, PEX, PP and PB. Relining of old pipes can be done with plastic pipes, with epoxy resin relining or by glass fibre reinforcement. The performance of epoxy relining can be discussed since diverse results are obtained.

When using corrosion resistant materials, such as stainless steel or plastic materials, one should be aware of the possibility for corrosion of the fittings and couplings. In some cases, the galvanic properties can be devastating.

During the conference, research needs were indicated in the following areas:

- material science related to:
  - microbiological and toxicological properties
  - corrosion and material degradation
- corrosion control actions;
- environmental aspects and life cycle assessment.

References


