

Internal Corrosion Control in Water Distribution Systems

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Chapter 1

Overview of Internal Corrosion Impacts in Drinking Water Distribution Systems

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INTRODUCTION

Prior to development of a corrosion control program, it is important to first gain an understanding of the factors that influence internal corrosion and metal release in drinking water distribution systems. Afterward, implementation of an effective corrosion control program can be accomplished in eight steps (Table 1-1).

Table 1-1 Eight steps to implementing an effective corrosion control program

Step	Discussed in Chapter(s)
• Develop an understanding of the general concepts behind internal corrosion and metal release in drinking water distribution systems	Ch. 1, Ch. 2
• Determine the extent and magnitude of corrosion	Ch. 3
• Determine the possible causes of corrosion	Ch. 2, Ch. 3
• Assess corrosion control alternatives	Ch. 4
• Develop a corrosion control strategy	Ch. 4
• Implement a corrosion control program	Ch. 5
• Monitor the effectiveness of the corrosion control program	Ch. 3, Ch. 6
• Optimize the corrosion control program if necessary	Ch. 5, Ch. 6

Selection of an effective corrosion control strategy is not a one-time event. Changes in source water quality, treatment, or distribution operational practices may require a system to reevaluate, revise, and reimplement a corrosion control program. To assist the reader in navigating the process described in Table 1-1, this manual is organized accordingly.

PURPOSE OF THIS MANUAL

Internal corrosion of drinking water distribution systems and home plumbing systems has long been a recognized issue facing the drinking water industry—one that has many health, water quality, and economic implications.

This manual was written with the intent to provide a practical overview of internal corrosion issues, to identify appropriate corrosion response and control methods, and to develop corrosion control monitoring programs. It is not intended to provide detailed summaries of corrosion chemistry. References to additional resources are given where the reader might find more detailed information useful.

Although this manual briefly touches on internal corrosion of nonmetallic pipe surfaces, such as asbestos–cement and cement mortar–lined ductile or cast-iron pipe, it primarily focuses on corrosion of metal pipe surfaces, solders, and plumbing fixtures, such as those composed of lead, copper, and iron. For the purposes of this manual, the term *corrosion* refers not only to the electrochemical phenomenon that causes metal loss from pipe surfaces but also to the dissolution of existing pipe scales and corrosion by-products. Internal corrosion—that is, corrosion on the interior surface of metal pipes and fixtures—is the focus of this manual because of the potential for metal release to adversely impact distributed water quality.

CUSTOMER AND INFRASTRUCTURE IMPACTS OF INTERNAL CORROSION

Internal corrosion can cause degradation of water quality, infrastructure performance and structural failures, and scaling and reequilibration issues. It may have substantial economic impacts on water utilities and consumers alike. This section discusses the most common issues resulting from internal corrosion of drinking water distribution and home plumbing systems.

Water Quality Deterioration

Internal corrosion of distribution system piping and home plumbing may cause several water quality problems, including potential health concerns, discoloration, and taste-and-odor issues. These problems are primarily the result of corrosion of metal pipe surfaces, pipe solder, and plumbing fixtures or dissolution of existing pipe scales, although some problems may be attributable to corrosion of nonmetallic system components (e.g., increases in asbestos concentrations).

Health concerns. The majority of the health concerns associated with internal corrosion are related to the release of trace metal concentrations (e.g., lead, copper, cadmium, and so on) from corroding metal surfaces. The potential health concerns related to increased metal concentrations in drinking water are discussed further in the regulatory section in this chapter.

Color. Many of the color issues typically encountered in drinking water are attributable to internal corrosion (Kirmeyer et al. 2000). Corrosion of cast-iron pipe or dissolution of existing scale on cast-iron pipe may result in rust-colored water or red water due to the presence of ferric iron (Fe(III)). Red water can stain laundry and plumbing fixtures. Iron corrosion may also result in yellow or black water, which is a result of the presence



Courtesy of District of Columbia Water (DC Water).

Figure 1-1 Red water sample from a US distribution system

of ferrous iron (Fe(II)). Ferrous iron may occur in waters with low dissolved oxygen concentrations. Black water may also be the result of the presence of manganese in source waters. Copper corrosion may result in blue water, which can also stain bathroom fixtures and hair. Gray or black water may also be attributable to hot water heaters. Corrosion of zinc in galvanized piping may result in a milky appearance.

Red water (Figure 1-1) may occur as a result of “hydraulic entrainment”—that is, the suspension and transport of loose corrosion deposits resulting from changes in flow or direction of flow—or “iron uptake”—that is, the release of ferrous ions at the pipe surface and subsequent oxidation to ferric iron and precipitation in the bulk water (Smith et al. 1998). Alternating periods of stagnation, anaerobic conditions, and temperature have been observed to cause red water, as have significant changes in alkalinity and chlorine residual (oxidation–reduction potential [ORP]). Maintaining consistent water quality and maintaining conditions that produce a hard iron scale are critical to minimizing the potential for red water (Smith et al. 1998; Reiber 2006).

Blue water may be the result of the presence of either dissolved or particulate copper corrosion by-products. Dissolved copper by-products are primarily the result of low pH and may usually be eliminated by raising pH to above 7.5 (Edwards et al. 2000). However, it is often more difficult to determine the cause of particulate copper corrosion by-products, which are found in many home plumbing systems. Particulate copper corrosion by-products are thought to be the result primarily of microbiological, water quality, or physical factors or some combination of factors that frequently result in pitting corrosion and/or pipe failure in addition to blue water (Edwards et al. 2000; Bremer et al. 2001).

Taste and odor. Dissolved and particulate iron may cause taste and odor at low concentrations. The presence of iron has been shown to result in metallic taste (Khiari et al. 2002). In addition to metallic taste, cast-iron corrosion may also result in musty tastes and odors (Kirmeyer et al. 2000). Aluminum and zinc may contribute to an astringent mouthfeel, and zinc may also result in a sour taste. Reactions of disinfectants with cement–mortar linings in ductile-iron pipe may also result in astringent, oily (rancid), pine, and phenolic odors (Khiari et al. 2002). High pH may cause the release of phenols from corroding asbestos–cement pipe, which can react with chlorine to form chlorophenols (Kirmeyer et al. 2000).

Infrastructure Impacts

In addition to affecting water quality, internal corrosion may also impact distribution and plumbing infrastructure. Most notably, internal corrosion may result in failures of home plumbing systems, causing extensive property damage. Deterioration of distribution system piping and valves as well as deterioration of meters and other in-line devices may also result from corrosion.

Home plumbing failures. The most significant home plumbing failures that occur as a result of internal corrosion are copper pitting and pinhole leaks. Pitting corrosion, though not well understood, not only damages copper plumbing but the associated leakage may also cause substantial damage to homes and result in mold growth and other issues that may pose health concerns (Edwards 2004). Table 1-2 summarizes the conditions under which potential copper corrosion has been traditionally thought to occur.

In addition to pitting corrosion, microbially influenced corrosion (MIC) of copper piping may also cause pitting and failure of home plumbing (Cantor et al. 2003; Cantor et al. 2006). In fact, it is believed that MIC is an often overlooked contributor to corrosion of plumbing systems. It has been demonstrated that MIC frequently may occur in plumbing systems with long stagnation times, in sulfide-containing waters, and in areas in which there is little to no disinfectant residual remaining (Bremer et al. 2001; Jacobs et al. 1998; Cantor et al. 2003).

Corrosion of distribution system piping may lead to pipe and valve failures resulting in increased water losses. In areas of low or negative pressure, inflow and infiltration are possible, as are bacterial contamination and other contamination from surrounding soils and groundwaters. Failure of corroded valves may also cause operational issues, such as failure to isolate water mains in the event of a line break, loss of pressure, negatively impact the ability to conduct distribution flushing, and creation of stagnant areas or areas of low flow in the distribution system (e.g., if a valve stem breaks in the closed position). Failures of meters and other in-line devices may reduce system revenues because of inaccurate meter readings and may minimize the ability to accurately determine water loss or identify main breaks.

Scaling and Reequilibration

Scaling and reequilibration are two key factors that may impact corrosion and system performance. Formation of protective metal scales is the primary corrosion control mechanism regardless of the technology employed. For example, when pH and alkalinity adjustment are used as the primary lead control technology, the objective is to form metal solids (e.g., lead carbonate and lead oxides) on the pipe surface and thereby prevent corrosion, or dissolution, of lead. Similarly, the objective of orthophosphate addition is the formation of a lead phosphate layer (Vik et al. 1996).

Controlling the type of scale formed and subsequently maintaining the stability of those scales are key to an effective corrosion control program. Iron scales, for example, are present in either the ferrous (Fe^{2+}) form or ferric (Fe^{3+}) form. Ferrous iron scales are much softer than ferric iron scales and are more likely to contribute to red water (Reiber 2006). Creating conditions in which harder ferric iron scales are formed and maintained is ideal to maintaining water quality.

After a protective scale is formed in distribution piping or home plumbing, maintaining scale stability is essential to effective corrosion control treatment. Changes in distribution system water quality may result in reequilibration of existing scales causing red water, increased tap lead or copper concentrations, or other issues.

For example, in 2002, the Washington Aqueduct switched from free chlorine to chloramine to reduce disinfection by-product (DBP) concentrations in its customer agencies' systems. As a result of this change, the ORP of the finished water changed, causing

Table 1-2 Summary of potential copper corrosion issues

Characteristic of Corrosion	Type of Corrosion			
	Uniform Corrosion	Type I Pitting (Cold Water)	Type II Pitting (Hot Water)	Type III Pitting (Soft Water)
Pit shape	No pits	Deep and narrow	Narrower than Type I	Wide and shallow
Type of problem present with corrosion	Blue or green water, high by-product release	Pipe failure	Pipe failure	Blue water, voluminous by-product releases, pipe blockage
Scale morphology on attacked surface	Tarnished copper surface or loose powdery scale	Underlying Cu ₂ O with overlying malachite, calcite, or other basic copper salts, occasionally CuCl underlies Cu ₂ O	Underlying Cu ₂ O with overlying bronchantite, some malachite	Underlying Cu ₂ O with overlying bronchantite, some malachite
Water quality	Soft waters of low pH (<7.2)	Hard, cold well waters between pH 7.0 and 7.8, high sulfate relative to chlorides and bicarbonate, high CO ₂	Hot waters, pH below 7.2, high sulfate relative to bicarbonate, occasional Mn deposits	Soft waters, pH >8.0
Initiating factors	None noted	Stagnation early in pipe life, deposits within pipe include dirt or carbon films, high chlorine residuals, water softeners, alum coagulation	Higher temperatures, high chlorine residuals, alum coagulation, particles	Stagnation early in pipe life, pH >8.0, alum coagulation, low chlorine residual
Ameliorating factors and treatments	Raise pH or increase bicarbonate	NOM, increase bicarbonate and pH	Lower temperatures, higher pH, increase bicarbonate and pH	NOM, avoid stagnation early in pipe life, increase hardness and alkalinity, elevate chlorine residual to >0.5 mg/L

NOM = natural organic matter
 Source: Edwards et al. 1994.

a shift in the speciation of the existing lead scales and elevated lead concentrations in the District of Columbia Water (DC Water) service area (USEPA 2007). It should be noted that the conversion to chloramine was just one factor that contributed to the lead release. Many operating chloraminated systems have not experienced similar results. Refer to Appendix B for more details of the Washington, D.C., project.

Economic Issues

Internal corrosion may have a number of economic or cost impacts. Failure of distribution system piping and home plumbing may necessitate costly repairs, not only of failed piping but also of other assets damaged as a result of the pipe failure. There are also more subtle economic issues associated with corrosion. Increased lead and copper levels may not only result in negative publicity but may also have the potential to result in litigation. The costs associated with legal action may be substantial. Water quality issues resulting from corrosion (e.g., color, taste and odor, and lead) may also cause negative customer perceptions and not only impact (reduce) usage but also cost utilities potential future customers.

REGULATORY IMPACTS

Lead and Copper

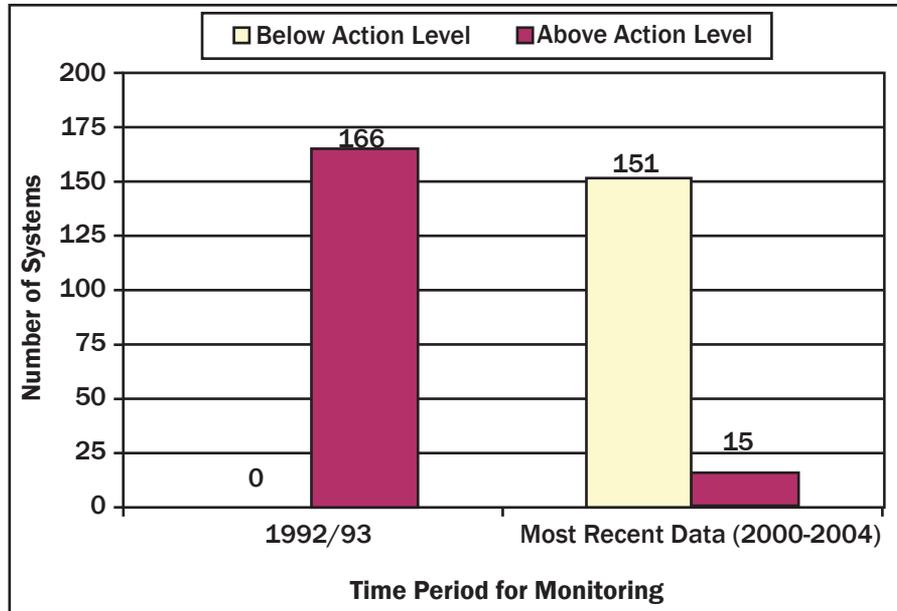
The Lead and Copper Rule (LCR) was promulgated in 1991 with the purpose of reducing drinking water exposures to lead and copper (56 FR 26460) (*Federal Register* 1991). The purpose of the LCR is to protect public health by minimizing lead and copper levels in drinking water, primarily by reducing water corrosivity (USEPA 2004a). Lead has been demonstrated to cause delays in physical and mental development in infants and children and has been linked to deficits in attention span and learning abilities (USEPA 2006a). Short-term copper exposure may cause gastrointestinal distress; long-term exposure may cause liver or kidney damage. In individuals with Wilson's disease, which causes the body to retain copper, copper can cause severe brain damage, liver failure, and death (NIH 2006).

USEPA estimates that approximately 20 percent of human lead exposure is from lead in drinking water (USEPA 2006a). The LCR established a maximum contaminant level goal (MCLG) of zero for lead and an MCLG of 1.3 mg/L for copper. The rule established a National Primary Drinking Water Regulation for lead and copper that consisted of a treatment technique requirement including corrosion control treatment, source water treatment, lead service line (LSL) replacement, and public education. The rule set an action level (AL) of 0.015 mg/L for lead and an AL of 1.3 mg/L for copper. If the 90th percentile concentration for lead or copper is above the AL, public water systems may be required to initiate water quality parameter monitoring for key corrosion control parameters, install corrosion control treatment, begin source water monitoring or treatment, replace LSL, or undertake a public education program.

Internal corrosion of lead service lines, brass meters and plumbing fixtures, and copper plumbing contributes to the concentrations of lead and copper in drinking water. Pure lead pipe (lead service lines), lead solder, and brass with greater than 8 percent lead were banned by the 1986 Safe Drinking Water Act Amendments (Dudi et al. 2005). "Lead-free" brass, however, may contain as much as 8 percent lead by weight. Greenville Utilities in Greenville, N.C., exceeded the lead AL in 2004 and 2005 despite the fact that the system does not contain any lead service lines. In this case, the exceedance was attributed to leaching from lead-based solder and plumbing fixtures containing lead (Landers 2006). California banned the use of pipe solder with lead content greater than 0.2 percent in 1987. On Jan. 1, 2010, a new California law went into effect defining "lead free" as less than 0.25 percent. All pipes, fittings, and fixtures must be lead free.

Impact of the LCR on tap-water lead concentrations. A review conducted by USEPA of LCR compliance monitoring data for public water systems serving more than 3,300 people shows that since 2000, fewer than 4 percent of those systems have exceeded the lead AL (USEPA 2004b). Prior to 2002, states were not required to report 90th percentile lead concentrations to USEPA unless those values exceeded the AL. Consequently, it is difficult to compare the tap-water lead concentrations immediately following implementation of the LCR to current levels. However, USEPA did evaluate data from 166 large public water systems that exceeded the AL following initial LCR monitoring in 1992 and 1993 (USEPA 2006f). Following monitoring conducted by these same utilities between 2000 and 2004, only 15 of those systems continued to exceed the AL (Figure 1-2).

A closer look at the data presented in Figure 1-2 reveals tap-water lead concentrations have decreased significantly in those systems that initially exceeded the lead AL. Figure 1-3 shows that, for those 166 large systems that exceeded the AL in 1992–1993, the average 90th percentile lead concentration decreased from nearly 32 µg/L to 8.2 µg/L. Over that same period, the maximum 90th percentile lead concentration decreased from 211 µg/L to 84 µg/L.



Source: USEPA 2006f.

Figure 1-2 Number of large US water systems exceeding the lead action level

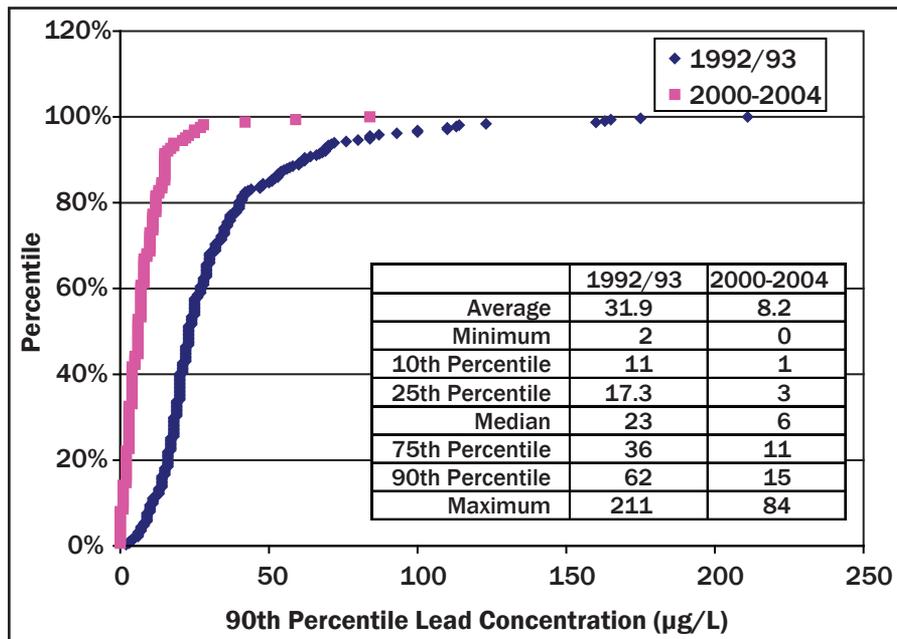


Figure 1-3 Comparison of 90th percentile LCR monitoring data for 166 large public water systems

Revisions to the Lead and Copper Rule. USEPA revised the LCR in 2007 (72 FR 57781, [*Federal Register* 2007]) with the intent of enhancing implementation in the areas of monitoring, treatment, customer awareness, and lead service line replacement. In addition, the 2007 revisions intended to improve public education by ensuring drinking water customers receive “meaningful, timely, and useful information needed to help them limit their exposure to lead in drinking water.”

The most significant revisions to the LCR clarify some of the confusion regarding sample collection and reporting. Specifically, the LCR revisions require that all compliance monitoring results, including those above the required number of samples, be included in the 90th percentile determination and that all samples be taken within the same calendar year. The remainder of the revisions address customer notification for those residents in a utility's sampling program and provisions to deal with LSL that were previously "tested out" due to levels below the AL.

Iron

USEPA established a secondary maximum contaminant level (SMCL) of 0.3 mg/L for iron, which represents a "reasonable goal for drinking water quality" (40 *Code of Federal Regulations* [CFR] 143.3). SMCLs control contaminants that primarily affect the aesthetic quality of drinking water and are not federally enforceable, although state primacy agencies have the authority to include them in state drinking water regulations. When present at sufficiently high levels, iron may result in rusty color, deposit of sediment, metallic taste, and reddish or orange staining.

Much of the iron present in water is the result of natural mineral deposits and, when present in source waters at concentrations above the SMCL, iron is frequently removed at the water treatment facility. If not removed, source-water iron may result in red water in the distribution system. However, internal corrosion of unlined cast-iron pipe, galvanized pipe, or dissolution of existing pipe scales in iron pipe may also result in aesthetic issues in drinking water distribution systems.

Cadmium

Short-term exposure to high concentrations of cadmium may result in nausea, vomiting, diarrhea, muscle cramps, salivation, sensory disturbances, liver injury, convulsions, shock, and renal failure. Long-term exposures may cause kidney, liver, bone, and blood damage (USEPA 2006b). Consequently, USEPA has established an MCLG of 0.005 mg/L for cadmium as well as a maximum contaminant level (MCL) of 0.005 mg/L.

Cadmium is primarily present in drinking waters due to erosion of natural deposits but may also be present due to leaching from cement–mortar lined pipes (Guo et al. 1998; Berend and Trouwborst 1999) or as a result of corrosion of galvanized piping. It has also been observed that the amount of lead and cadmium released from galvanized piping decreased with the age of the pipe due to the formation of a passivating layer on the pipe surface (Meyer 1980).

Zinc

Zinc in drinking water is primarily an aesthetic concern as it may result in a metallic taste. As a result, USEPA has established an SMCL of 5 mg/L for zinc. Zinc may be present in drinking water due to erosion of natural deposits or as a result of dezincification of brass plumbing fixtures. Several studies of low-alkalinity waters have found that iron and zinc were the principal corrosion by-products of galvanized plumbing (Dangel 1975; J.M. Montgomery 1982).

The zinc coating on galvanized pipe may contain lead, copper, cadmium, chromium, aluminum, barium, and other impurities. There are a number of standards regarding galvanized pipe, most notably by the American Society for Testing and Materials (ASTM) in the United States. As a result of these impurities, corrosion of galvanized pipe may result in the release of trace metal concentrations.

Asbestos

Asbestos in drinking water is most commonly present as a result of degradation of asbestos–cement piping used in drinking-water distribution systems. Though it may be present in natural soils, it does not often migrate to groundwater through soils (USEPA 2006c). Short-term exposure to asbestos in drinking water is not known to cause any health issues; long-term exposure may result in increased risk of developing benign intestinal polyps. USEPA has established an MCLG of 7 million fibers per liter (M.L.) and an MCL of 7 M.L. for asbestos.

Biological Regrowth and Chlorine Demand

The Surface Water Treatment Rule was finalized in 1989 and requires maintenance of a disinfectant residual in the distribution system, among other requirements (54 FR 27486 [*Federal Register* 1989a]). The Total Coliform Rule (TCR) imposes monitoring requirements for total coliform, as well as for fecal coliform and *Escherichia coli* (54 FR 27544 [*Federal Register* 1989b]). A Revised Total Coliform Rule “Agreement in Principle” was signed in September 2008, which will change the requirements associated with the rule. Biological regrowth and chlorine demand may be impacted by corrosion in a number of ways and vice versa. Chlorine and other oxidants impact the ORP, which is a factor in maintaining effective corrosion control. Conversely, corrosion by-products can exert an oxidant demand, diminishing distribution system disinfectant residuals and resulting in increased potential for microbiological regrowth. Microbiological regrowth not only may threaten compliance with the TCR but also may result in increased potential for MIC to occur.

Release of Trace Metals from Cementitious Coatings

Barium, cadmium, chromium, and aluminum have been found to leach from cement–mortar lining in distribution piping (Guo et al. 1998; Berend and Trouwborst 1999). While this leaching represents a potential water quality and public health concern, it is not the focus of this manual.

ADDITIONAL READING

The reader is advised to become more knowledgeable in the following areas:

- The water quality and operational factors that influence internal corrosion and metal release in drinking water distribution systems
- The potential water quality, health-related, infrastructure, and regulatory concerns associated with internal corrosion
- The secondary impacts associated with changes in source-water quality, treatment, or distribution operations and the potential for those changes to impact existing corrosion control effectiveness (i.e., reequilibration of existing pipe scales)

References for this chapter give detailed information on these topics and the other topics discussed. The reader is encouraged to follow up on the referenced material that is publicly available to obtain keener insight into this discussion.

In addition to the references, the following resources provide substantial discussions regarding these topics and will be extremely valuable to the reader in developing an understanding of the factors that influence corrosion, implementing an effective corrosion treatment and monitoring program, and assessing the cause of future corrosion-related water quality issues.

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