CHAPTER 5

CORROSION OF WATER WELLS

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5.1 GENERAL

Corrosion is the deterioration of a material, which results from a reaction with its environment. This environment comprises the physical, chemical, and mechanical conditions or surroundings of the material. Although metals and PVC are the most widely used materials for water well casing, there has been an increase in the use of nonferrous materials (e.g., thermoplastic, fiberglass) for use in specialized applications (contaminant remediation or monitoring) and extreme environments. However, this chapter focuses on the corrosion issues related to commonly used water well casing and screen materials (e.g., carbon steel, alloy, stainless steels).

The corrosion of ferrous metals in groundwater may be caused by electrochemical or physical processes. The various types of corrosion that can be generated from contact between water-well components and groundwater include electrochemical, crevice, and galvanic corrosion, as well as stray electrical current or microbial induced corrosion. Physical processes also may corrode metals through fluid or particle effects.

In addition to material selection, the design and operation of the water well will affect the performance of the well.

5.2 THEORY OF CORROSION

5.2.1 Electrode Reactions

The corrosion of metals may be caused by electrochemical processes involving both oxidation and reduction reactions (Fig. 5-1). The corrosion reaction involves oxidation and occurs at the anodic area. An oxidation

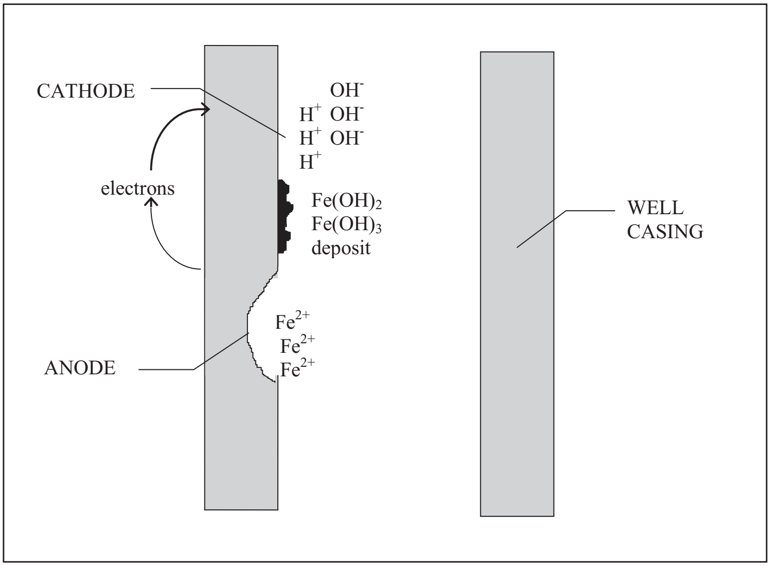


Fig. 5-1. Corrosion processes on a metal surface
Source: McLaughlan (2002)

reaction involves an increase in valence or the extraction of an electron from an ion or atom. Reduction reactions occur in a cathodic region and involve a decrease in valence or the consumption of electrons. For a corrosion cell to exist, the anodic and cathodic areas must be connected so that an electrical circuit is formed. In water wells, water with dissolved ions will allow the transfer of ions to the anodic and cathodic sites, whereas metal surfaces will facilitate electron transfer.

5.2.2 Anode

At the anode, positively charged metal atoms leave the solid surface and go into solution. The oxidation reaction occurring may be generalized as

$$M \leftrightarrow M^{n+} + ne^{-} \tag{5-1}$$

where

M = metal
e^{-} = electron
n = number of electrons.

The value of n depends primarily on the nature of the metal.

5.2.3 Cathode

At the cathode, electrons generated from the anode react with positive ions in the water to preserve solution neutrality. Cathode reactions that can occur during the corrosion of metals are (NACE 1984):

Oxygen reduction (acid solution)

$$O_2 + 4H^+ + 4e^- \leftrightarrow 2H_2O \tag{5-2}$$

Oxygen reduction (neutral and alkaline solution)

$$O_2 + 2H_2O + 4e^- \leftrightarrow 4OH^- \tag{5-3}$$

Hydrogen evolution

$$2H^+ + 2e^- \leftrightarrow H_2 \tag{5-4}$$

Metal ion reduction

$$M^{n+} + e^- \leftrightarrow M^{(n-1)+} \tag{5-5}$$

Metal deposition

$$M^{n+} + ne^- \leftrightarrow M \tag{5-6}$$

At the cathode, more than one of these reactions may occur simultaneously.

5.2.4 Passivity

Metals may become passive and lose their chemical reactivity, which enhances their corrosion resistance. This passivity may be due to a thin oxide or adsorbed layer protecting the metal surface. If the passive film is disrupted, strong corrosion cells may operate between the active and passive surfaces of the metal. To maintain the passivity of stainless steel, a low concentration of dissolved oxygen is required.

5.2.5 Polarization

The retardation of electrochemical reactions (polarization) due to protective films may result from a buildup of corrosion products (e.g., $Fe(OH)_3$ or carbonate $[CO_3^{2-}]$). Other ions (Ca^{2+}, Mg^{2+}) also may precipitate and polarize the surface. These precipitates will decrease the diffusion of O_2 and H_2 at the metal surface and decrease the corrosion rate.

Depolarization involves removing the factors that resist the current. Sulfate-reducing bacteria may depolarize the cathode by utilizing dissolved hydrogen and, therefore, promoting the hydrogen evolution reaction and corrosion (Hamilton 1985).

5.3 TYPES OF CORROSION

5.3.1 Electrochemical Corrosion

Electrochemical corrosion occurs when a concentration cell is formed on the metal surface. A concentration cell is formed when there are differences in the potentials across the metal surface. These differences may be caused by inherent heterogeneity of metal at the microscopic scale due to the presence of impurities and inclusions of metal oxides and sulphides. The thermal and mechanical history of the metal surface due to activities involving welding, abrasion, and strain also may create potential differences across a metal surface.

A deposit or biofilm that does not cover the immersed surface of a metal uniformly also can cause a concentration cell (Fig. 5-2). At the location with the thicker biofilm, oxygen is consumed completely within the biofilm, whereas at the site where the biofilm is thinner, oxygen can penetrate to the surface of the metal and create cathodic depolarization through oxygen reduction. This condition could occur, for example, when a piece of clean pump riser pipe is connected to an older section of pipe (which is covered by deposits) or through the patchy development of

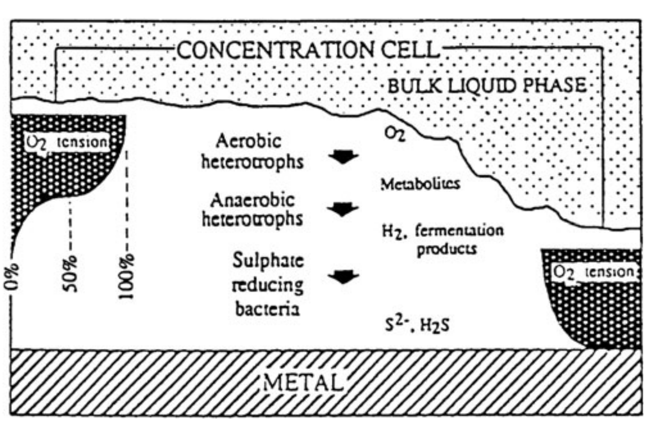


Fig. 5-2. Concentration cell formed under a biofilm
Source: Hamilton (1985); reproduced with permission from Annual Review of Microbiology

biofilms on a pipe surface. Many iron hydroxide deposits within water well environments are likely to contain microorganisms, which can exacerbate electrochemical reactions within the deposit.

The form of the corrosion is influenced by the distribution and potential of the anodic and cathodic areas across the metal surface. Where the areas are microscopic or are dynamic and shift, then the corrosion pits may be uniform across the surface. Where there are large differences in potential between the areas, then the corrosion pit may be small and localized. In water wells, localized pitting may corrode casing rapidly, leading to well failure.

5.3.2 Microbially Influenced Corrosion

Increasingly, microbes are being recognized as playing a role in corrosion in aqueous environments. Although bacteria, fungi, algae, and protozoa can be involved, within water wells it is bacteria that are of primary concern. Whereas potable groundwater aquifers are relatively nutrient poor compared with other environments, various types of bacteria are adapted for the range of environmental conditions found in water wells. The bacteria that can be associated with microbially influenced corrosion in groundwater are iron-oxidizing bacteria, slime-forming bacteria, and sulfate-reducing bacteria.

The iron and manganese oxidizing bacteria gain benefit from converting ferrous iron (Fe^{2+}) to ferric iron (Fe^{3+}), which then can form precipitates. The deposits formed can comprise iron oxyhydroxides, bacteria, particulates, and ions from the groundwater, such as chloride. These biofouling deposits then can create concentration gradients across the surface of the metal leading to localized corrosion. Commonly identified bacteria of this group include stalked bacteria (*Gallionella*) and sheathed bacteria (*Leptothrix*).

The slime-forming bacteria occur in a wide range of conditions from anaerobic through micro-aerobic to aerobic and environments from lakes to wells. These bacteria are characterized by their ability to form extracellular polymers that allow the rapid growth of biofouling deposits on the surfaces. They also play an important role in creating metabolic products used by other bacteria and may oxidize ferrous iron.

Sulfate-reducing bacteria are found widely in soils and water-formed deposits that have anaerobic conditions. They also are implicated in the corrosion of many different types of metals. Sulfate-reducing bacteria gain energy by converting sulphate to sulphide. They utilize dissolved hydrogen (H_2) or organic acids in this process. They can promote corrosion through cathodic depolarization, which involves utilizing dissolved hydrogen evolved at the cathode. The sulphides produced during this process also may be corrosive.

However, these microorganisms often live in a biofilm, which can contain a range of chemical environments that do not occur in the bulk water chemistry. These environments can favor electrochemical corrosive processes, which may not occur in the rest of the groundwater. Within these biofilms a range of conditions promotive of corrosion may occur. Bacteria can convert dissolved organic carbon in the groundwater into fermentation products, such as organic acids. These acids can be corrosive. Any sulfate-reducing bacteria in the biofilm may depolarize the cathode by utilizing dissolved hydrogen. The biofilm can trap dissolved ions, such as chloride, within it. The irregular thickness and conditions within the biofilm may allow concentration cells to form.

5.3.3 Galvanic Corrosion

Galvanic activity occurs when a metal is connected electronically to a dissimilar metal in the presence of an electrolyte. The potential of a metal in solution is related to the energy that is released when the metal corrodes. The corrosion potential of metals can be used to rank them relative to each other in a galvanic series based on their properties in seawater at near ambient conditions (see Fontana and Greene 1985). It is possible the relative order may change in other environments; however, this order is likely to hold for most groundwater.

The materials comprising a particular galvanic group have similar properties, and galvanic corrosion is unlikely if materials within the same group are connected electrically (Fontana and Greene 1985). A corrosion cell can be created when materials of two different corrosion potentials are connected. The farther the two materials are apart from one another in the galvanic series, the greater the risk of galvanic corrosion. Besides, it may be pointed out that there is a difference in the corrosion potential, for example, between a stainless steel in a passive state and an active state. An active state occurs when the passivating film on the surface of the metal has been destroyed. Corrosion cells can be set up on a metal between its active and passive surfaces.

The degree of galvanic corrosion will be influenced by the ratio of the cathodic to anodic areas. As the ratio of cathodic to anodic areas increases, the corrosion rate at the anode increases. So a small section of mild steel when connected to a large section of stainless steel is likely to corrode rapidly.

5.3.4 Erosion Corrosion

Erosion corrosion involves electrochemical corrosion and the mechanical interaction of water and any particles within it and the metal surface.

The corroded metal surface often is characterized by pits or gullies and grooves. Erosion or wear can occur through mechanical abrasion of the metal surface, particularly from entrained particles or the removal of any protective film that exposes fresh surfaces to attack. It can be significant when the flow rate and particle concentrations are above critical thresholds. A practical limit of sand content in pumped water based on submersible pump wear is often around 5 to 8 mg/L.

Cavitation corrosion involves the formation and rapid collapse of gas bubbles in the water. The gas bubbles form in areas of low pressure, which then implode under conditions of high pressure. When this occurs against a metal surface, the localized pressure change can create a damaged surface. Cavitation damage occurs under conditions of highly turbulent flow and is relatively rare in well casings. However, it can occur in groundwater pumps, particularly in and around pump impellers.

5.3.5 Stray Current Corrosion

Currents cause this type of corrosion from electrical equipment using an unintended metallic structure, such as an underground pipeline as a low-resistance pathway. The current will enter the structure at a particular location (which becomes cathodic) and leave the structure at another. Where the current leaves, the structure experiences an anodic reaction, and corrosion occurs. The main sources of stray currents are from direct current (D.C.) electric tractions (e.g., subways, trams, and railway), D.C. industrial devices (e.g., welding machines), high-voltage electrical power transmission lines (mainly direct current), and foreign cathodic protection systems.

5.3.6 Crevice Corrosion

Crevices occur where surfaces are shielded or covered, such as under deposits, gaskets, disbonded coatings, seals, and lap joints or in threaded joints (Kain 1987). Within a crevice, an environment can form that has very different characteristics to the water outside the crevice. The pH may drop to low values (e.g., pH = 1) due to dissolved, iron-forming hydroxides, which increases the hydrogen ion (H^+) concentration and, hence, lowers the pH. Within the crevice the chloride concentration is also higher than that in the water outside the crevice. The chloride ions migrate against the electric current to the pit. The surface outside the crevice will become cathodic. It is difficult to predict the rate of crevice corrosion because of variability in crevice tightness and geometry.

5.4 CORROSIVE PROPERTIES OF WATER

The environment around a metal surface will control the corrosion rate. This includes both the chemical and physical properties of the water.

5.4.1 Dissolved Ions

The corrosion rate generally increases as the salinity of the water increases. High levels of dissolved ions create high conductivity water, which increases the rate of current transfer between different sections of the casing or between the casing and the earth. It also allows anodes and cathodes to operate over long distances, increasing the opportunity for corrosion. Other processes involve dissolved ions (e.g., Cl^-, SO_4^{2-}), which can form acids (e.g., HCl, H_2SO_4) in water causing pitting corrosion, whereas other ions, such as bicarbonate, carbonate, and hydroxide, may decrease the corrosion rate by forming protective scales.

5.4.2 Oxygen

The dissolved oxygen content is recognized as the major factor influencing corrosion rates of carbon steel. In de-aerated conditions, the rate of corrosion of steel is much lower. When oxygen concentrations increase, oxygen reduction occurs at the cathode. This increases corrosion, and an uneven distribution of corrosion products can form on the surface of the metal leading to localized corrosion from concentration cells. In stainless steel, a small amount of oxygen is needed to maintain the passive state and corrosion resistance of the metal, but the surface needs to be kept deposit free to prevent zones of oxygen depletion from forming under the deposit and leading to concentration cells.

5.4.3 Carbon Dioxide

Carbon dioxide is soluble in water and reacts to form a weak acid (H_2CO_3). This can create a pH of less than 6 where an acid attack can predominate. Corrosion by carbon dioxide occurs in water wells, particularly in deep wells, where the effect is exacerbated by elevated water temperatures.

5.4.4 Hydrogen Sulphide

Hydrogen sulfide (H_2S) is recognized as a corrosive agent in the natural gas industry where the water has high temperatures, pressures, and chloride contents. These conditions are unlikely to occur in many potable water-supply wells. However, sulfide inclusions, particularly in older well casings when quality control procedures were not quite so rigorous, are possible. These can act as sources of pit nucleations.

5.4.5 Flow Rate

The flow rate may affect corrosion rates due to influences on the electrochemical reactions or mechanical (erosion) effects. In general, corrosion rates increase with increasing velocities up to a point. Increased flow rates affect electrochemical reactions through increased reductant (e.g., oxygen, hydrogen) supply to the reaction surface (cathode), which promotes corrosion. However, for stainless steels, corrosion also may occur in zones where there is very low flow because some oxygen is needed to maintain the metal in a passive state. Erosion corrosion can occur at higher velocities due to the removal of any protective films on the metal surface, cavitation, or abrasion from particles.

5.4.6 pH

The relationship between pH and corrosion rate reflects a mixture of hydrogen ion (H^+) effects and carbonate equilibrium processes involving carbon dioxide and carbonate. The increased H^+ concentration that occurs at a low pH accelerates the corrosion of most metals. Below a pH of 5, the oxide and hydroxide layers, which can protect a metal surface, tend to dissolve. Both hydrogen evolution and oxygen reduction will occur at the cathode. As the pH increases (>5) the protective oxide and hydroxide scales can form and the corrosion rate decreases. The type of corrosion may change from being uniform when there are no scales to being localized underneath the surface deposits when they form.

5.4.7 Temperature

Temperature can affect the corrosion rate in several ways. Because corrosion often is based on electrochemical reactions, an increase in temperature will increase the corrosion rate. However, as the temperature increases the solubility of oxygen decreases, which may tend to decrease corrosion at the cathode from oxygen reduction. In studies on seawater, a 50% increase in corrosion rates was found as the temperature rose from 7 °C to 29 °C (Roberge 2012).

5.4.8 Deposit Formation

Although thin films on a metal surface may be protective, thick deposits can create concentration cells that are promotive of corrosion. Water quality that is conducive to deposit formation includes those that have a tendency to biofoul and are rich in dissolved iron, carbonates, and sulfides.

5.5 CORROSION OF WATER-WELL SYSTEMS

5.5.1 Corrosion of Well Casings and Screens

It is difficult to observe directly the extent of corrosion in water well casings. However, it is possible to characterize the different environments within a well (Roscoe Moss Company 1990), each with their own factors and processes that control the extent of corrosion in that zone.

5.5.1.1 External Casing Zone The zone of external casing incorporates the outer surface of the well casing in contact with the ground. The corrosiveness in this zone depends on the nature of the soil or sediment in contact with the casing. The extent of soil corrosion has been related to soil resistivity, pH, redox, sulfide content, aeration, and moisture. Soil characteristics that promote corrosion include low resistivity (e.g., clays rather than sands), low pH (<4), reducing conditions (Eh < 100 mV), and the presence of sulfides and moisture. In particular, where soil or sediment layers in contact with the casing have different soil characteristics, then differential concentration cells on the casing can be set up, which accelerates corrosion. This type of corrosion is more often found in soils and sediments in the shallow subsurface rather than at depth. Caution may be needed where reactive sediments are used for backfill or drilling additives are not removed fully from the well. Water wells may be designed with a cement grout at the surface and an inert filter pack to isolate the well casing from subsurface sediments. If this were the case, then the corrosion rate is due to the groundwater and similar to that for the internal surfaces of the well casing.

5.5.1.2 Atmospheric Zone This zone occurs above the static water level. The nature and rate of corrosive attack will be dependent on the nature and composition of any moisture film on the surface of the casing. For iron above a critical humidity level of 60%, a thin moisture film may form on the casing surface, which can absorb atmospheric pollutants (e.g., chlorides) and promote corrosion. Both the number of hours the atmosphere is above the critical humidity and the amount of airborne deposition of contaminants will control the rate of corrosion. This type of corrosion often is negligible compared to other types of well corrosion, because this zone in a well often is relatively isolated from the atmosphere and various sources of contaminants.

5.5.1.3 Splash Zone The splash zone is the internal surface of the casing between the static and pumping water levels. This section of the casing is subject to a periodic wetting cycle caused by changing water levels in a well due to pump operation, as well as humidity. Whenever the pump is turned on, a thin wet film remains on the well casing between the static water level and the pumping level. As the water on the surface of the casing evaporates, any salts within it concentrate, promoting corrosion. The exposed metal surface is likely to dry at different rates causing differential concentration cells. The dewatering of well screens creates conditions that promote corrosion. The well casing also may suffer intense localized corrosion at the water line if the water level remains fixed for long periods. Iron oxide products from corrosion are likely to form in the splash zone to a greater extent than in submerged casing. A concentration cell may form due to differences in the nature and amount of the corrosion products above and below the water line. A laboratory study using high-purity iron found corrosion rates up to three times greater than those observed under continuously immersed conditions (Dunn et al. 2000). Major factors controlling corrosion in this zone are the amount of time that a wet film is present on the casing (related to pump operating schedules and casing surface) and the water chemistry (e.g., salt concentration).

5.5.1.4 Submerged Casing Zone This zone represents the well casing and well screens that are in continuous contact with groundwater. Within this zone different types of corrosion may occur due to material selection, flow conditions, and the changes in the material properties arising from well installation and operation.

Often well screens are made from a different material than the well casing. When dissimilar metals are connected, a galvanic couple is formed, which promotes corrosion. In particular, long sections of stainless-steel screens, which are connected to short sections of mild-steel casing, can cause the mild steel to act as an anode and corrode rapidly. In this situation, the use of stainless-steel casing as spacers is preferred. Welded joints on well screens or between sections of casing also may be areas where corrosion may occur. The metal in the weld seam and those areas affected by heating may have different properties from the surrounding metal.

Well screens also may be vulnerable to corrosion because of their high surface area and exposure to higher flow velocities than other sections of the casing. These higher flow rates may remove any protective film that builds up. The upper limit for screen entrance velocity is 0.46 m/sec (1.5 ft/sec) (AWWA 1997).

Well casings, screens, and riser pipes also are subject to various stresses during installations and well operations. There are axial forces that can pull the casing apart or compress it and radial forces that tend to collapse the casing. Casing fatigue can occur from inadequate well design by suspending or having long lengths of unsupported casing in an open hole. During well construction, the casing may be jacked, driven, or twisted in an effort to make the casing fit the hole. The stresses imposed on the casing can cause it to deform and weaken the casing joints. The sections of fatigued casing also are more vulnerable to corrosion processes. During well operation, iron biofouling deposits often build up on the casing near the pump inlet and on the upper sections of well screens. The buildup of corrosion or biofouling deposits on the surface of the casing may cause localized corrosion. These deposits can create conditions for corrosion by creating concentration cells and microbially influenced corrosion.

If the casing failure is very localized, then the performance of the well may be partially impaired. Small amounts of sand may enter the well increasing pump corrosion. However, if the thickness of the casing is reduced over a larger area, then the risk of massive failure, such as well casing rupture and loss of the pump down the well, increases. The relationship between collapse strength and casing thickness is complex. For a 150 mm and 200 mm casing a reduction in the casing thickness of 25 and 45% result in a reduction in the collapse strength of about 45 and 70%, respectively. How important this is in a particular well depends on the stresses imposed by the water and the strata, as well as the safety margins incorporated into the well design. Detailed information on casing stresses is provided by Roscoe Moss Company (1990).

5.5.2 Corrosion of Pumping Equipment

The pumping equipment includes downhole pump items, the riser pipe used to transmit the pumped water to the surface, and any discharge headwork. Corrosion of this equipment may occur due to material selection, water properties (such as sand and gas content), and changes to material properties during pump installation and maintenance.

The surface of pump impellers can be vulnerable to erosion from particles as well as cavitation. Pump performance is affected by wear on either the leading edge or the outside edge of the impeller. Pumped water can be redirected through the increased impeller clearance resulting in it being pumped again. This leakage reduces the efficiency of the pump. Wear on the impeller surface also can occur through cavitation. This is evidenced at the wellhead by noisy pump operation and fluctuations in both power consumption and water yield. The bearings in submersible pumps are liable to failure from sand pumping, particularly as many impellers are free to float rather than being fixed axially to the pump shaft. The pumps are designed to operate in downthrust with the bearing clearance sufficient to be lubricated by the pumped fluid but exclude abrasive particles. If there is no load during pump startup, the impellers go into upthrust, causing the thrust bearing clearance to increase and allowing very large grains to enter. When the pump stabilizes, the impellers go into downthrust with abrasion of the thrust bearing from the sand grains (Wilson 1990).

Riser pipes, which have threaded joints, are vulnerable to several types of corrosion. When riser pipes are screwed together, the tools used to grip the pipe often roughen up the pipe surface near the joints. This roughens the surface and can initiate corrosion. Any protective coating on the pipe may be damaged. These unprotected areas then become anodic to the protected surfaces. Threaded joints also are liable to crevice corrosion from corrosive groundwater if they are not sealed with a hard setting-jointing compound. Any irregularities in the internal surface of the riser pipe can create the conditions for erosion. In the riser pipe used for line shaft pumps, the shaft centralizers can cause flow restrictions resulting in flow velocities in excess of 20 m/s, which can initiate erosion.

At the wellhead, galvanic corrosion may occur when there is no electrical isolation between dissimilar metals used for the discharge head, ancillary devices (e.g., flowmeters), and the pipeline. Interference current corrosion can occur due to influences of nearby direct current sources with the pipeline or casing.

5.6 PREDICTION OF CORROSION

Estimates of corrosion rates may be used to aid in design processes, such as material selection or for service life estimates.

5.6.1 Scaling Indexes

There have been many attempts to relate corrosion to water quality but no predictors have been found to be universally applicable. Well-known indexes include the Langelier Saturation Index (LSI) and the Ryznar Stability Index (RSI). These indexes are used widely in municipal water system and cooling water system evaluations. These indexes do not measure the corrosivity of steel but are based on the ability of water to precipitate a calcium carbonate film that can act as protective film on the metal surface to protect against generalized corrosion. The use of these indexes to evaluate the corrosivity of metal is limited because they do not account for the following:

1. Microbial factors,
2. Interaction of calcium and carbonate with other compounds in solution (e.g., chelates),

3. Capacity of water to keep producing a scale,
4. Rate at which the scaling reaction will occur, and
5. Effect of dissolved oxygen, chlorides, sulphates, and flow velocity on corrosion.

In some cases these indexes have been developed using empirical data from high-alkalinity water, and caution should be exercised when extrapolating these results to other environments, such as waters with low alkalinity, low pH, and high chloride and sulfate concentrations relative to alkalinity. Another limitation can be whether the chemical analysis of the sample is representative of the water in the localized environments where corrosion often occurs and whether the sample has been collected and analyzed properly. Field-based measurements of water samples are needed.

Pisigan and Singley (1985) found the Langelier Saturation Index was unreliable as a corrosion predictor but may indicate the ability of water to maintain a calcium carbonate deposit. In general, these scaling indexes are useful, because they are easy to calculate and require few analytic inputs, but they can serve only as a guide to understand scaling processes in water. Along with other water quality and geological data these indexes can be used in a weight of evidence approach to evaluate the likelihood of corrosivity of water in a particular environment.

5.6.1.1 Langelier Saturation Index The Langelier Saturation Index (Langelier 1936) may be defined as

$$\mathrm{LSI} = \mathrm{pH} - \mathrm{pH_s} \tag{5-7}$$

where

LSI = Langelier Saturation Index, (dimensionless)
pH = measured (actual) pH of the water, (dimensionless)
$\mathrm{pH_s}$ = pH of the system if saturated with $CaCO_3$ at the measured calcium and alkalinity value, (dimensionless).

The value for $\mathrm{pH_s}$ can be approximated (Faust and Aly 1998) as

$$\mathrm{pH_s} = A + B - \log_{10}\left[\mathrm{Ca^{2+} as\ CaCO_3}\right] - \log_{10}\left[TALK\right] \tag{5-8}$$

where

A = A temperature-dependent constant (see Table 5-1), (dimensionless)
B = A correction factor (see Table 5-2), (dimensionless)

Table 5-1. Constant A as a Function of Water Temperature

Water Temperature (°C)	A	Water Temperature (°C)	A
4	2.1761	18	1.9512
6	2.1422	20	1.9212
8	2.1090	22	1.8916
10	2.0763	25	1.8497
12	2.0442	30	1.7710
14	2.0127	40	1.6409
16	1.9817	50	1.5105

Source: Schock (1984); reproduced with permission from American Water Works Association

Table 5-2. Correction Factor B for Various Ionic Strengths and Temperatures

Ionic Strength (I)	TDS (mg/L)	4 °C	16 °C	25 °C	50 °C
0.0000	0	9.70	9.70	9.70	9.70
0.0003	10	9.74	9.74	9.74	9.74
0.0008	30	9.76	9.77	9.77	9.77
0.0013	50	9.78	9.78	9.79	9.79
0.0020	80	9.80	9.80	9.81	9.81
0.0026	100	9.81	9.82	9.82	9.82
0.0038	150	9.84	9.84	9.84	9.85
0.0050	200	9.86	9.86	9.86	9.87
0.0063	250	9.87	9.87	9.88	9.89
0.0075	300	9.89	9.89	9.89	9.90
0.0088	350	9.91	9.90	9.91	9.91
0.0100	400	9.91	9.91	9.92	9.93
0.0125	500	9.91	9.94	9.94	9.95
0.0150	600	9.95	9.95	9.96	9.97
0.0175	700	9.97	9.97	9.97	9.99
0.0200	800	9.98	9.98	9.99	10.00
0.0225	900	9.99	10.00	10.00	10.02
0.0250	1000	10.01	10.01	10.02	10.03

Notes: For calcium analysis reported as mg Ca/L rather than mg $CaCO_3$/L, 0.30 should be subtracted from values of B reported here. TDS is estimated by Langelier's approximation $TDS = 2.5 \times 10^5\ LSI$.

Source: Schock (1984); reproduced with permission from American Water Works Association

TALK = Alkalinity expressed in mg/L as $CaCO_3$. For many waters with pH between 6 and 9.5, the $TALK = [HCO_3^-]$ expressed in mg/L as $CaCO_3$ (Faust and Aly 1998).

Generally it is recognized that the LSI may indicate only the corrosive tendency of water within a pH range 6.5 to 9.5 (AWWA 1986). Waters that have a negative LSI are undersaturated, whereby a value of zero is saturated. Waters that have a positive LSI are supersaturated with respect to $CaCO_3$ and may therefore precipitate a carbonate film.

5.6.1.2 Solved Design Example 1 Determine the Langelier Saturation Index, LSI, for the following water analysis:

- pH (measured) = 8.4
- Total Dissolved Solids = TDS = 258 mg/L
- calcium hardness (as $CaCO_3$) = 110 mg/L; to convert to Ca hardness (as $CaCO_3$) from Ca^{2+} (mg/L) then multiply by 2.5
- alkalinity (as $CaCO_3$) = 145 mg/L
- temperature = 12 °C.

Solution From Eq. (5-8)

$$\begin{aligned}\mathrm{pH_s} &= A + B - \log_{10}[\mathrm{Ca^{2+} as\ CaCO_3}] - \log_{10}[TALK]\\ &= 2.05 + 9.87 - 2.04 - 2.16\\ &= 7.72\end{aligned}$$

From Eq. (5-7)

$$\begin{aligned}\mathrm{LSI} &= \mathrm{pH} - \mathrm{pH_s}\\ &= 8.4 - 7.72\\ &= 0.7\end{aligned}$$

This small value of LSI suggests that the water has a slight tendency toward preciptating a calcium carbonate scale that may be protective against uniform corrosion.

5.6.1.3 Ryznar Stability Index The Ryznar Stability Index (RSI) was derived empirically from scale thickness observed in a municipal water system and the water chemistry. It was defined by Ryznar (1944) as

$$\mathrm{RSI} = 2(\mathrm{pH_s}) - \mathrm{pH} \tag{5-9}$$

where

pH = measured pH of the water, (dimensionless)
pH_s = pH of the system if saturated with $CaCO_3$ at the measured calciumand alkalinity value and can be calculated from Eq. (5-8), (dimensionless).

The Ryznar Stability Index can be interpreted as follows:

RSI << 6	the tendency to scale increases as the index decreases
RSI > 7	calcium carbonate formation probably does not lead to a protective corrosion inhibitor film
RSI >> 8	mild steel corrosion becomes an increasing problem.

These values were verified against field data for incrustation and corrosion in wells (Mogg 1972) and used for guidance on well screen material selection (see Table 5-3).

5.6.2 Corrosion Rate Tests and Data

Where the water well installation environment is characterized adequately (water chemistry, hydraulic conditions), then it may be possible to use historical data or information from other local well installations or even databases to give corrosion data suitable for design purposes. In other environments, it may be necessary to rely on testing more extensively to establish the required corrosion data. These corrosion tests may comprise laboratory, field, and service studies.

Table 5-3. Guidelines for Selecting Well Screen Materials

Well Screen Material	Limits of Ryznar Stability Index for Material
Low-carbon Steel	Between 7.0 and 8.0
Armco Iron	Between 6.5 and 8.0
Silicon Red Brass	Between 6.0 and 8.5
Everdur Bronze	Less than 9.0
Super Nickel	Less than 9.0
Monel 400	Less than 9.5
Type 304 Stainless Steel	Less than 12.0
Type 304 ELC Stainless Steel (Extra Low Carbon)	Less than 15.0
Type 316 Stainless Steel	Less than 15.0
Type 316 Stainless Steel (Extra Low Carbon)	Less than 18.0

Source: Mogg (1972); reproduced with permission from Wiley

5.6.2.1 Laboratory Tests These comprise studies where both the material and the environmental conditions that would occur in the water-well installation have been simplified and controlled. These types of studies are useful particularly for comparative studies of different materials, protective schemes, or environmental variables.

5.6.2.2 Field Tests In these studies, the environmental conditions are more representative of the conditions to which a material would be exposed during service. However, for testing environments within the water well, which are not very accessible (e.g., well screen, sump), some tests may be undertaken at the discharge head, which may have different environmental conditions. These studies utilize test specimens (e.g., metal sections or coupons) of the material of interest rather than actual components. Therefore, environmental conditions that act on the actual component (e.g., stress) may not normally be accounted for in the field test. An example of a field test is described in McLaughlan (2002) and McLaughlan and Stuetz (2004).

The following is a brief description of a downhole coupon test procedure for different metal coupons placed in a water well to determine corrosion tendencies. The procedure utilizes the five most commonly used casing and screen materials.

Field Coupon Testing Downhole coupon testing to determine optimum casing and screen materials should be conducted over at least a 1-year period in a well that is not pumped. It is recommended that three sets of coupons be installed in the well consisting of the following metals:

1. Mild steel,
2. Copper-bearing steel,
3. High strength–low alloy (e.g., Corten),
4. 304 stainless steel, and
5. 316L stainless steel.

The three sets should be submerged in a rack assembly (made out of 316L stainless steel) and each set (i.e., five coupons) should be pulled periodically from the well during the 1-year period. Each sample set should be photographed, the scale removed, and samples weighed and compared against their original weights to calculate the amount of metal lost to corrosion during the period submerged.

5.6.2.3 Service Tests This comprises evaluating the performance of a material in service. It could comprise keeping operational and maintenance records on the water well and reconciling this with a detailed and critical examination of the component of interest at periodic inspections during service or at failure. For pumping equipment, this may entail examination during removal of the equipment from the well. For the well casing, periodic inspections may involve well inspections using downhole closed circuit television cameras (CCTV) or geophysical equipment.

5.6.2.4 Electrochemical Measurement The conventional method of using weight-loss measurement to establish corrosion rates is tedious and may involve difficulties in retrieving specimens during ongoing field monitoring. Electrochemical methods allow the measurement of instantaneous corrosion rates.

5.6.3 Standards

Various standards abound that are relevant, particularly for the design of corrosion control devices and corrosion measurement. These have been developed by NACE and ASTM. Some relevant standard test methods are as follows:

- ASTM D2688-94 (1999) Standard Test Methods for Corrosivity of Water in the Absence of Heat Transfer (Weight Loss Methods),
- ASTM G31-72 (2004) Standard Practice for Laboratory Immersion Corrosion Testing of Metals,
- ASTM G44-99 (2013) Standard Practice for Exposure of Metals and Alloys by Alternate Immersion in Neutral 3.5% Sodium Chloride Solution,
- ASTM G46-94 (2013) Standard Guide for Examination and Evaluation of Pitting Corrosion, and
- NACE TM0169 (2000) Laboratory corrosion testing of metals.

5.6.4 Resources

The Internet provides a vast resource of material that can be useful. Several useful sites are indicated following:

- Corrosion Doctors: http://www.corrosion-doctors.org
- Material Property Data: http://www.matweb.com/search/searchsubcat.asp
- ASTM Standards: http://www.astm.org.

5.7 EVALUATION OF CORROSION RATE DATA

Corrosion data represent unique interactions between a material and its environment. Although some data can be generalized into quantitative relationships, other data may need to be used in an empirical manner because of the complexity of the processes or environmental variables involved. The accuracy of those data in representing the conditions for a specific water-well installation needs careful consideration. This becomes particularly important if the data are collected from a database rather than from site-specific tests at the location where the data will be used. Whereas some types of corrosion data, such as uniform corrosion with specific concentrations of dissolved ions and uniform flow, may be somewhat easier to adapt for another environment, other data, such as crevice corrosion or pitting of stainless steels, may be more difficult. The following factors should be considered (Anderson 1992) in evaluating corrosion data:

- Material involved, including composition, metallurgical condition, surface condition and mechanical properties,
- Environment and the exposure conditions within the environment with particular emphasis on the time dependent environmental conditions at the material/environment interface,
- Corrosion test method used,
- Methods and measurement techniques used to describe these components, and
- Delineation of controlling factors with respect to specific forms of corrosion for the material and environment of interest.

5.7.1 Weight Loss and Penetration Calculations

The most frequently used method of appraising corrosion rate is either weight loss (e.g., $g/m^2/day$) from a test specimen or penetration rate (e.g., mm/year). Conversion factors between these units are available (see Table 5-4).

When interpreting these data, it needs to be recognized that the corrosion rate is not always constant but often decreases in time. Therefore, the rate measured may be unique to that exposure period. Another limitation of this measurement is that it assumes that the corrosion is uniform and occurs evenly over the whole surface of the test specimen. This will not be the case where localized corrosion involves pitting or crevice corrosion.

5.7.2 Exposure Period

There are little published data on long-term corrosion rates in groundwater. Data found generally for mild steel in natural water indicate that the corrosion rate is not constant with time but usually decreases as the length of exposure increases. A long-term, field-based immersion test

Table 5-4. Unit Conversions for Corrosion Rates of Metals

	Factor for Conversion to					
Unit	mdd	g/m^2/d	μm/yr	mm/yr	mils/yr	in./yr
mdd	1	0.1	36.5/*d*	0.0365/*d*	1.144/*d*	0.00144/*d*
g/m^2/d	10	1	365/*d*	0.365/*d*	14.4/*d*	0.0144/*d*
μm/yr	0.0274*d*	0.00274*d*	1	0.001	0.0394	0.0000394
mm/yr	27.4*d*	2.74*d*	1000	1	39.4	0.0394
mils/yr	0.69*d*	0.069*d*	25.4	0.0254	1	0.001
in./yr	696*d*	69.6*d*	25400	25.4	1000	1

Notes: mdd = milligrams per square decimeter per day; μm/yr = microns per year; g/m^2/d = grams per square meter per day; mils/yr = mils per year; mm/yr = millimeters per year; in./yr = inches per year; *d* = metal density in grams per cubic centimeter, where carbon steel = 7.85 g/cc^3 and Type 316 stainless steel = 8.03 g/cc^3.
Source: Wranglén (1985); reproduced with permission from Springer

using corrosion coupons was undertaken at 24 sites across Australia. The corrosion rate of mild steel at many of the sites ranged between 0.1 to 0.3 mm/year. However, under extreme conditions that rate increased by up to a factor of 3. Stainless steel was found to have minimal corrosion under the same conditions. Galvanized steel was found to offer minimal protection compared with mild steel when the pH was below 7 (McLaughlan and Stuetz 2004). In a field study in seawater, Phull et al. (1997) found that the average corrosion rates were similar at 6 months and 1 year (168 and 172 μm/year), decreasing to 117 μm/year after 3 years and 107 μm/year after 5 years. However, there was no simple trend with time across all test sites studied.

5.8 PROTECTIVE MEASURES FOR CORROSION

The major design choices that can have a significant effect on corrosion within the well are well screen placement, casing, well screen material selection, casing thickness, gravel pack choice, and operational factors that will influence the corrosion rate.

5.8.1 Casing Design

Inappropriate selection of materials or structural design of water wells can lead to the creation of corrosive environments within a water well installation.

One potential area for corrosion is near the joint between the mild-steel casing and stainless-steel screens. In particular, long sections of stainless-steel screens that are connected to a short section of mild-steel casing can cause the more corrosion-resistant stainless steel to act as a cathode and less corrosion-resistant mild steel to act as an anode and thus corrode rapidly. The larger the ratio of the area of the cathode (screen) to the anode (casing), the greater the corrosion rate. Roscoe Moss Company (1990) suggests that the mild-steel section should be at least two times the thickness of the stainless-steel section and its length at least three times its diameter. An alternative approach for short spacers between well screens is to use stainless-steel sections. Welded joints on well screens or between sections of casing are areas where corrosion may occur.

The design of the gravel pack can influence the extent of external casing corrosion from the soil and aquifer. When inappropriate material is used to backfill around the casing, then conditions conducive to soil corrosion may be set up. In these cases, cement should be used to insulate the external surface of the casing.

5.8.2 Material Selection

The selection of ferrous materials for water well construction in potable groundwater is limited when issues related to structural integrity, corrosion resistance, availability, and economics are taken into account. In potentially corrosive environments, it is important to consider well design and material selection, because the well is a permanent structure, and little can be done to change the design or materials after construction.

Mild-steel casing generally is used for the well casing, whereas a choice of mild steel or various stainless steels (type 304 or type 316L) are used for well screens. There are few reported studies about field-based corrosion rates specific to groundwater environments. However, some general corrosion data from other environments can be a useful guide for design purposes. Under long-term immersion in freshwater, the corrosion rate of carbon steel often is stated to be between 0.1 and 0.2 mm/year. Corrosion rates of carbon steel in seawater often are reported in the range of 0.075 to 0.2 mm/year for exposure times of at least 6 months (Phull et al. 1997). Caution must be used with these types of rates as they are averaged over the surface of the metal corrosion coupon. When corrosion is localized in pits, the rates are much higher over a small area and can lead to structural failure earlier than expected based on average or uniform corrosion rates.

Stainless steels are used where a higher degree of corrosion resistance is required. Stainless steels rely on a passivating film for their corrosion resistance. When this passivity is maintained, they exhibit extremely low corrosion rates. However, when it is destroyed, stainless steels will corrode at rates similar to a carbon or low-alloy steel. It is, therefore, important to select an appropriate grade of stainless steel based on its corrosion resistance. In freshwaters (e.g., <600 mg/L TDS) type 304 stainless steel has been found to give excellent results. It has a lower resistance to pitting by chloride ions than type 316L stainless steel because of the lower molybdenum content. In more saline and extreme environments, other materials need to be considered. Forward and Ellis (1994) found that in saline groundwater (e.g., 20,000 mg/L TDS) type 316L stainless steel generally was adequate for pump equipment and screens, whereas the more expensive type 904L stainless was necessary when hydrogen sulfide was present. Zinc-free bronze pumps also can provide good results with the option of coating with epoxy if problems arise.

Nonferrous materials (thermoplastic, fiberglass) are being used increasingly for water-well construction. These are particularly suited for use in corrosive environments where the wells are less than 300 m deep.

5.8.3 Groundwater Well Operating Conditions

The operation of a groundwater well can have a significant effect on the environmental conditions within the well and, hence, the corrosion rate. Frequent pump cycling creates alternate wetting and drying conditions within the splash zone of the casing, which can exacerbate corrosion. Overpumping can increase the flow rates across metal surfaces in the well screen and pump, increase particle migration through the gravel pack, and create turbulence and cavitation. In extreme cases, well screens may be dewatered, which creates oxygenated wet films that promote corrosion.

5.8.4 Protective Coatings

Protective coatings prevent the contact of corrosive waters with a metal surface, but there has been little use of protective coatings on well casings. An abrasion of the coating creates a bare spot ("holiday"), which becomes anodic to the rest of the protected casing. The corrosion rate at this spot is much greater than if there was no protective coating. The coating of only the anodic areas is not recommended due to the possibility of preferential corrosion. The cathodic areas also should be coated. Problems with the abrasion of coatings can occur during casing handling and installation. The surfaces also are vulnerable during well equipment removal and other operations inside the well.

5.8.5 Cathodic Protection

Cathodic protection is used widely in water and oil industries to mitigate the effects of corrosion on pipelines, gas and oil well casings, and storage tanks. However, there have been no widely reported applications to groundwater well casing.

Cathodic protection eliminates the current flow among various parts of a structure. It does this by providing a flow of electrons to a surface and thus creating a cathode, which does not become corroded. The amount of current needed to keep the structure in a protected or cathodic state depends on the environment, such as soil resistivity and casing to soil potential.

There are two sources of cathodic protection current:

- Sacrificial anodes made of zinc, magnesium, or aluminum that can be considered as current drains, and
- Impressed current, where an electric generator creates a direct current (D.C.) positive output to the anode and negative output to the well casing.

Cathodic protection works on surfaces that are in a direct line with the anode. Separate systems are required for external and internal casing surfaces and for intervals of the riser pipe. Incrustation can occur on a cathodic surface, which is a consideration when designing a system for the protection of well screens.

There are difficulties associated with obtaining good electrical contact between sacrificial anodes and internal casing surfaces. Adequate surface preparation is much easier for pump columns. Cathodic protection has found most applications in external casing and storage tank corrosion control.

Protective coatings have been found useful in controlling external corrosion on riser pipes under moderately corrosive conditions. Areas that are particularly vulnerable are around the threaded joints and near the pump-riser pipe connection. When a threaded pump column is screwed together, the riser pipe surface near the joints often is roughened, and the protective coating damaged by the tools used to grip the pipe. Adhesive tapes offer a quick and easy method to coat a pipe and are useful especially around areas that have to be disassembled periodically. The threaded joints should be coated with a hardening thread compound that will exclude water from the joint reducing crevice corrosion. This is important, because once a continuous pathway through the joint into the well is established, then fluid jetting can enlarge the opening rapidly. Coal tar-based products have been used widely as a coating on riser pipes, although there may be problems with the leaching of hydrocarbons into the groundwater. Galvanized steel has a coating of zinc and other coatings that preferentially corrode and then protect the metal underneath. Where highly corrosive conditions occur, then the use of PVC riser pipe or reinforced plastic hoses and the use of submersible pumps is desirable.

5.9 TROUBLESHOOTING FOR WELL CORROSION

5.9.1 Water Quality Indicators

Analysis of pumped water samples can give an indication of the processes occurring within a pumping well. A change in the concentration of specific water quality indicators can be used to indicate whether corrosion processes are operating. The most important water quality indicator is the level of ferrous iron (Fe^{2+}) in the water. Because groundwater can have significant concentrations of Fe^{2+}, it is necessary to establish that the source of dissolved iron is from the corrosion of the casing rather than from the aquifer. This may be established by comparing water samples with other wells from the aquifer and establishing trends through time. Increases in other parameters, such as turbidity, also may be indicative of corrosion. The accuracy of this approach relies on the corrosion products being dislodged by the pumped water and then measured at the discharge head. Very localized corrosion pitting is difficult to detect, whereas more uniform corrosion across a larger surface will produce more corrosion byproducts and may be detected. Corrosion products are most likely to be dislodged during pump startup due to the change in flow rate. However, if the well is subjected to biofouling, then changes in the dissolved iron concentration may be attributable to mobilizing these deposits. Changes in other water quality parameters (e.g., pH, Eh, electrical conductivity, major cations and anions) can indicate corrosion of the well casing has allowed water from different aquifers into the well.

5.9.2 Well Inspection

Well casing cannot be inspected directly; thus, it is necessary to use geophysical methods or a downhole video camera. A downhole video camera provides a visual log of the internal casing condition. Sometimes it can be difficult to obtain good quality logs due to water conditions and the limitations of the video equipment. Although a black and white log may be suitable to identify massive failure of casing, lack of color can make distinguishing between casing scale and casing pits difficult. Color cameras often are preferable.

Turbid water often may occur in corroded or biofouled wells due to the dislodgement of deposits during pump removal. Chemical agents, such as Calgon, may work or the well can be back-flushed with water from the surface. It may even be desirable to brush or chemically treat the casing before the inspection to identify hidden corrosion points. Particular attention during the video inspection should be given to sections of the casing identified as likely to have accelerated corrosion. This can include welded and screw casing joints, mild-steel casing connected to well screens, sections of casing where deposits have formed, pumping water line, well screens, splash zone, and well sump.

5.10 SOLVED DESIGN EXAMPLE 1

The following design example is presented with permission from the City of Ontario, San Bernardino County, CA, and is based on a case study performed for the city by Geoscience Support Services, Inc., Claremont, CA. The material for the design example was summarized by Dennis E. Williams.

5.10.1 Background

A corrosion field test of steels commonly used in well casing and screens has been conducted for the City of Ontario's Well No. 18. The purpose of the testing was to determine the most appropriate material for new wells located within the City of Ontario's boundaries. The test was conducted from May 2003 to May 2004 and consisted of placing metal coupons at a depth of 950 ft (568 ft below the static water level) in Well No. 18 and observing corrosion rates over time. Specifically, the study involved

- Installation of metal coupons in Well No.18,
- Retrieval of the coupons after various exposure times,
- Calculation of corrosion rates from measurements of loss of coupon weights,
- Depth-specific water quality and scale sampling,
- Analysis of water quality and scale for corrosion and microbiological parameters,
- A flowmeter survey to determine variation of vertical flow in the well, and
- A comparison of construction and rehabilitation costs for three different well designs.

5.10.2 History of Well No. 18

Various corrosion-related problems over the years prompted the City of Ontario to evaluate the optimum well casing and screen materials to use for future wells. The City of Ontario's Well No. 18 was selected for this study because it was not in operation (i.e., the pump had been removed). According to the well log, Well No. 18 was originally drilled in 1926 to a depth of 1,035 ft and completed with 20 in. double-wall "stovepipe" casing and perforated with a Mills knife (common construction for cable tool wells of that period).

A video, along with geophysical and flowmeter surveys, were performed by Pacific Surveys of Claremont, CA, in April 2003. The geophysical survey consisted of temperature, fluid resistivity, and fluid electrical conductivity measurements. The temperature survey indicated a steady temperature increase from approximately 71.5°F, at the static water level (382 ft below ground surface [bgs]), to 73.5°F, where flowing water was observed at 550 ft bgs. Fluid electrical conductivity also decreased in this interval.

The video survey showed that some perforations appeared enlarged (possibly as the result of the Mill's knife perforation procedure), and cobbles in the native formation material were observed through the perforation openings. The presence of scale also was observed from 360 ft bgs and increased with depth. Water appeared to be flowing downward between 545 to 549 ft bgs. The presence of flowing water in the well reflects a downward vertical hydraulic gradient (i.e., water is moving from the upper portion of the well to the lower portion). However, the temperature and electrical conductivity gradient in the lower portion of the well indicated stagnant conditions below 700 and 850 ft bgs. This was an important finding, because it is well known that corrosion is more prevalent under stagnant water conditions. Groundwater samples from Well No. 18 showed that the water was a calcium-bicarbonate type.

5.10.3 Downhole Coupon Testing

Coupon testing is a simple in situ (i.e., downhole) method of determining corrosion rates on various types of metals. In this method, a set of metal samples with different chemical compositions (i.e., coupons) were manufactured to specific dimensions (2 in. × 3/4 in. × 1/8 in.), and the initial weights, surface area, and density of the coupons recorded. Coupons can be manufactured with a variety of finishes, including a mill finish or grit-sanded using a 120 grit belt, and with autogenous welds. The coupons were mounted on a stainless-steel rack, separated by Teflon spacers, and submerged in the well for a specified time (i.e., *exposure period*). At the end of each exposure period, coupons were retrieved, grit-sanded (to remove all corroded metal), and weighed to determine the mass of metal lost. The metal loss rate in terms of thickness over time, measured in mils/year (1 mil = 1/1,000 in. = 0.0254 mm), was determined by dividing the mass of metal lost by the density, final surface area of the coupon, and exposure time.

For the downhole coupon testing, four sets of metal coupons were made. Each set consisted of five different steel types. Three sets were placed in the well for the corrosion testing, and one set was used for background or "reference" samples. The metal coupons used in this study were manufactured from five steels commonly used in well casings and

Table 5-5. General Properties of Coupons Used in Well No. 18 Test

Steel Coupon Material	Description
C1010 Mild Steel	A high-strength, high-carbon steel
Copper-Bearing Steel	Provided by the Roscoe Moss Company, Los Angeles
Corten A Steel	A high-strength, low-alloy steel
304 Stainless Steel	A high-chromium, high-manganese steel
316L Stainless Steel	A high-chromium, high-manganese, low-carbon steel

Notes: Copper-bearing steel conforms to ASTM Specification A139, Grade B containing not less than 0.2% copper by ladle analysis.

For Corten A Steel, it should be noted that there are several types of high-strength, low-alloy steels (refer to ASTM standard A606-01). As such, the various types contain different percentages of alloys. For example, type 2 was used in this study. Type 4 contains additional alloying elements and provides a higher level of corrosion resistance.

screens: mild, copper-bearing, high strength–low alloy (Corten A), type 304 stainless, and type 316L stainless. The chemical compositions of the coupon materials are shown in Table 5-5.

All of the coupons except for the copper-bearing steel were manufactured by Metal Samples, Inc. of Munford, AL, and included an autogenous weld. (An autogenous weld is prepared without the use of filler metal.) The second coupon type (copper-bearing steel), was provided by the Roscoe Moss Company, Los Angeles, with a mill finish and brazed acetylene torch weld. Four sets of coupons composed of each of the five alloys were weighed and measured by Metal Samples prior to exposure. Table 5-6 summarizes details of the coupons and testing.

Three sets of metal coupons, each coupon set consisting of five different steel types, were mounted on a stainless steel rack (see Fig. 5-3) and submerged in Ontario Well No. 18 on May 20, 2003, at a depth of 950 ft bgs. The submergence depth was 568 ft below the static water level of 382 ft bgs. This depth was chosen on the basis of the geophysical and video surveys as a location where the water was stagnant and corrosion conditions favorable.

The first set of coupons (identified by number 1a) was removed on August 20, 2003, after an exposure time of 92 days. The first set (reinstalled on December 11, 2003, and identified by the number 1b) was removed on May 27, 2004, after an exposure time of 168 days. (As an added point of measurement and to simulate the effect of servicing and reconditioning wells, the first set of coupons was reinstalled on December 11, 2003, after

Table 5-6. Summary of Coupons Used in Ontario Well No. 18 Corrosion test May 20, 2003 to May 27, 2004

Coupon Set	Identification (ID) Number	Metal Type	Comments
1a	C1010W-1a	Mild Steel	First Sample Set
	1a	Copper-bearing Steel	Installed: May 20, 2003
	CORTAW-1a	High-strength, Low-alloy (Corten)	Removed: August 20, 2003
	304W-1a	304 Stainless Steel	Exposure Time: 92 days
	316LW-1a	316L Stainless Steel	
1b	C1010W-1b	Mild Steel	First Sample Set, Which Was Removed on August 20, 2003 and Reinstalled on December 11, 2003
	1b	Copper-bearing Steel	
	CORTAW-1b	High-strength, Low-alloy (Corten)	Installed: December 11, 2003
	304W-1b	304 Stainless Steel	Removed: May 27, 2004
	316LW-1b	316L Stainless Steel	Exposure Time: 168 days
2	C1010W-2	Mild Steel	Second Sample Set
	2	Copper-bearing Steel	Installed: May 20, 2003
	CORTAW-2	High-strength, Low-alloy (Corten)	Removed: December 11, 2003
	304W-2	304 Stainless Steel	Exposure Time: 205 days
	316LW-2	316L Stainless Steel	
3	C1010W-3	Mild Steel	Third Sample Set
	3	Copper-bearing Steel	Installed: May 20, 2003
	CORTAW-3	High-strength, Low-alloy (Corten)	Removed: May 27, 2004
	304W-3	304 Stainless Steel	Exposure Time: 373 days
	316LW-3	316L Stainless Steel	
4	C1010W-4	Mild Steel	Reference Coupons
	4	Copper-bearing Steel	Never Installed in the well
	CORTAW-4	High-strength, Low-alloy (Corten)	Exposure Time: 0 days
	304W-4	304 Stainless Steel	
	316LW-4	316L Stainless Steel	

Notes: Copper-bearing steel has no formal ID number, is made by California Steel Industries (Fontana, CA), and conforms to ASTM Specification A139, Grade B, containing not less than 0.2% copper by ladle analysis.

Sample set "1a," which was installed on May 20, 2003, and removed on August 20, 2003, was cleaned and reinstalled on December 11, 2003. After reinstalling, the sample ID designation changed from "1a" to "1b."

Fig. 5-3. Installing the test coupons in the coupon holder
Source: Courtesy: Dennis E. Williams, Goescience Support Services, Inc., Claremont, CA; reproduced with permission from City of Ontario, CA

being cleaned and measured by Metal Samples. The reinstalled first set of coupons, identified by number 1b, was removed on May 27, 2004, for an exposure time of 168 days.) The second set (identified by the number 2) was removed on December 11, 2003, after and an exposure time of 205 days. The third set (identified by the number 3) was removed on May 27, 2004, after an exposure time of 373 days. A fourth set of coupons (identified by the number 4) was not installed in the well but stored in corrosion-resistant containers for use as a reference set. At removal, each of the coupons was photographed with a binocular microscope and sent to Metal Samples, Inc., for cleaning and measurements. Fig. 5-4 shows the timeline of events surrounding the coupon rack installation and retrieval.

5.10.4 Depth-Specific Water Quality and Scale Sampling

Laboratory results from the sample obtained at 950 ft bgs were consistent with historical samples obtained during operation of this well. The Langlier Index calculated from water quality samples was 0.05 and

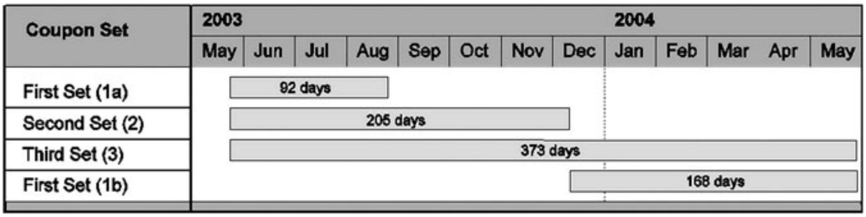


Fig. 5-4. Timeline of coupon testing, City of Ontario Well No. 18
Source: Courtesy: Dennis E. Williams, Geoscience Support Services, Inc., Claremont, CA; reproduced with permission from City of Ontario, CA

the Ryznar Stability Index was 7.43. These values indicate that the groundwater is potentially corrosive, especially for less corrosion-resistant material (e.g., mild steel). Although iron-related and slime-forming bacteria were identified in the groundwater sample, their populations were nonaggressive. Analysis of the scale collected from the well below 800 ft bgs, shows that it is mainly a product of corrosion and is not bacterially mediated or a product of carbonate encrustation.

5.10.5 Flowmeter Survey (Spinner Log)

The flowmeter survey showed downward vertical gradients between approximately 500 ft bgs to 700 ft bgs. However, the amount of flow could not be quantified because of the very low flow velocities. Results from the spinner log indicate that water below 700 ft is stagnant, and the casing below this depth may be more susceptible to increased corrosion when the well is idle for long periods (e.g., months). Note: Wells that stand idle typically require redevelopment when recommencing pumping due to biofouling or scale deposits. Industry experience has shown that wells with regular pumping cycles and an appropriate maintenance program provide high efficiencies for many years without problems. A maintenance program should include periodic testing for well efficiency and comparison against the original value to gauge the degree of production loss. Subsequent improvement of this production loss typically employs both mechanical and chemical redevelopment.

5.10.6 Coupon Test Results

Metal loss rates, mpy (mils/year), as calculated from the coupon tests after an exposure time of 373 days are summarized as follows:

- Mild steel: 2.7256 mpy,
- Corten steel: 2.6894 mpy,

- Copper-bearing steel: 2.2422 mpy,
- 304 stainless steel: 0.0155 mpy, and
- 316L stainless steel: 0.0090 mpy.

where 1 mil/year = 0.001 in./year

Fig. 5-5 summarizes the coupon test period and results for the copper-bearing steel samples. Fig. 5-6 summarizes test results in terms of metal loss rate versus time for five test coupons:

- Mild steel chart code–C1010W,
- Copper-bearing steel,
- High-strength–low alloy (Corten) chart code–CORTAW,
- Type 304 stainless steel chart code–304W, and
- Type 316L stainless steel chart code–316LW.

In general, the less corrosion-resistant alloys experienced significant corrosion, whereas the stainless-steel alloys had very little corrosion. The long-term corrosion resistance can be determined by comparing the corrosion rates of the third set of coupons (exposure time of 373 days). Corrosion rates also decreased over time, most probably due to the buildup of a passive-resistance layer that protects the metal from corrosion to a certain extent.

5.10.7 Cleaning and Reinstalling the First Set of Coupons

As noted earlier, the first set of coupons (labeled 1a) was reinstalled after cleaning by grit-sanding and remeasuring. This was done at the request of the city to simulate the effect of servicing and conditioning of the well. Results show that corrosion rates for the reinstalled sample set (labeled 1b) were lower than the corrosion rates for the first set (1a) and the second (2) even though the second set had a longer exposure time. One explanation is that the "grit" finish applied to the samples after cleaning provided a more corrosion-resistant layer than the original mill finish.

5.10.8 Effect of Metal Loss on Casing Collapse Strength

The long-term metal loss rate can be used to predict the loss of casing collapse strength at any given future time. Multiplying the long-term corrosion rate by a given period of time yields the future thickness and outside diameter of well casing. This information can be used in Timoshenko's equation (see Roscoe Moss Company 1990) for collapse strength of well casing.

Assuming an average useful life expectancy of a municipal well of approximately 30, 60, or 90 years, the long-term corrosion rate from the third set of coupon samples (373 day results) was used to calculate future

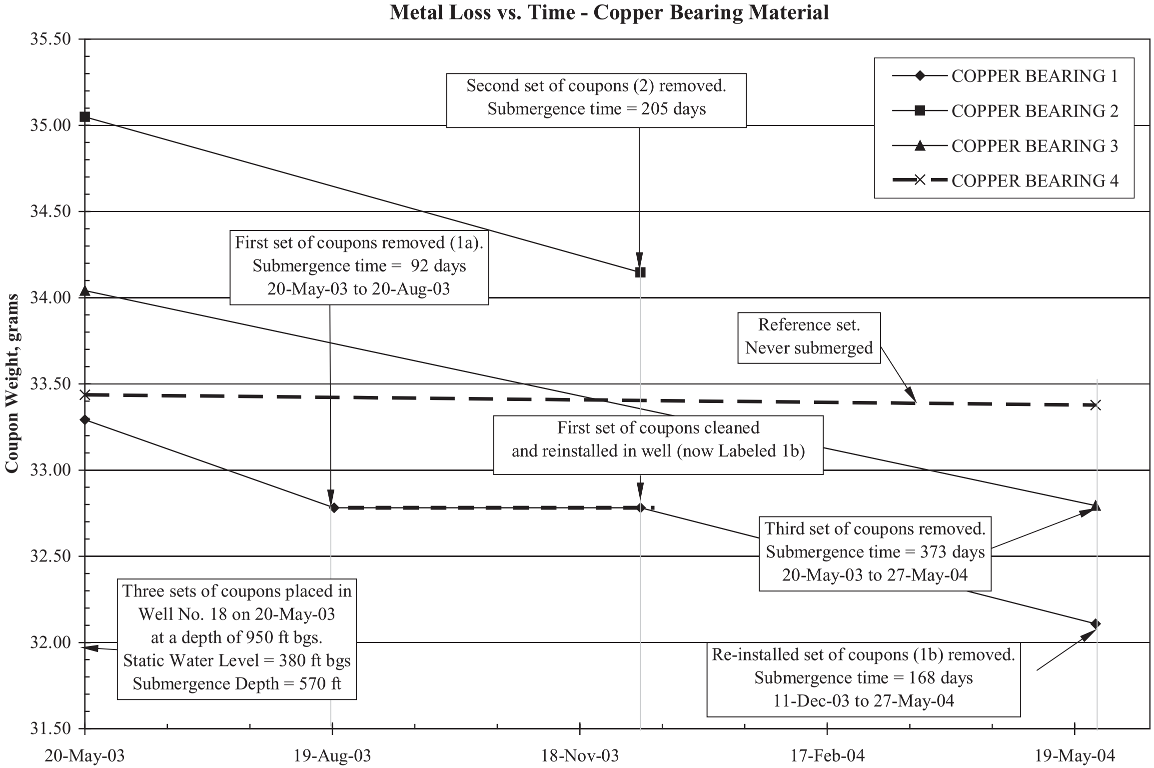
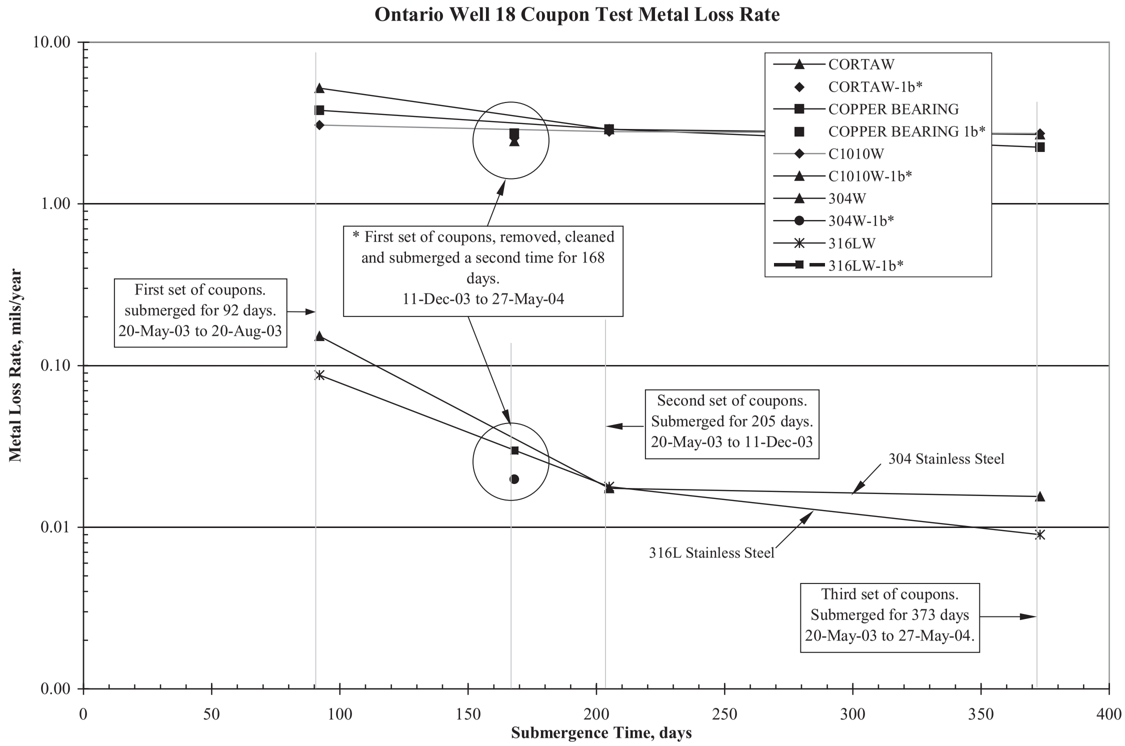


Fig. 5-5. Metal loss versus time for copper-bearing material
Source: Courtesy: Dennis E. Williams, Geoscience Support Services, Inc., Claremont, CA; reproduced with permission from City of Ontario, CA



* Coupon ID's numbered 1b are identical to the first set, but resubmerged after cleaning

Fig. 5-6. Metal loss versus time, City of Ontario Well No. 18
Source: Courtesy: Dennis E. Williams, Geoscience Support Services, Inc., Claremont, CA; reproduced with permission from City of Ontario, CA

reduction in wall thickness and outside diameter (OD). Table 5-7 shows the initial casing collapse strength for the five metal alloys used in the coupon test and the casing collapse strength after 30, 60, and 90 years of exposure.

As can be seen in the table under the predicted corrosion rates, stainless steel suffered almost no loss of strength, whereas the collapse strength of less corrosion-resistant alloys reduced to 45 to 53% of the original collapse strength after 30 years.

5.10.9 Cost Comparisons for Different Well Design Materials

To make a useful recommendation regarding the selection of casing material, a cost comparison of well construction and maintenance was performed between three different well designs consisting of the following casing and screen material (Fig. 5-7):

1. All copper-bearing blank casing and copper-bearing louvered screen,
2. A combination consisting of copper-bearing blank casing in the upper half of the well and stainless steel louvered screen in the lower half of the well, and
3. All stainless-steel blank casing and stainless-steel louvered screen.

The cost comparison was divided into two sections including initial construction costs and rehabilitation costs and was performed for three time periods after initial construction of the well (30, 60, and 90 years). The future value of construction and rehabilitation costs was calculated on the basis of a 3.0% annual inflation rate (personal communication, Construction Finance Department, IndyMac Bank 2004). The cost comparison parameters and calculations are shown in Table 5-8.

5.10.9.1 Summary of Cost Comparisons The costs of well construction and rehabilitation for each of the three well designs over the 30-, 60-, and 90-year periods were totaled and compared to the all-copper-bearing steel well design (Table 5-9). At the end of the 30-year period, both the combined copper-bearing/stainless steel and all stainless-steel wells cost less than the all-copper-bearing steel well. The difference in cost extended over the 60- and 90-year periods showed that the combined copper-bearing/stainless steel and all-stainless-steel wells cost less than or half as much as the all-copper-bearing steel well. Fig. 5-8 shows the comparisons.

5.10.10 Findings and Design Recommendations

5.10.10.1 Findings Ontario Well No. 18 originally was drilled in 1926 to a depth of 1,035 ft and completed with 20 in. casing (common

Table 5-7. Collapse Strength of Metal Alloys after 30, 60, and 90 years of Exposure

Casing Material	I.D. [inches]	Wall Thickness [inches]	O.D. [inches]	Original Collapse Strength [ft of water]	Long Term Corrosion Rate [mils/year]	Predicted Metal Loss [inches]	Future Wall Thickness [inches]	Future O.D. [inches]	Future Collapse Strength [ft of water]	Percent of Original Collapse Strength
After 30 Years										
C1010W	20	0.3125	20.6250	364	2.7256	0.0818	0.2307	20.5432	163	45%
COPPER BEARING	20	0.3125	20.6250	364	2.2422	0.0673	0.2452	20.5577	192	53%
CORTAW	20	0.3125	20.6250	364	2.6894	0.0807	0.2318	20.5443	165	45%
304W	20	0.3125	20.6250	343	0.0155	0.0005	0.3120	20.6245	341	100%
316LW	20	0.3125	20.6250	343	0.0090	0.0003	0.3122	20.6247	342	100%
After 60 Years										
C1010W	20	0.3125	20.6250	364	2.7256	0.1635	0.1490	20.4615	49	13%
COPPER BEARING	20	0.3125	20.6250	364	2.2422	0.1345	0.1780	20.4905	80	22%
CORTAW	20	0.3125	20.6250	364	2.6894	0.1614	0.1511	20.4636	51	14%
304W	20	0.3125	20.6250	343	0.0155	0.0009	0.3116	20.6241	340	99%
316LW	20	0.3125	20.6250	343	0.0090	0.0005	0.3120	20.6245	341	100%
After 90 Years										
C1010W	20	0.3125	20.6250	364	2.7256	0.2453	0.0672	20.3797	5	1%
COPPER BEARING	20	0.3125	20.6250	364	2.2422	0.2018	0.1107	20.4232	21	6%
CORTAW	20	0.3125	20.6250	364	2.6894	0.2420	0.0705	20.3830	6	2%
304W	20	0.3125	20.6250	343	0.0155	0.0014	0.3111	20.6236	339	99%
316LW	20	0.3125	20.6250	343	0.0090	0.0008	0.3117	20.6242	340	99%

Table 5-8. Summary of Cost Comparison for Three Different Well Designs

			Casing and Screen Materials			
Item No.	Cost Description	Units	All Copper-Bearing Steel Blank Casing and Screen	Hybrid Copper-Bearing Steel Blank Casing with Stainless Steel Screen[1]		All Stainless Steel Blank Casing and Screen
Well Construction Parameters				**Casing**	**Screen**	
1	Casing Wall Thickness	in.	5/16	3/8	5/16	5/16
2	Casing Inside Diameter	in.	20	20	20	20
3	Casing Outside Diameter	in.	20 5/8	20 3/4	20 5/8	20 5/8
4	Casing Length	ft	1,000	500	500	1,000
5	Perforated Length of Casing	ft	500	0	500	500
6	Casing Weight per Foot	lbs/ft	67.793	81.602	69.380	69.380
7	Total Casing Weight	lbs	67,793	40,801	34,690	69,380
Well Construction Costs						
8	Price of Blank Casing per Pound of Steel	$/lb	$0.96	$0.96	$3.00	$3.00
9	Cost of Blank Casing	$	$65,081	$39,169	$104,070	$208,140
10	Price of Perforations per Foot	$/ft	$50			
11	Cost of Perforations	$	$25,000			
12	Price of Mechanical Connector[1]	$	N/A	$5,000		N/A

Continued

Table 5-8. Summary of Cost Comparison for Three Different Well Designs (*Continued*)

			Casing and Screen Materials		
Item No.	Cost Description	Units	All Copper-Bearing Steel Blank Casing and Screen	Hybrid Copper-Bearing Steel Blank Casing with Stainless Steel Screen[1]	All Stainless Steel Blank Casing and Screen
13	Total Cost of Casing and Screen	$	$90,081	$173,239	$233,140
14	Cost of Well Constuction Minus the Cost of Casing	$	$300,000		
15	Total Cost of Well Construction for One Well [In 2004 Dollars]	$	$390,081	$473,239	$533,140
16	Serviceable Life of Well	years	30	90	90
17	Number of Wells Required to be Drilled Over 30-Year Time Period		1	1	1
18	Total Cost of Well Construction Over 30 Years[2]	$	$390,081	$473,239	$533,140
19	Number of Wells Required to be Drilled Over 60-Year Time Period		2	1	1
20	Total Cost of Well Construction Over 60 Years[2]	$	$1,336,910	$473,239	$533,140
21	Number of Wells Required to be Drilled Over 90-Year Time Period		3	1	1
22	Total Cost of Well Construction Over 90 Years[2]	$	$3,635,112	$473,239	$533,140

Rehabilitation Costs					
23	Present Cost for Rehabilitation	$	$125,000		
24	Service Interval	years	5	10	10
25	Number of Rehabs. Required Over 30 Year Period		5	3	3
26	Total Cost of Rehabilitation Over 30 Year Period[2]	$	$995,131	$697,161	$697,161
27	Number of Rehabs. Required Over 60 Years		10	6	6
28	Total Cost of Rehabilitation Over 60 Years[2]	$	$3,410,575	$2,389,355	$2,389,355
29	Number of Rehabs. Required Over 90 Years		15	8	8
30	Total Cost of Rehabilitation Over 90 Years[2]	$	$9,273,491	$4,709,194	$4,709,194
Total Cost for Well Construction and Rehabilitation					
31	Total Cost Over 30 Years[2]	$	$1,385,212	$1,170,400	$1,230,301
32	Total Cost Over 60 Years[2]	$	$4,747,485	$2,862,594	$2,922,495
33	Total Cost Over 90 Years[2]	$	$12,908,603	$5,182,433	$5,242,334

Notes:

[1] The long-term reliability of the *Hybird Copper-Bearing Blank Casing with Stainless Steel Screen* design is not known.

[2] Dollars adjusted for inflation. Inflation rate used at 3% per year. Standard construction industry inflation rate, based on personal communication, Construction Finance Department, IndyMac Bank, August 24, 2004.

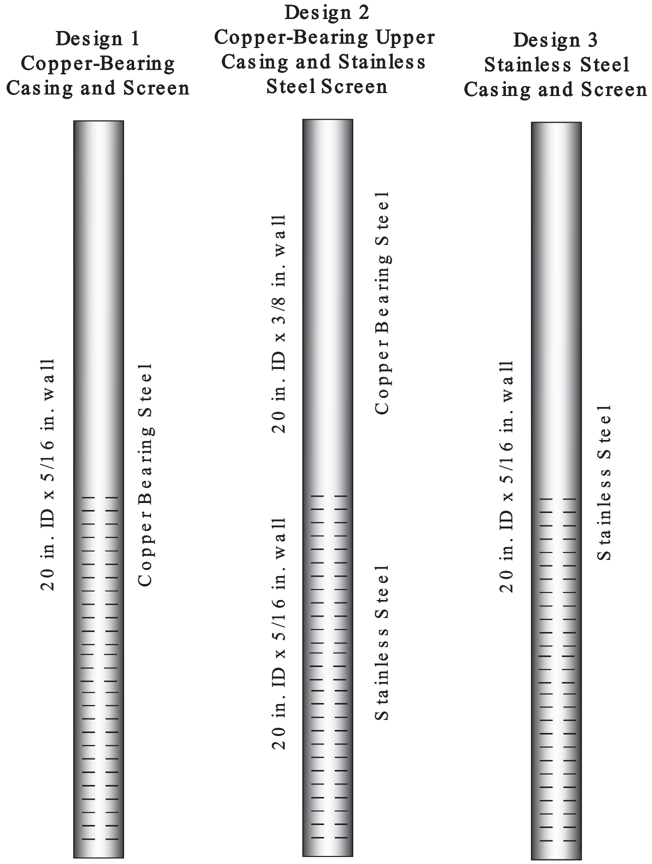


Fig. 5-7. Summary of proposed well designs
Source: Courtesy: Dennis E. Williams, Geoscience Support Services, Inc., Claremont, CA; reproduced with permission from City of Ontario, CA

construction for old cable tool wells). The well was acquired by the City of Ontario in 1963 and used for municipal water supply until 2000. To determine the most appropriate well casing and screen materials for future wells, the City of Ontario commissioned a corrosion investigation, which took place in the city's Well No. 18 between May 2003 and May 2004. The following are major findings from that investigation:

- Total depth at the time of the video log (April 4, 2003) was 1,013 ft bgs. Static water level at the time of the April 4, 2003, survey was 382 ft bgs; the presence of scale was observed at 360 ft bgs and increased with depth, and water appeared to be moving between 545 and 549 ft bgs.

Table 5-9. Summary of Well Construction and Rehabilitation Costs Over Time

	After 30 Years		After 60 Years		After 90 Years	
Well Design	Total Cost	Cost Savings Compared to Design 1	Total Cost	Cost Savings Compared to Design 1	Total Cost	Cost Savings Compared to Design 1
Design 1 - All Copper-Bearing Casing and Screen	$1,385,212	—	$4,747,485	—	$12,908,603	—
Design 2 - Copper-Bearing Casing/ Stainless-Steel Screen	$1,170,400	16%	$2,862,594	40%	$5,182,433	60%
Design 3 - All Stainless-Steel Casing and Screen	$1,230,301	11%	$2,922,495	38%	$5,242,334	59%

Hydraulics, of Wells Task Committee. Hydraulics of Wells : Design, Construction, Testing, and Maintenance of Water Well
Systems, edited by Nazeer Ahmed, et al., American Society of Civil Engineers, 2014. ProQuest Ebook Central, http://ebookcentral.proquest.com/lib/uts/
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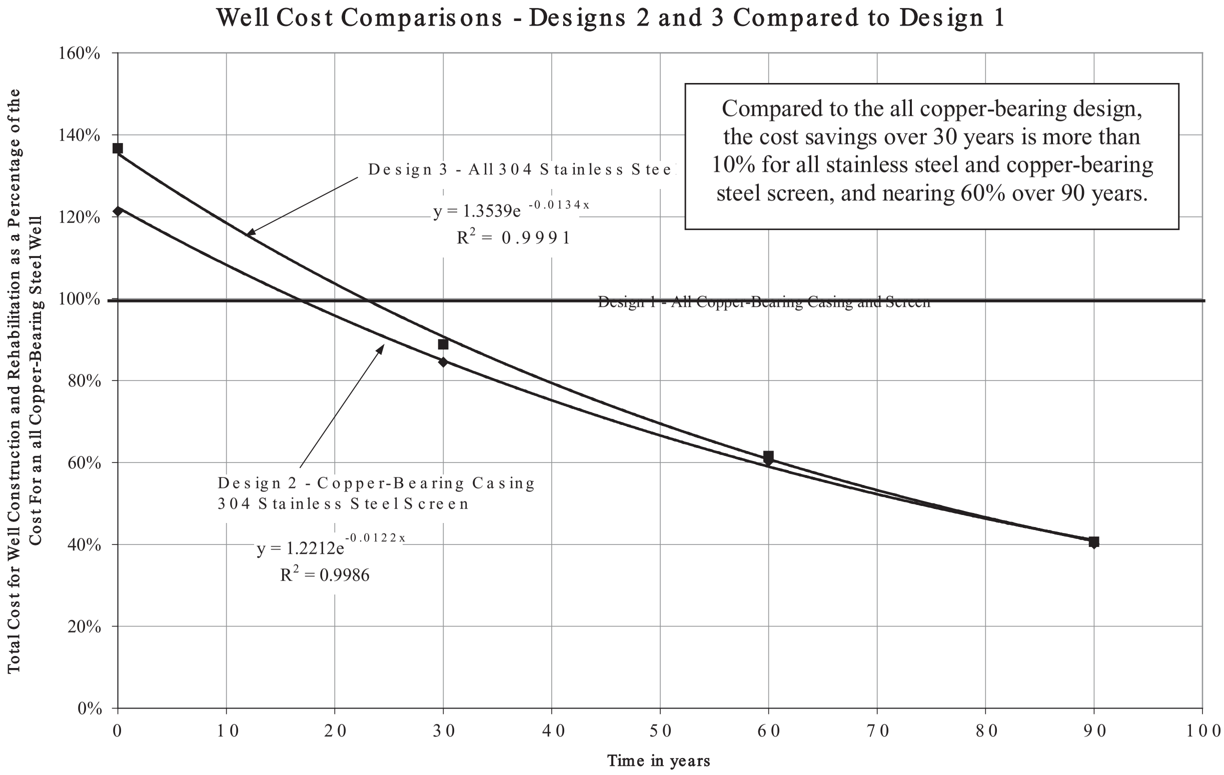

Compared to the all copper-bearing design, the cost savings over 30 years is more than 10% for all stainless steel and copper-bearing steel screen, and nearing 60% over 90 years.

Fig. 5-8. Well cost comparisons

Source: Courtesy: Dennis E. Williams, Geoscience Support Services, Inc., Claremont, CA; reproduced with permission from City of Ontario, CA

- The temperature and electrical conductivity gradient in the lower portion of the well indicated stagnant conditions below 700 to 850 ft bgs; this is supported by the flowmeter survey, which indicated that below 700 ft, water is stagnant and materials below this depth may be more susceptible to increased corrosion when the well is idle for long period (e.g., months).
- A Ryznar Index of approximately 7.5 was measured from water samples reflecting slightly corrosive conditions.
- Analysis of the scale collected from the well below 800 ft shows it to be mainly a product of corrosion and not bacterially mediated or a product of carbonate encrustation.
- Flowmeter survey data indicate downward vertical gradients between approximately 500 ft and 700 ft bgs.
- In general, the less corrosion-resistant alloys experienced significant corrosion, whereas the stainless-steel alloys had very little corrosion:
  - mild steel: 2.7256 mpy,
  - Corten steel: 2.6894 mpy,
  - copper-bearing steel: 2.2422 mpy,
  - 304 stainless steel: 0.0155 mpy, and
  - 316L stainless steel: 0.0090 mpy.
- Cleaning and reinstalling coupons show that corrosion rates for the reinstalled sample set were lower than the corrosion rates for the first set; one explanation is that the "grit" finish applied to the samples after cleaning provided a more corrosion-resistant layer than the original mill finish.
- Under the predicted corrosion rates, stainless steel suffered almost no loss of strength, whereas the collapse strength of less corrosion-resistant alloys reduced to 45 to 53% of the original collapse strength after 30 years.
- After 60 and 90 years, the well construction costs for the copper-bearing/stainless-steel and all-stainless-steel wells were less than half the cost of the all copper-bearing steel design.
- If during the life of the an all-copper-bearing steel well, only one replacement is necessary, then the use of the all-stainless-steel or the copper-bearing/stainless-steel designs are more cost effective.
- Water quality of potential future well sites should be evaluated and the corrosion indexes calculated (i.e., Ryznar Stability Index and Langlier Index).; should the water quality suggest potential for corrosion (as was found in Well No. 18), then the all-stainless-steel design is recommended.
- The relative costs savings using the copper-bearing/stainless-steel design and the all-stainless-steel design are approximately the

same over the all-copper-bearing design. However, due to some uncertainty with the copper-bearing/stainless-steel combination design over the lifetime of the well, the all type 304 stainless-steel casing and screen is recommended.

5.10.10.2 Design Recommendations Primarily based on results from the coupon study and cost comparisons, the city is considering using type 304 stainless steel for future casing and screen materials. This decision was made on the basis of reduced maintenance cost over less corrosion resistant materials and longer life expectancy. These two main factors, combined with the increasing difficulty in acquiring property for new well sites, has shown city planners that the use of a more corrosion-resistant material, such as type 304 stainless steel, is more beneficial on a long-term planning basis.

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