# Materials and Installation Requirements For Handling Corrosive Waters

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## INTRODUCTION

In the early period of the domestic oil industry, the handling of waters produced from the solution gas-drive reservoirs in the eastern fields was only a minor problem. However, with the development of water-drive production in the Gulf Coast fields, the materials and equipment for efficiently and economically disposing of produced water became of increasing importance. The expanded use of waterflooding during the past fifty years has further emphasized the necessity for suitable system design and proper materials.

The early period of waterflooding coincided with the time of major research on oil field corrosion and until the results of these studies were applied, frequent corrosion failures occurred in water-handling systems. As an example, in 1930 the expected life of tank roofs and bottoms, in one field handling sour crude oil and water, was a year and a half. A study of salt water disposal lines in eight Gulf Coast fields during the same period, indicated an average operating period of 11 to 40 months.

Although this paper refers specifically to handling of sour waters, the observations can, in general, be applied to any water-handling system. This statement is based on the fact that the corrosivity of water is principally a function of the dissolved oxygen. While acidic produced-waters are particularly corrosive when aerated, all waters when contaminated with air, induce a pitting-type corrosion that will usually result in rapid failure of iron or steel materials.

## SYSTEM DESIGN REQUIREMENTS

Waterflooding on a major scale began in the Permian Basin in the 1950 to 1960 period. It was recognized that with primary source waters and most produced waters being acidic and containing hydrogen sulfide, corrosion would be a problem. Another item of concern was whether sulfide stress cracking might be a source of difficulty. Table 1 lists pH, hydrogen sulfide and total solids in typical formation waters in the Permian Basin.

TABLE 1

TYPICAL PERMIAN BASIN INJECTION WATERS

| Formation or Field | Total Solids | pH | $H_2S$ |
|---|---|---|---|
| Hendricks Reef | 8,274 ppm | 6.32 | 179 ppm |
| San Andres — Lawson | 98,198 " | 5.68 | 1,282 " |
| Ellenburger | 50,484 " | 6.15 | 9 " |
| 5600'—Goldsmith | 203,530 " | 6.50 | 0 " |
| Devonian | 55,532 " | 6.15 | 272 " |
| Tubbs | 193,962 " | 5.90 | 0 " |
| Holt | 100,152 " | 6.85 | 656 " |
| San Andres — Goldsmith | 86,487 " | 7.00 | 870 " |
| McElroy | 19,261 " | 5.85 | 1,176 " |
| Waddell | 52,485 " | 6.90 | 970 " |

Initially it was assumed that removal of the hydrogen sulfide prior to injection would be desirable. One procedure investigated involved aeration of the water in a cooling tower arrangement. Although this eliminated most of the hydrogen sulfide, it also saturated the water with oxygen. This so drastically increased the corrosivity of the water that this approach was not practical.

Another method considered for removal of hydrogen sulfide was a submerged combustion system which was theoretically feasible. A pilot plant of the system, built and field-tested, indicated that control would be extremely difficult. Also, plant requirements for handling the volumes of water eventually required, made the method prohibitively expensive.

Laboratory studies and field tests on the corrosivity of both the primary injection and produced-waters were conducted during the same period. This work established that providing the waters could be maintained oxygen-free, the level of corrosion would not be as severe as had been originally anticipated. Also, the attack would be of a general nature rather than pitting. Based on these studies, it was decided that a closed design would be the most practical approach for injection of the Permian Basin waters. It was also recognized that special attention would be required in the selection of materials and protective coatings used to minimize corrosion.

## CLOSED SYSTEMS — PROBLEMS

The primary water source for the initial flooding operations was the Hendricks Reef. Water produced from the Reef went directly through the pump station to tank storage at the injection stations. Water produced with oil (field-produced waters) made up only a small percentage of the total fluid injection. This water was usually co-mingled with the reef water by periodic batching from the oil production batteries to the injection plant.

Primary emphasis in the design of the early systems was on the water supply facility, injection plant and injection wells. The waters from production facilities were not initially considered to be sources of significant problems. In many of the early installations, corrosion failure began to occur after unreasonably short operating periods. The corrosion was of the deep pitting type, typical of oxygen-contaminated waters. Reviews of systems where early corrosion was experienced, frequently disclosed a significant volume of water entering the systems from the production facilities. Also, corrosion problems were principally in the field water gathering systems and injection portion of the projects. With the major source of air contamination determined to be from the production side of the systems, studies were started to locate the source of the problem.

The initial study, started on the assumption that it would be of short duration, developed into a number of projects that continued over an extended period. The extended testing was attributable to the failure to recognize the large number of potential sources of air contamination in a closed-system water injection project. Some of the potential sources of air-entrance into closed systems between the producing and the injection well are discussed in the following paragraphs.

### Producing Wells

The producing well is not a usual source of air contamination, but under certain operating conditions air can enter the system at this location. When the flood becomes effective, maximum production requires maximum pressure draw-down in the wellbore. This is usually achieved by keeping the well pumped-off, and often the casing annulus is opened to the atmosphere to prevent trapping of gas with attendant build-up of back pressure.

This procedure will not cause difficulty during the period of low water cut. If, after water breakthrough, the wells are pumped-off with the casing onnulus open, air contamination of produced water can develop. Air, entering through the casing, will oxidize the short head of oil usually present in the annulus of a pumped-off well. This oil blanket then acts as a permeable filter allowing air to diffuse into the produced water. While this is an unusual source of difficulty, it has been encountered and should be investigated when air entrainment cannot be located at the more usual sources of leakage.

A more frequent source of leakage in high-water-cut wells that are pumped-off, is the polish rod stuffing box. When wells are over-pumped a slight vacuum can occur at the wellhead with each pump stroke. Under these conditions air will intermittently enter the well fluids unless the stuffing box is tight and has the type of packing that will hold a vacuum. This problem has occurred most frequently with the polish-rod stuffing box, but it could also occur in other packing-type seals between the wellhead and flowline check valve.

### Production Tank Battery

Water-handling equipment at the production tank batteries has been the most frequent source of air contamination of produced water. In early flooding operations, this was largely caused by failure to recognize the limited ability of oil blankets on water held in storage tanks, to prevent oxygen entering the water. In a system where the water has only a short storage interval in the tanks, a thick oil blanket, frequently replaced, is reasonably effective. However, in many early installations, oil carried-over in the produced water was considered adequate for blanketing the tanks. These inadequate blankets, coupled with the low water producing rates, resulted in the produced water being essentially saturated with oxygen and being highly corrosive when delivered to the injection plants.

After this problem was recognized, gas blankets were installed and this source of difficulty was largely eliminated. However, where batching of the produced water is at high pumping rates the control valves, pipe size and delivery pressure of the supply gas for the blanket must be considered. There have been a number of installations where the pumping rates of the water markedly exceeded the gas-replenishment capacity of the blanketing system and thus caused air to enter the system. If the gas supply is from a low-pressure separator with a high water-cut, gas availability must also be considered in sizing of the water transfer pumps, pumping rate and period of pumping.

## Transfer and Injection Pumps

Pump installations and methods of operation are probably the largest continuing source of air contamination in flood systems. This is generally caused by failure to recognize that, for a given set of pumping conditions, either a positive displacement or a centrifugal pump will endeavor to deliver a specific volume of fluid. When water is not available at the pump suction in adequate volume and at sufficient pressure, cavitation with accompanying partial vacuum occurs within the pump. With packing and shaft wear, air will be drawn into the pump to contaminate the water in the system.

This contamination is easily prevented once the problem is recognized and the pump system properly designed. Transfer pumps should be as close to the tank as possible. The suction piping should be of the same size or larger than the pump inlet port. Valves in the line should be through-ported and full-opening. Change of flow direction should be avoided as much as possible, i.e., ells, tees, etc. Where direction must be changed, 45° fittings or long-radius units should be used.

With a suction system as short as practical and properly sized, the only remaining major requirement is maintenance of adequate pressure for water movement. At production facilities the tank head is the usual pressure source for pump loading. The head requirement will vary with each installation and the pressure-head specifications of the pump manufacturer should be treated as a minimum requirement.

High-speed, high-pressure plunger pumps with rapid water charging rates and valving arrangements, are particularly susceptible to cavitation if suction head is not maintained. Several manufacturers suggest that even with oversized manifolding and minimum spacing between the pumps and tanks, a head of six to ten feet is desirable. Also, most manufacturers have suction-type, surge-dampening units available. These units, either built into the pump body or attached close to the suction, should be considered if there is any possibility that pump cavitation might occur.

## Injection System

If the water has been maintained air-free through the injection pump and a positive pressure is maintained to the formation, air contamination cannot occur in the injection system. However, several unusual instances occurred in early flooding of "stripper" operations. In one case where individual well injection-pressures varied from a vacuum to several hundred pounds per square inch, serious corrosion was noted in the wellheads of the wells on vacuum. In this system the injection water was maintained under pressure up to a flow regulator at the wellhead. After the flow regulator, the water passed through the water meter and into the well. The wellhead corrosion coupons exhibited the deep pitting-type attack typical of air-contaminated sour water. Because the wellheads were under vacuum, leaks at threads were suspected and the units were disassembled, threads cleaned and taped with Teflon and all gaskets replaced. The corrosion persisted, indicating the meter to be the source of leakage. Inspection of the meter showed the seal on the counter drive shaft to be of the self-energizing cup type. These provide an excellent low-friction seal under pressure, but under a low vacuum the seal will disengage from the shaft, permitting air entrainment in the injection water.

The corrosion problem most frequently encountered on the injection side of our systems is caused by failure to seal mating components. The slightest seep providing a continuous water phase between the atmosphere and the injection water will quickly corrode the joints. This is because oxygen dissolves into the water at the seep and diffuses into the wetted joint section. While the amount will not be of a significant quantity in the total injection stream, it will create an extremely corrosive fluid in the joint and quickly develop a significant leak. Absolute pressure-tight joints and sealing surfaces throughout the system are primary requirements for trouble-free operation.

Table 2 is a partial listing of potential sources of air contamination of injection waters in flood projects.

TABLE 2

POTENTIAL SOURCES OF AIR CONTAMINATION AND CORROSION PROBLEMS

| Producing Wells | Production Facilities | Injection Facilities |
| --- | --- | --- |
| Well Annulus | Produced Water Tank | Water Well Annulus |
| Polish Rod Stuffing Box | Inadequate Gas Blanket | Supply Water Tanks |
| Wellhead Valves | Inadequate Oil Blanket | Inadequate Gas Blanket |
| | Transfer Pump Piping | Injection Pump Manifold |
| | Transfer Pump Shaft Seal | Injection Pump Seals |
| | | Piping Joints & Seals |
| | | Water Meters (Vacuum Only) |
| | | Wellhead Valves (Vacuum Only) |

## PIPING REQUIREMENTS FOR HANDLING CORROSIVE WATER

Although the completely closed systems markedly reduced corrosion, the rates were still sufficiently high to require special consideration in the selection of materials used. Because of the size of many Permian Basin flood projects, steel was the only logical material for the large-diameter piping needed to handle the large volumes of pressurized water. However, with many projects having an anticipated operating life of from 15 to 20 years, protective coatings and linings were needed. The anticipated life of most of the flood projects also suggested that, where practical, the use of corrosion-resistant piping materials should be given careful consideration. This resulted in the widespread field testing of various types of plastic pipe. The following sections discuss experiences with various piping materials and linings used in water injection operations in the Permian Basin.

### Extruded Plastic Pipe

In many early water injection projects, attempts were made to use various extruded plastic pipe. Unfortunately, it was applied in many installations where it was not suitable for the pressure, pressure surge and temperature conditions. Although extruded plastic pipe should not be excluded from water injection projects, the limitations of this pipe must be carefully considered so that installation will be made only where the material is applicable. It should be recognized that almost all data on plastic pipe in trade brochures are based on test procedures of the American Sanitary Association Standards. The temperature base used in this standard is 73.4°F. One suggested operating temperature specification for this pipe for general oil field use would be 100°F. For this temperature the down-rating factor for the pipe will be approximately 0.6. With few exceptions, the extruded plastic pipe is also fatigue-sensitive under surging operations and must be further down-rated where pressure fluctuations occur. In general, our recommendation would be to consider extruded plastic pipe only in open-end systems, free of all surging, and then only after down-rating the specified operating pressure by 50 per cent.

### Glass Filament Wound Epoxy Pipe

During the past several years there has been a marked increase in the use of glass filament-epoxy pipe in water injection projects. The results to date have been extremely good and this pipe is our first choice where it meets systems requirements including pressure and cost considerations. The pressure ratings on this pipe are conservative. It does not corrode. It is easily installed and to date, only two relatively minor problems have occurred. In some early installations the epoxy binder has slowly degraded when subjected to the ultraviolet rays of the sunlight. This has resulted, after approximately five years, in the pipe beginning to seep and having to be replaced. Where such pipe is not buried or protected from direct rays of the sun, we recommend that it be painted. A recent development to prevent deterioration from ultraviolet radiation is the use of a pigmented epoxy and an inner surface sealing liner. These changes in manufacturing should minimize the problem, but this type of pipe has not been in operation long enough to be certain that the problem has been corrected. Another failure with this pipe has been separation of the tapered epoxy-cemented joints. In most instances this has probably been caused by improper joint cleaning or improper mixing of the epoxy cement. While we do not consider this to be a criticism of the pipe, it does point out that adequate supervision of field installation of this pipe is required.

### Plastic Liners in Steel Pipe

A number of plastic pipe liners have been developed for use in steel pipe. In one type, the inserted plastic tubing is molded directly to the next tubing section, eliminating the problem of sealing and protection at the pipe coupling. With several of the other systems, joint inserts and sealing combinations are used. Field experience with the liner type of systems has been inconsistent. In a number of the installations, we have had very good service. In other instances, we have experienced either frequent joint failures or collapse of the plastic liner. From engineering considerations, the insert liner type of system is approved but careful control of application of the cemented-in liners and field supervision of joint make-up are necessary for a trouble-free installation.

### Baked-On Coatings

In smaller pipe and injection lines, the baked-on coating has probably been the most widely-used procedure for corrosion protection. Initially, most of these coatings were of the thin-film multiple-coat types. However, within the past five years thick film coatings have been developed for water handling. These have a high order of resilience, assuring less damage during stringing and running operations. These materials have the further advantage in that when the coatings are properly applied, their greater thickness further assures a holiday-free system. Laboratory tests have generally established that if properly applied, all of the baked-on coatings, regardless of whether they are of the thin or thick film types, will give good protection in water-handling operations. In practically all instances where investigations have been conducted on failures with baked-on type coatings, these failures were attributed to either improper cleaning, coating application, baking of the coatings or field-induced failures resulting from improper transporting or laying procedures. Where the baked-on coatings are properly applied and handled, good service has been obtained from all the various materials.

### Cement Linings

In large-diameter piping, cement lining has been the only economically feasible approach. Early experiences with both mortar mixes and pozzolan-type linings have been varied, with many instances of highly unsatisfactory performance. We have recently completed an extensive investigation of cement linings, and a paper titled "Causes and Prevention of Failures in Cement Pipe-lining" will be presented at the Permian Basin Conference of the AIME in May. The recent linings applied under optimum conditions are expected to give good service.

### External Coatings

External corrosion of pipe was not anticipated in early system designs because of this area's low rainfall and sandy soil. For this reason none of the piping was coated and wrapped. However, the many mud and salt water pits and line breaks have created large areas which are very corrosive so that line-failures resulting from external attack have been frequent. Today we consider it mandatory to coat and wrap all field lines and in most instances, cross-country lines. We also suggest that wherever feasible, the use of cathodic protection be considered.

## CORROSION RESISTANT ALLOYS FOR HANDLING CORROSIVE WATERS

Although it is impractical in flood projects to consider corrosion-resistant metals for such items as pipe or lease vessels, it is possible to consider such materials where the major cost of equipment is fabrication. Frequently pumps, small valves, and the trim on large valves are specified to be furnished in corrosion-resistant metals. The following sections discuss alloys that are often used in sour-water-handling operations.

Monels

In fabricated equipment where failures will be of serious consequence the Monels would be preferred materials. The Monels have a distinct advantage over most of the other corrosion-resistant materials considered in that their corrosion rate is not markedly increased by aeration of the water. Also, since Monels are resistant to sulfide stress corrosion cracking, the material can be used at high stress levels with greater confidence. The K-Monel alloy is recommended for such parts as valve stems or shafts subject to high stress. While from theoretical considerations Monels would be preferred for many fabricated items of equipment, the cost and lack of availability, except on special order, will preclude its use under most circumstances.

Stainless Steels AISI 300 Series

This is the 18% Cr, 8% Ni stainless steel group. These alloys are mostly of the non-hardenable type and have generally given good corrosion-resistance in sour field waters. The yield and tensile strengths of this series are less than those of most steels normally used in oil field equipment and this must be considered in designing parts subject to high stresses. The alloys also have a tendency to gall in running fits and this factor should be taken into consideration in metal-to-metal, sliding or rotating fits, i.e., threads, pistons, valve stems, etc. Some manufacturers furnish items of the AISI 300 series with mating surfaces precoated or treated to prevent galling. For parts not subject to frequent disassembly, these treatments are satisfactory and the possibility of galling can be discounted.

The corrosion resistance of the AISI 300 series stainless steel is dependent on a passive oxide film that forms on the metal surfaces. The metal will not corrode as long as the film is maintained and generally, the 300 series has performed well in sour water systems. However, there have been failures caused by isolated pitting, indicating failure of the oxide film. In a completely-closed air-free system the oxide film cannot be replenished, so with the attack concentrated at isolated pits, failure can occur quickly. The type-316 stainless alloy is generally preferred for water service.

Stainless Steels AISI 400 Series

Although equipment fabricated from the AISI 400 stainless steel series is most readily available, this material cannot be recommended for systems handling sour waters. In this group, Cr is the primary alloying metal, its percentage varying in the 12 to 30 per cent range. Such stainless steels are generally hardenable by either cold work or heat treating, and in the hardened condition will exhibit higher physicals than the AISI 300 series. The alloys give good corrosion-resistance in some media; however, they do not have the corrosion-resistance of the Monels or the AISI 300 series. In sour water, this material will be subject to a pitting-type corrosion, with the susceptibility to attack and the rate of attack increasing as the hardness, tensile and yield strengths of the metals increase.

Aluminum Bronze Alloys

For the past several years, the aluminum bronze and other bronze alloys have been used extensively for water injection, particularly in piston-type injection pumps and have generally given good service. However, there have been several premature failures where pump units have been operated for long periods at pressures approaching their rated operating pressures. These failures, of the fatigue type, reflect the present limited knowledge of the use of aluminum bronze alloys in injection pumps. The two principal uncertainties are the endurance limits for various operating conditions and internal stresses in cast and machined parts. Research studies have established that heat-treating and stress-relieving are required for development of ultimate performance of the material. But the limitations of the alloy in the as-cast form have still not been established. From cost considerations, the use of the alloy in the as-cast condition has distinct advantages.

The use of the various bronze alloys will undoubtedly spread in our water-handling operations. However, until further research has established the limitations of these alloys, we cannot be certain about the operating specifications for equipment manufactured from them.

Inconel, Hastelloy, Stellite, and Colmonoy.

These are the specialty alloys most commonly found in oil field equipment. Inconel has excellent corrosion-resistance and very good physical characteristics. Although this metal is not generally used in stock items, it has found widespread use in springs for corrosive service, particularly where such springs may also be subject to sulfide stress cracking type of environment.

Hastelloy, Stellite and Colmonoy all have excellent corrosion-resistant properties in sour waters and are primarily used as facings or trim in valves, etc.

## ELECTROLYTIC CORROSION

One of the sources of corrosion frequently overlooked in water-handling installations is that associated with the coupling of dissimilar metals. Failures from electrolytic attack are usually associated with small piping and control items that are not of serious consequence. However, such attack can be avoided with a minimum of consideration in the planning period. Table 3 lists the Galvanic Series of metals normally used in oil field equipment. In the coupling of equipment, every effort should be made to select metals in close proximity in this series. Where metals widely separated in the series must be joined, an insulating arrangement should be used between the metals. On the supply side of the systems, this can often be accomplished with short sections of non-metallic conductors. On the injection side, the use of insulated-type couplings are required.

Electrolytic corrosion has been frequently encountered in couplings having insert seal rings. Seal rings in these units should be of a material as similar to the body as possible; under no circumstances should copper, bronze or plated rings be used with steel bodies in systems handling water.

TABLE 3

Galvanic Series in Sea Water

1. Magnesium and alloys
2. Zinc or galvanized metals
3. Aluminum (soft alloys)
4. Cadmium or cadmium plating
5. Aluminum (hard alloys)
6. Steel, cast iron, wrought iron
7. Stainless steels (AISI 400 Series, active)
8. Solder (50% lead, 50% tin)
9. Stainless steel (AISI Series 300, active)
10. Lead
11. Tin
12. Naval brass, maganese bronze, yellow brass, admiralty brass, aluminum bronze, red brass, copper, silicon bronze
13. Inconel
14. Monel
15. Stainless steel (AISI Series 300, passive)

## CONCLUSION

Field studies of waterflood projects during the past 20 years have established specifications for systems handling corrosive waters. The primary operating requirement is that the system be air-free. This requires pressure and vacuum piping to be completely tight from the producing to the injection wells.

Non-aerated sour water, although corrosive, can be controlled by coatings and corrosion-resistant materials.

The major problems encountered in the injection of sour waters have been solved. Based on present knowledge, it is possible to design flood systems which will gave extended periods of trouble-free service.