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EVALUATION OF THE CORROSIVITY OF DEMINERALIZATION CONCENTRATE ON INJECTION WELL MATERIALS AND ASSOCIATED REGULATORY ISSUES

ST. JOHNS RIVER WATER MANAGEMENT DISTRICT

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Evaluation of the Corrosivity of Demineralization Concentrate on Injection Well Materials and Associated Regulatory Issues

Prepared For

St. Johns River Water Management District

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INTRODUCTION

Purpose and Scope

The purpose of this evaluation is to provide the St. Johns River Water Management District (SJWRMD) and the Florida Department of Environmental Protection (FDEP) with information necessary to determine appropriate injection well design requirements for disposal of liquid generated by demineralization processes (demineralization concentrate) used to produce drinking water. Physical and chemical characteristics of waste concentrate generated by existing drinking water treatment systems using demineralization processes were used to determine acceptable corrosivity rates for carbon steel injection well casing. Alternate well design concepts were developed and evaluated for situations where demineralization concentrate corrosivity exceeds the acceptable limits for carbon steel designs. An evaluation methodology was developed and described to aid in determination of the appropriate well design and construction technology requirements based on concentrate corrosion rate factors.

Management Issues

SJRWMD has developed a Demineralization Concentrate Management Plan (Reiss 2003), which presents an assessment of demineralization concentrate management options within SJRWMD. SJRWMD evaluated the following concentrate management alternatives using a GIS-based screening process:

- Subsurface injection
- Surface water discharge
- Coastal ocean discharge
- Open ocean discharge
- Brackish wetland discharge

The subsurface injection alternative is the topic of this evaluation.

One of the recommendations in the Demineralization Concentrate Management Plan (Reiss 2003) developed for SJRWMD includes an evaluation of the appropriateness of making revisions to FDEP UIC rules so that the standard injection well design used by existing municipal well operators can be utilized for demineralization concentrate disposal.

Under current United States Environmental Protection Agency (EPA) regulations and FDEP Underground Injection Control (UIC) rules (40 CFR Part 146 and Chapter 62-528, respectively), demineralization concentrate is classified as non-municipal, non-hazardous, corrosive waste. This classification requires injection using a well equipped with a tubing and packer assembly, or fluid seal design with a fluid filled annulus between the injection tube and inner well casing. Continuous monitoring of this fluid-filled annulus allows for real-time monitoring of internal mechanical integrity of the injection well. The tubing and packer requirement precludes many municipal injection well operators from utilizing existing domestic waste injection wells for management of the demineralization concentrate.

The fluid seal design option, although not common, is real-time monitoring of a light immiscible fluid such as diesel fuel in the annular space between the injection casing and injection tubing. No packer is required in this design.

Non-corrosive municipal waste can be injected using a well of standard type design incorporating a fully cemented carbon steel injection casing with no tubing and packer assembly or annulus monitoring required.

EXISTING UIC REGULATIONS

Well Classification

Well construction standards for injection wells are set forth in the Code of Federal Regulations (40 *CFR* Part 146) and Chapter 62-528 of the Florida Administrative Code (*F.A.C.*). EPA has granted primacy for the UIC program in Florida to FDEP. One of the conditions for this authorization is that the Florida rules governing underground injection must be at least as stringent as the federal regulations. Therefore, Chapter 62-528, *F.A.C.,* is largely patterned after 40 *CFR* Part 146. In both the federal regulations and state rules the criteria for determining well construction standards for injection wells are the source and characteristics of the waste (chemical content, corrosiveness, and density) and the groundwater quality of the injection zone.

The following categories of wells are governed under both the state rules and federal regulations:

Class I - Wells used to inject hazardous waste (new hazardous waste wells were banned in Florida in 1983), other (nonhazardous) industrial waste, radioactive waste, or municipal waste below the lowermost underground source of drinking water (USDW). A USDW is an aquifer containing groundwater with a total dissolved solids (TDS) concentration less than 10,000 milligrams per liter (mg/L).

Class II - Wells used to inject fluids associated with the production of oil and natural gas or fluids used to enhance hydrocarbon recovery.

Class III – Wells, which inject fluids for extraction of minerals (none in Florida).

Class IV - Wells or septic systems, which are used to dispose of hazardous or radioactive wastes into or above a USDW (banned in Florida).

Class V - Wells not included in the other well classes, which generally inject non-hazardous fluid into or above a USDW (e.g., stormwater drainage wells, aquifer storage and recovery wells, large septic systems).

Based on the management options identified in the Demineralization Concentrate Management Plan developed by SJRWMD, this evaluation will focus on Class I wells used to inject municipal and nonhazardous industrial waste below the lowermost USDW. The base of the USDW is defined as groundwater with a total dissolved solids (TDS) concentration exceeding 10,000 milligrams per liter (mg/L).

Class I Well Construction Standards

Federal Regulations

The federal criteria and standards applicable to Class I wells are contained in 40 CFR 146.12 (c) as follows:

> *(c) All Class I injection wells, except those municipal wells injecting noncorrosive wastes, shall inject fluids through tubing with a packer set immediately above the injection zone, or tubing with an approved fluid seal as an alternative. The tubing, packer, and fluid seal shall be designed for the expected service.*
>
> *(1) The use of other alternatives to a packer may be allowed with the written approval of the Director. To obtain approval, the operator shall submit a written request to the Director, which shall set forth the proposed alternative and all technical data supporting its use. The Director shall approve the request if the alternative method will reliably provide a comparable level of protection to underground sources of drinking water. The Director may approve an alternative method solely for an individual well or for general use.*

State of Florida Rules

The state well construction standards for Class I wells are contained in 62-528.410 *F.A.C.*, as follows:

> *(1) General Design Considerations.*
>
> *(e) All Class I injection wells except those municipal wells (publicly or privately owned) injecting noncorrosive wastes, shall inject fluids through tubing with a packer set immediately above*

> *the injection zone, or tubing with an approved fluid seal as an alternative. All existing non-municipal wells constructed without tubing and packer or a fluid seal shall modify their design to incorporate a tubing and packer or fluid seal no later than July 1, 1997, or cease injection unless an alternative to a packer has been approved by the Department…. Existing wells receiving non-municipal waste through a tubing and packer shall not be allowed to remove the tubing and packer as long as injection of non-municipal waste continues unless an alternative to a packer has been approved by the Department.*

Key Definitions

As presented in both state and federal regulations, the well construction standards for Class I wells injecting demineralization concentrate in Florida depend on the definition of the terms "municipal" and "noncorrosive." Rule 62-528.200 (45), *F.A.C.* contains the following definition for municipal injection wells:

> *Municipal injection well means an injection well, publicly or privately owned, which is used to inject fluids that have passed through the head of a permitted domestic wastewater treatment facility and received at least secondary treatment pursuant to Rule 62-600.420, F.A.C.*

Neither the state nor federal UIC regulations contain a specific definition of noncorrosive waste.

Standard Class I Well Design Criteria (Municipal Injection Wells)

Key design criteria for Class I municipal injection wells include:

1. Final casing string — seamless, mild steel pipe with minimum 0.500-inch wall thickness
2. Final casing string — nominal 10-inch overdrill with nominal 5-inch of cement from the bottom of the casing to land surface
3. Remaining casings — nominal 5-inch overdrill with nominal 2.5 inches of cement from the bottom of the casing to land surface

4. Fluid velocity –– must not exceed 10 feet per second (ft/sec) in the injection casing.
5. Design Life –– 30 years (Underground injection wells are typically funded, in whole or in part, by bond issues with 20 to 30 year maturities.)

Tubing and Packer Design Criteria (Non-municipal Injection Wells)

Key design criteria for Class I nonmunicipal injection wells include:

1. Final casing string — seamless, mild steel pipe with minimum 0.500-inch wall thickness
2. Final casing string — nominal 10-inch overdrill with nominal 5 inches of cement from the bottom of the casing to land surface
3. Remaining casings — nominal 5-inch overdrill with nominal 2.5 inches of cement from the bottom of the casing to land surface
4. Fluids — must be injected through a tubing and packer set immediately above the injection zone or through tubing with an approved fluid seal as an alternative, or an approved alternative design
5. Fluid velocity — must not exceed 10 feet per second (ft/sec) in the injection tubing (However, FDEP has allowed the injection velocity to exceed 10 ft/sec in uncemented injection tubing)
6. Design Life –– 30 years (Underground injection wells are typically funded, in whole or in part, by bond issues with 20 to 30 year maturities.)

Regulatory Issues

To determine the appropriate uses of alternative well design criteria for Class I injection wells injecting demineralization concentrate, the following issues are relevant:

- Corrosivity of demineralization concentrate
- Appropriateness of disposing of demineralization concentrate in municipal injection wells
- Appropriateness of alternative demineralization concentrate injection well management options

Most of the Class I injection well systems disposing of secondarily treated domestic wastewater in Florida are designed without a tubing and packer assembly. Retrofitting the wells with a tubing and packer assembly would reduce the allowable injection rates probably resulting in the need for additional wells. The current FDEP definition of municipal injection well requires operators blending demineralization concentrate with domestic wastewater for injection, to blend demineralization concentrate into the headworks of the treatment plant if they wish to use existing wells with no tubing and packer assembly for disposal. This option is generally not feasible because the introduction of highly saline demineralization concentrate can disrupt the biologic processes within the treatment system and take up valuable plant capacity. In addition, the salinity can impair a plant’s ability to produce reclaimed water suitable for reuse. Class I wells that don’t meet the municipal definition are considered nonmunicipal wells. Therefore, the current definition of a municipal well in Chapter 62-528, F.A.C., would need to be changed if current Class I injection well systems are to be allowed to dispose of demineralization concentrate without introducing the concentrate at the headworks of the plant. The federal regulations would not require modification.

An appropriate definition for noncorrosive waste must be developed specifically for the state UIC rules governing Class I well construction standards. This evaluation provides information that can serve as the basis for defining noncorrosive wastes in the context of the UIC program.

CORROSIVITY

Definitions of Corrosivity

As a first step in defining corrosivity a literature search of standards and definitions was conducted. Corrosivity is generally defined as the rate of corrosion of a substance. According to the *Dictionary of Civil Engineering* (Scott 1981) corrosion is defined as "the gradual removal or weakening of metal from its surface by chemical attack. Corrosion can be of two types – the high temperature type that occurs in fires will not be discussed here. The low-temperature type, very much more widespread, requires the presence of water and oxygen and is helped by sulfur dioxide and carbon dioxide, and probably by other materials in small quantities in water or air. It is always electrolytic, and results in oxidation, or rusting, of iron or steel. In Britain the loss of thickness of steel sheet piles submerged in fresh water on both faces is about 0.1 mm yearly. In salt water, the loss is about 50% more. But below groundwater level, submerged in calm conditions of undisturbed soil, steel will suffer so little corrosion that no protection is needed. Above groundwater level in disturbed soil (thus in the presence of both air and water) some protection is needed, whether metal or paint or concrete coating or cathodic protection. Copper, lead, zinc, and aluminum when not in contact with other metals form a thin film of oxide, the patina, which protects them from further oxidation, but if they – especially zinc or aluminum – are in contact with iron through an electrolyte (which may be merely an invisible film of dirty water on the surface of the metal) they will dissolve in sacrificial protection of the iron. They are therefore used in metal coating to protect iron and steel. Weather-resisting steel has good corrosion resistance in air."

EPA and FDEP Definition

EPA defines corrosivity of hazardous waste in terms of a corrosion rate of greater than 250 mils per year (mpy) (1 mil = 0.001 inch) in federal regulation 40 CFR 261.22. Further, the test methods are standardized in EPA Publication SW-846 (EPA 1998)), using NACE TM-69 (NACE 1972) as a base method. Corrosive wastes are extremely acidic or alkaline (i.e., have pH less than or equal to 2 or greater than or equal to 12.5). The FDEP adopted the EPA definition for hazardous waste (40 CFR 260 and 261) in rule 62-730.030, *F.A.C.*

Corrosivity and Corrosion Rate

In accordance with 40 CFR 146.12 (c), a reasonable corrosion rate limit would be "the corrosion rate that would allow an acceptable service life of the materials used in the construction of the underground injection well." In this evaluation, a service life of 30 years is used for determination of acceptable corrosion rates. Bond issues with 20 to 30 year maturities are typically used to fund, in whole or in part, underground injection wells. The 30-year criterion is commonly used for injection well planning and design purposes. It should be noted that some active injection wells in Florida have been in service for over 30 years and still maintain mechanical integrity. These wells are either injecting municipal wastewater or are equipped with tubing and packer.

The corrosion rate of injection well materials (casings) is a function of the physical and chemical properties of the effluent and the corrosion resistance of materials used in construction. This evaluation describes the physical and chemical properties of effluent that would likely cause an unsuitable corrosion rate for the standard injection well material (carbon steel casing without a tubing and packer assembly). Alternative well design and materials selection are also addressed.

Characterization of the Effluent

The effluent under consideration in this evaluation is the discharge from the membrane -softening [nanofiltration (NF)] or liquid separation technology [reverse osmosis (RO)] processes. In the RO and NF processes, feedwater is pumped into a closed system where it is pressurized against a semi-permeable membrane. Some of the water passes through the membrane with the remaining feedwater becoming more "saline" (increased TDS). RO and NF are typically used to treat water with a TDS content above that permissible for potable water (500 mg/L). NF is essentially a lower-pressure version of RO where the purity of product is not as critical, or the level of the dissolved solids to be removed is lower. Two streams exit the RO and NF processes, one stream directed to the potable water distribution system (typically blended with other sources) and the other stream (effluent, commonly referred to as demineralization concentrate) disposed of under the auspices of a site-specific permit. One such method of effluent disposal uses underground injection wells.

Water used in RO and NF plants is typically pretreated to remove suspended solids and adjust the pH to optimize the performance of the semi-permeable membranes. Both the water bound for distribution and the demineralization concentrate are subject to post-treatment, primarily degasification to remove hydrogen sulfide (Figure 1).

The materials of construction used in RO and NF plants are, of necessity, corrosion resistant metal alloys (CRA) such has stainless steel and non-metallic materials such as polyvinyl chloride (PVC). This material selection is required because of the well-documented high corrosion rates for carbon steel in the aerated and saline environment characteristic of treatment processes. After post-treatment, the water bound for distribution is typically carried in cast iron or carbon steel or PVC piping.

Service Life Consideration

Determining the service life of any material in a corrosive environment is a complex process, which is subject to uncertainties. Data for use in service life prediction comes from three primary sources (Dickie 1982):

- Short-term laboratory-based studies
- Long-term in-service exposures
- Fundamental mechanistic studies

The success of any service life prediction methodology depends on the ability to use the strengths, understand the weaknesses, establish linkages, and integrate the knowledge from each of these data sources.
The service life of any material is affected by many variables. The relationships among these variables and the service life of the material are seldom well understood. This is particularly true in the case of injection well casing used in association with disposal of RO and NF demineralization concentrates.

Fault tree analysis is a deductive, systems analysis technique for graphically and logically relating the top event, failure of a carbon steel pipe, to its underlying faults (Haasl 1965) (Figure 2).

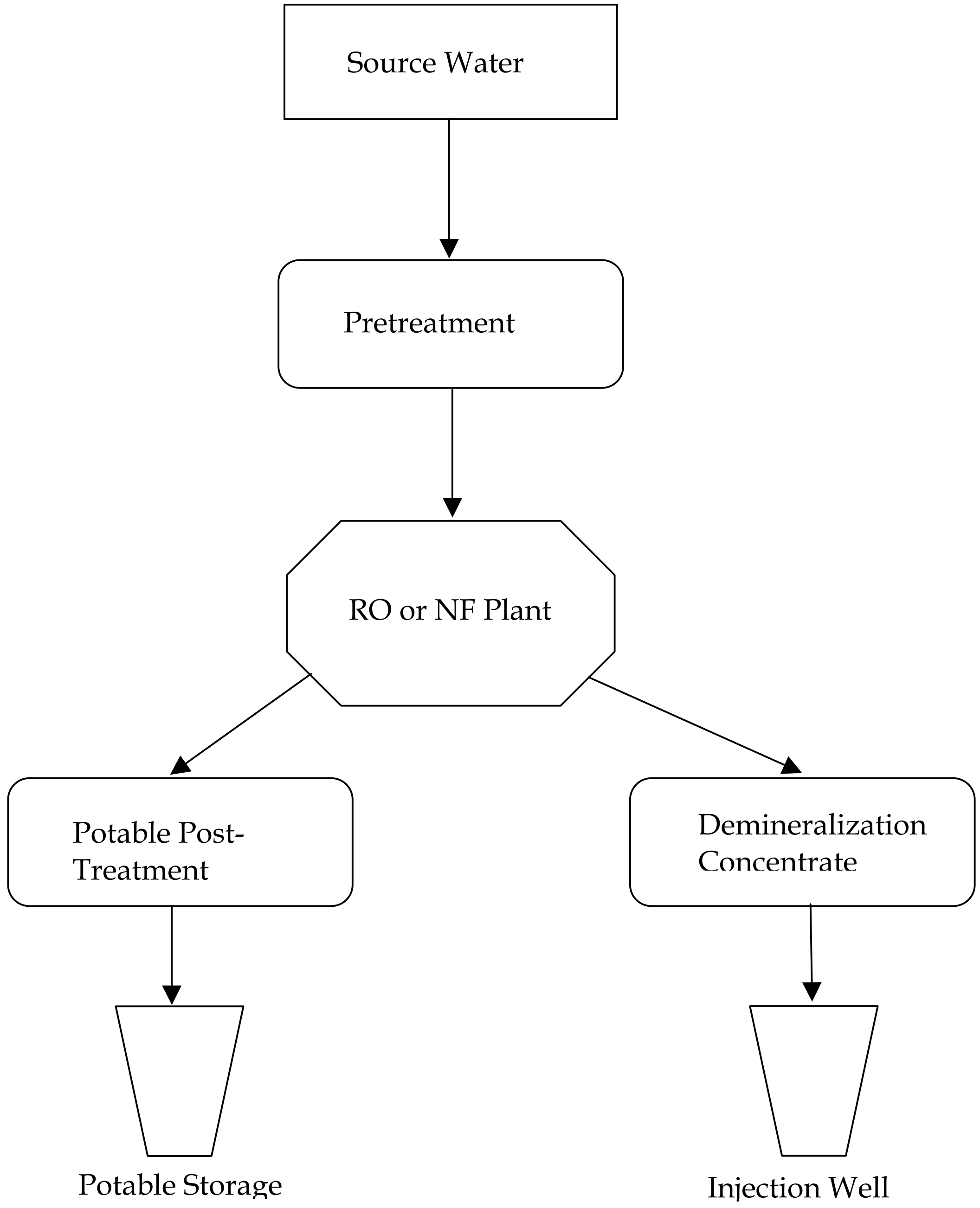


Figure 1. Typical reverse osmosis (RO) and nanofiltration (NF) treatment process

Figure 2 – Corrosion Fault Tree (Haasl 1965)
* microbiologically induced corrosion

Even with the fairly basic fault tree shown in Figure 2, there are many factors and accompanying interactions among these factors to be considered. Adding to the problem of service life prediction is the dearth of objective information on service histories and observed failure modes in operating injection wells. While there is a smattering of anecdotal evidence, it seems prudent to ignore this type of evidence, at least for the moment. The lack of information points to some obvious data gaps and the need for additional work subsequent to this evaluation.

The fault tree is a systematic view of the more important factors contributing to corrosion failure. For the purpose of this evaluation, only environmental factors are addressed. This assumes that the materials have been properly manufactured, specified and installed. Caution is necessary by making this assumption, as actual failures may, in fact, be caused by faults in these areas. The assumption is made to narrow the focus of this evaluation to the in-service corrosive environment of carbon steel pipe.

Corrosion of Carbon Steel

Corrosion is an electrochemical process that results in the dissolution of metal. This investigation focuses on the chemical and physical properties of aqueous solutions that contribute significantly to corrosion of carbon steel.

Corrosion requires four elements to proceed:

- Anode — The place where metal dissolution occurs and electrons are freed in reactions involving ions of the electrolyte
- Cathode — The place where the freed electrons are consumed in reactions involving ions of the electrolyte
- Electrolyte — The carrier of ionic current (In this investigation the electrolyte is the demineralization concentrate.)
- Metallic Pathway between the Anode and Cathode — The conductor of electron flow (in this evaluation the metallic path is the injection well casing or tubing).

In an injection well the steel casing provides a metallic pathway for electron flow between the anode and cathode, and the demineralization concentrate is the carrier of ionic current. The corrosion process is controlled by the rate of the reactions occurring at the anode and cathode.

Under immersed conditions in potable waters, carbon steels, low alloy steels, and cast irons exhibit essentially the same corrosion behavior (Davis and Scott 2003). The corrosion resistance of these materials is strongly affected by the ability to form protective scales and the stability of these scales in the injection well environment (particularly under the influence of fluid velocity). The corrosion rate is generally proportional to the oxygen content of the water (Hagen 2000). If thermal degassing or chemical addition is used to remove dissolved oxygen, the corrosion rate may be significantly reduced (Fontana 1986).

The principal anodic reaction for carbon steels, low alloy steels, and cast irons is the dissolution of iron (Uhlig and Revie 1985):

$$Fe \rightarrow Fe^{2+} + 2e^{-} \qquad \textbf{(1)}$$

The principal cathodic reaction is the reduction of water (Uhlig and Revie 1985):

$$1/2O_2 + H_2O + 2e^{-} \rightarrow 2OH^{-} \qquad \textbf{(2)}$$

Combining equations (1) and (2) results in (Uhlig and Revie 1985):

$$Fe + H_2O + 1/2O_2 \rightarrow Fe(OH)_2 \qquad \textbf{(3)}$$

The resultant reaction product can be further oxidized in the presence of oxygen to (Uhlig and Revie 1985):

$$Fe(OH)_2 + 1/2H_2O + 1/4O_2 \rightarrow Fe(OH)_3 \qquad \textbf{(4)}$$

Relations between the electrochemical and corrosion behavior of iron in water may be summarized by thermodynamic data (Pourbaix 1974). These relations are represented in diagrams that indicate the reduction potential and pH conditions under which iron does not react or can react to form specific oxides or complex ions. Pourbaix diagrams give a general idea of when corrosion is possible from a thermodynamic standpoint; however, they convey no information on corrosion rates. A later section of this document discusses corrosion rates and changes in corrosion rates based on chemical properties of the demineralization concentrate.

CORROSION OF STEEL

Important Factors

Corrosion processes in steel pipes transmitting water are complex due to the range of possible oxidants and reductants, the dependence of the reactions on localized conditions, and the complications arising from the formation of scales on the pipe surface. As a result, there rarely exists a single factor that can be used to reliably predict corrosion rates. In fact, studies have determined that corrosion rates are more commonly affected by a combination of the effects of the following significant attributes of water in relationship to corrosion.

- Dissolved oxygen
- Temperature
- Velocity
- pH
- Chloride concentration
- Dissolved solids concentration
- Scales
- Microbiologically influenced corrosion

Effect of Dissolved Oxygen

The predominant anodic reaction on bare steel in contact with water is the oxidation of metallic iron and the predominant cathodic reaction is the reduction of oxygen. In general, the corrosion of steel would, for all practical purposes, cease in the absence of dissolved oxygen. Unfortunately, the processes involved in conventional RO plants tend to saturate the water with oxygen.

The corrosion rate of steel in water containing dissolved oxygen is controlled by the diffusion rate from the bulk solution to the steel surface. For a given temperature and water velocity, the rate of oxygen consumption is equivalent to the corrosion rate and is directly proportional to the oxygen concentration in water, regardless of the concentration of most other constituents.

Scales that form on the pipe wall tend to provide diffusion barriers to constituents approaching and leaving the steel surface, resulting in a decrease in corrosion rate. As these scales increase in thickness, the influence of water velocity on mass transfer coefficients decreases. This is due to the scales acting as a physical barrier and constituents forming the scale reacting with the dissolved oxygen as it diffuses to the pipe wall. Regardless of the presence or absence of scale, if the dissolved oxygen concentration could be measured at the steel surface, the relationship between oxygen concentration and corrosion rate would be confirmed.

In summary, when water containing dissolved oxygen is in contact with steel, there is a large driving force for active corrosion under any realistic water quality conditions. Other water quality attributes, such as pH, alkalinity, and the concentration of dissolved inorganic ions, will have a negligible effect on corrosion rates (except for the increase in water conductivity, as described in the subsequent discussions of the effects of chloride concentrations and dissolved solids concentrations).

Effect of Temperature

All chemical reactions of practical significance are affected by temperature. As corrosion is an electrochemical reaction, the corrosion rate generally increases with increasing temperature.

There are also indirect effects of temperature on the corrosion rate of steel in water. For instance, an increase in water temperature tends to increase the oxygen diffusion rate and decrease viscosity. An increase of the mass transfer rate of oxygen from the bulk solution to the steel surface occurs. The result is an increase in the rate at which oxygen is supplied to the cathode and increased corrosion rate.

From a practical standpoint, water temperature fluctuations within the RO process do not significantly influence corrosion rates.

Effect of Velocity

The primary effect of water velocity is the increased diffusion rate of oxygen to the steel surface. For wells permitted after 1985, the maximum fluid velocity is 10 ft/sec. Usually, wells are operated below this value (Fontana 1986). Corrosion rates typically plateau at a velocity of approximately 10 ft/sec, and therefore velocity fluctuations within the injection well will not be evaluated in this study (Preban 1987).

Effect of pH

The solution pH is a measure of the acidity or alkalinity, with a pH of 7 being neutral. With steels, a pH of less than 5.5 generally results in significant increases in corrosion rates, due to the potential for reduction of the hydronium ion (H^+). However, in the normal ranges encountered in the RO and NF concentrate streams (pH 6-8), there is very little effect on corrosion rate.

Effect of Chloride Concentrations

Chloride comprises a relatively large proportion of the total dissolved solids (TDS) content of demineralization concentrate waste streams. The most deleterious effect of chloride is the contribution to pitting mechanisms and break down of protective iron oxides. Chloride salts also contribute to the increase in solution electrical conductivity. For the purposes of this evaluation the effect of chloride on the corrosion rate of iron has been evaluated collectively with other dissolved solids. Note that the Langelier saturation index (SI), as described in the discussion on the effects of scales, requires a determination of chloride concentration.

Effect of Dissolved Solids Concentrations

Solids content of water refers to the matter that remains as residue upon evaporation of water and includes dissolved and undissolved constituents. From a corrosion rate perspective, the TDS concentration has the predominant effect on solution conductance. TDS is composed primarily of inorganic salts containing sodium, calcium, potassium, chloride, carbonate, and sulfate. Increasing TDS also increases solution electrical conductance. This increase in conductance allows an increase in ionic current in the electrolyte of the corrosion cell. Thus, corrosion rates will increase with increasing TDS. Suspended solids and soluble organic material typically will not significantly affect corrosion rates, but may affect the composition and stability of scales.

Effect of Scales

The formation, behavior and effects of scales due to the precipitation reactions of corrosion products of steel have been extensively studied in the past century. Although there is a broad consensus regarding the qualitative importance of scales in terms of corrosion rates, many questions remain concerning their behavior in water systems.

Scale formation has been attributed to the precipitation of carbonate compounds on the surface of steel. Several methods have been developed for determining the tendency of a water solution to precipitate or dissolve calcium carbonate. The most common method utilized in water supply engineering is the Langelier saturation index (ASTM D 3739 2003). This method is used when TDS concentrations are less than 10,000 mg/L. A method developed by Stiff and Davis (ASTM D 4582 2001) is used for waters with TDS concentrations greater than 10,000 mg/L.

In both methods calcium carbonate saturation (or stability) indexes (SI), are calculated using TDS, calcium concentration, total alkalinity, pH, and temperature of the concentrate.

The Langelier saturation index can be calculated using the following formula:

$$LSI = pH - C - pCa - pAlk$$

Where:

LSI = Langelier saturation index
pH = negative log of hydrogen ion concentration
C = empirical constant (a function of total dissolved solids)
pCa = negative log of calcium concentration
pALK = negative log of alkalinity

The Stiff and Davis SI formula is as follows:

$$SI = pH - K - pCa - pAlk$$

Where:

SI = Stiff & Davis saturation index

pH = negative log of hydrogen ion concentration
K = an empirical constant (a function of ionic strength and temperature)
pCa = negative log of calcium concentration
pAlk = negative log of alkalinity

Calculation of SI involves operating on a variety of species, including carbonate, bicarbonate, sulfate, chloride, iron, calcium, magnesium, and sodium. Procedures for such calculations can be found in standard environmental engineering reference manuals. Many researchers have developed such indices to predict a water's tendency to form scales and the effect of those scales on corrosivity. A negative SI indicates a situation where water is unsaturated in respect to calcium carbonate and suggests that the water is corrosive. In spite of the popular use of such indices, their use alone often fails to predict corrosivity. This failure has been attributed to the complex nature of solution pH at or near the steel substrate. However, when used in conjunction with other water parameters, these saturation indices have produced good correlation in corrosion rate prediction models.

Effect of Microbiologically Influenced Corrosion

Microbiologically influenced corrosion (MIC) refers to a localized form of corrosion due to the metabolic byproducts from certain microorganisms (such as anaerobic sulfate-reducing bacteria and aerobic iron-oxidizing bacteria). Failure usually results from wall penetration and most often occurs in crevices formed under deposits that are conducive to the growth of these microorganisms.

Because demineralization facility processes tend to kill or inhibit microbiological growth, the effects of MIC are not addressed in this evaluation.

Corrosion Rate Model

In the absence of data from existing wells on corrosion-related damage, models and mechanistic studies can be used to develop a framework for this evaluation. The model presented later in this section must be viewed as a simplified, "big picture" attempt to begin the evaluation of corrosion in an injection well environment. The model presented here is a simplified mathematical representation of the major factors contributing to corrosion of carbon steel in an injection well. As with any model, additional information may lead to an improved model of corrosion rates in such environments. The primary value of the model presented here is an understanding of the relative importance of model input parameters as they relate to predicted corrosion rates.

A number of investigators have developed models for the calculation of corrosion rates using 4 to 13 chemical and physical parameters. These models are generally valid only for the controlled experimental conditions under which they were developed. Moreover, these models focus on generalized corrosion; however, pitting failure is probably the leading cause of pipeline leakage. Despite these limitations, predictive models can be used as a guide in formulating preliminary estimates of corrosion rates in injection wells for demineralization concentrate.

The parameters exerting the greatest influence on corrosion rates in injection wells for demineralization concentrate were evaluated for this project. Based on a review of the literature, the four-parameter corrosion rate model of Pisigan and Singley (1985) was selected to evaluate how the variation of key input parameters might influence corrosion rates. The model has the form:

$$CR = \frac{(TDS)^{0.253} \times (DO)^{0.820}}{(10^{SI})^{0.0876} \times (TOE)^{0.373}}$$

where:

CR = Corrosion rate in mpy
DO = Dissolved oxygen
TDS = Total dissolved solids
SI = Langelier saturation index (for concentrate < 10,000 mg/L TDS)
TOE = Time of exposure

A relative corrosion rate factor (CRF) can be calculated using the following formula:

$$CRF = \frac{\dfrac{(TDS_i)^{0.253} \times (DO_i)^{0.820}}{(10^{SI_i})^{0.0876}}}{\dfrac{(TDS_b)^{0.253} \times (DO_b)^{0.820}}{(10^{SI_b})^{0.0876}}} = \frac{(TDS_i)^{0.253} \times (DO_i)^{0.820} \times (10^{SI_b})^{0.0876}}{(TDS_b)^{0.253} \times (DO_b)^{0.820} \times (10^{SI_i})^{0.0876}}$$

where:

> Subscript *i* refers to the demineralization concentrate under consideration, and
> Subscript *b* refers to a baseline solution of a known corrosivity.

Note that the time of exposure parameters will cancel out, as will parameters that do not change between the baseline and demineralization concentrate solution under consideration.

Thus, once a baseline solution and associated corrosion rate are established, the corrosion rate associated with the demineralization concentrate can be computed from the CRF.

Establishing Target CRF

The model presented represents a comparison between a "baseline" water source and a demineralization concentrate under consideration. The baseline selected here assumes a solution approximating potable water (without chlorination). Steel piping in such service has documented service lives approaching the desired 30-year goal. Additionally, there are municipal wastewater injection wells in the Florida with more than 25 years of documented service.

Typical values of the parameters used in calculating a CRF have been researched in the literature and are presented in Table 1 (Davies and Scott 2003). The most questionable value is the corrosion rate selected. This selected corrosion rate discounts pitting (an important factor in some waters) and assumes a uniform dissolution of iron. Also, no factor of safety has been included, and the entire pipe thickness is used to determine service life. Ideally, subsequent investigations will be able to incorporate the effects of pitting and the other non-uniform degradation mechanisms. Therefore the results of this model should be treated as comparative, i.e., not dealing with absolute corrosion rates. A factor of safety may be desired in future analyses. For instance, one may desire to define failure as the point where 50% of wall thickness remains. Then, given the linear relationship of the assumed corrosion rate, calculated values given below would be decreased by a factor of 2. Similar relationships can be developed for any desired parameter.

Table 1. Typical values used to calculate corrosion rate factor (CRF)

Parameter	Values	Proposed Baseline
TDS	250-700 mg/L	450 mg/L
DO	1-10 ppm	5 ppm
SI	-0.7 - 0.9	-0.7, 0.0, 0.9
Corrosion Rate	8-13 mpy	11 mpy

The proposed baseline corrosion rate equates to an approximate service life of 45 years. Given the goal of a 30-year service life, a target CRF of 1.5 is used.

As a first approximation, the TDS of the demineralization concentrate required to achieve this CRF is calculated, assuming no changes in SI or DO during the RO process.

$$1.5 = \frac{(TDS_i)^{0.253}}{(450)^{0.253}}$$

$$TDS_i = 2{,}235 \text{ mg/L}$$

This computed value of TDS = 2,235 gives the maximum value assuming no change in any other variable. This is a relatively low value of TDS for an RO concentrate. RO concentrates may have TDS values ranging up to 30,000 or higher. A series of calculations can now be made using the equation above to calculate maximum TDS at various values of DO and SI.

A series of graphs (Figures 3 – 11) have been constructed using the SI proposed baseline parameters in Table 1. The graphs present varying CRF plotted against TDS, with DO values of 1, 5, and 10 ppm.

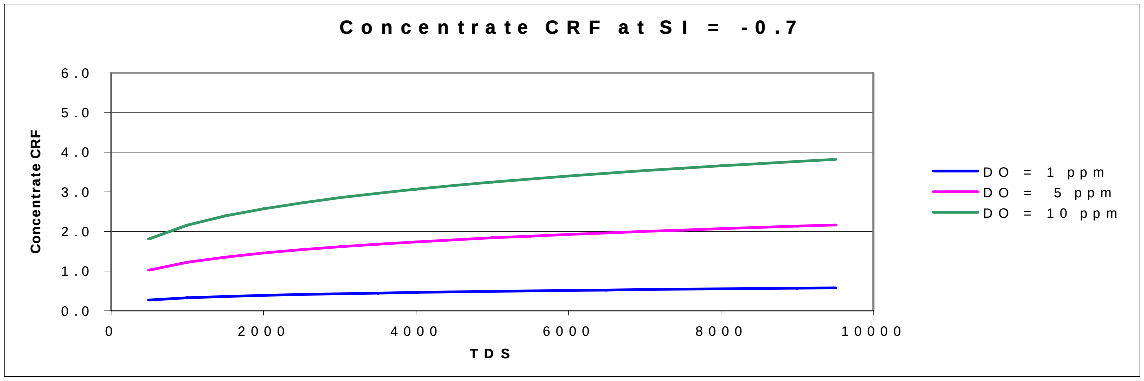


Figure 3. Concentrate CRF at SI = - 0.7 and baseline SI = - 0.7

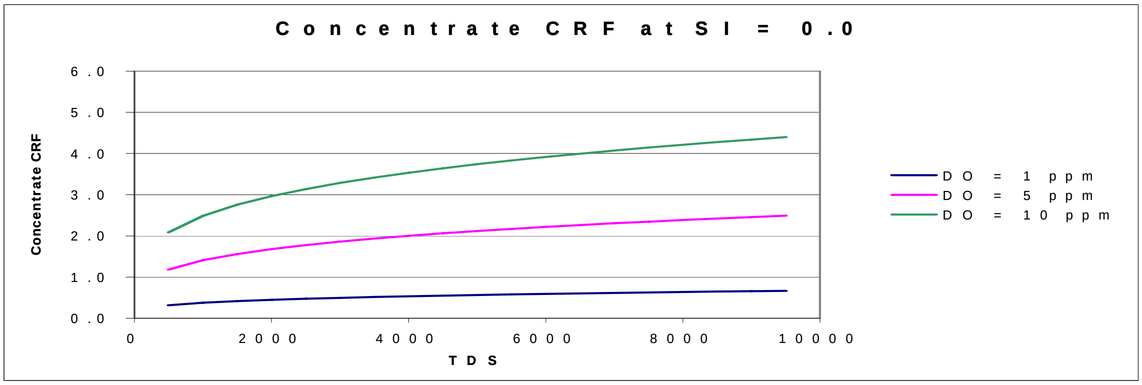


Figure 4. Concentrate CRF at SI=0.0 and baseline SI = –0.7

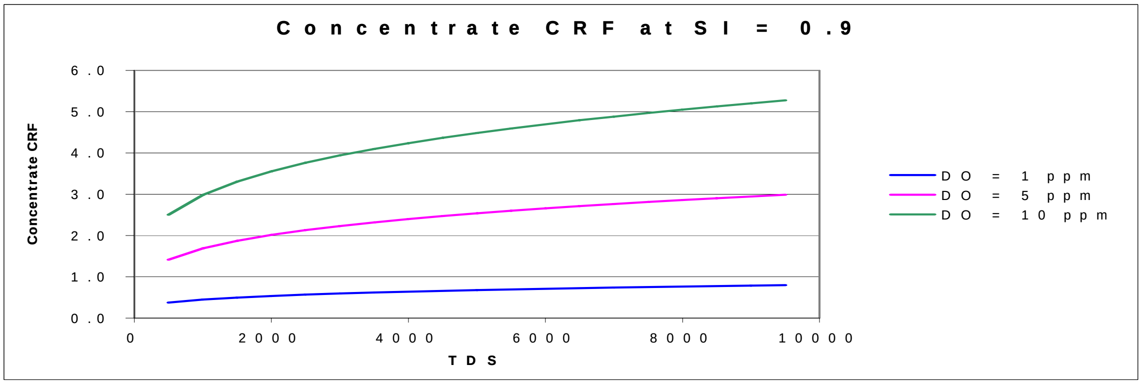


Figure 5. Concentrate CRF at SI = 0.9 and baseline SI = -0.7

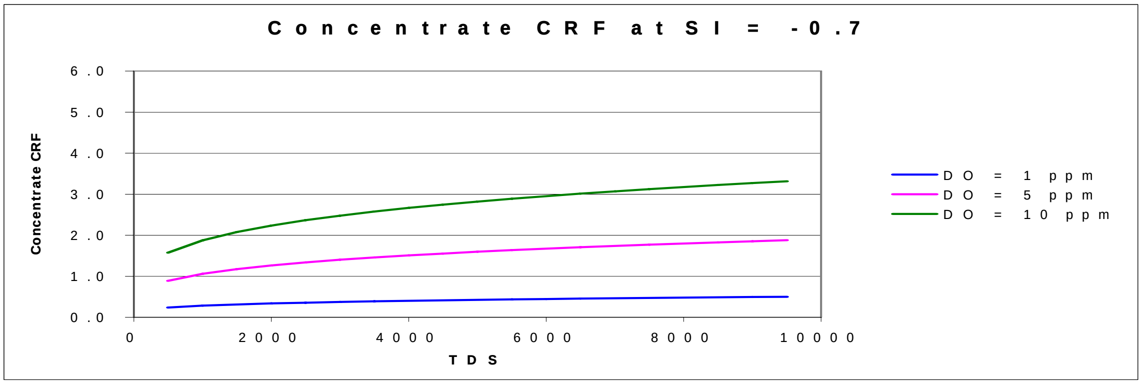


Figure 6. Concentrate CRF at SI = -0.7 and baseline SI = 0.0

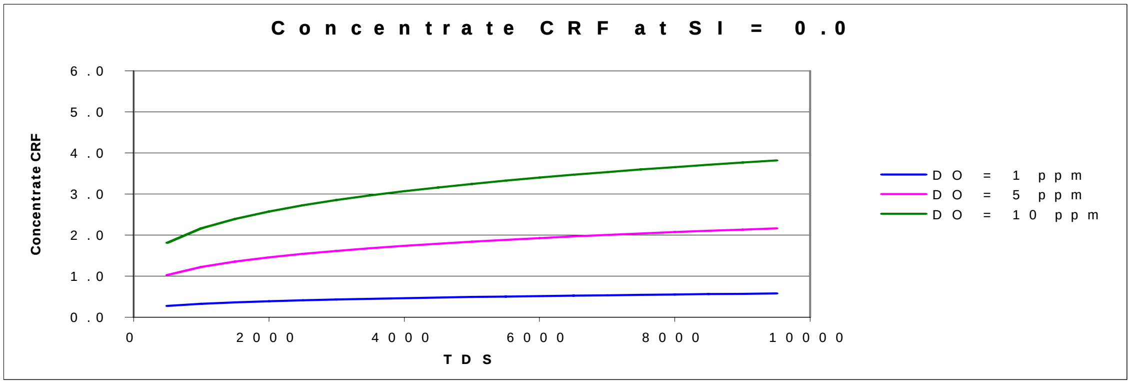


Figure 7. Concentrate CRF at SI = 0.0 and baseline SI = 0.0

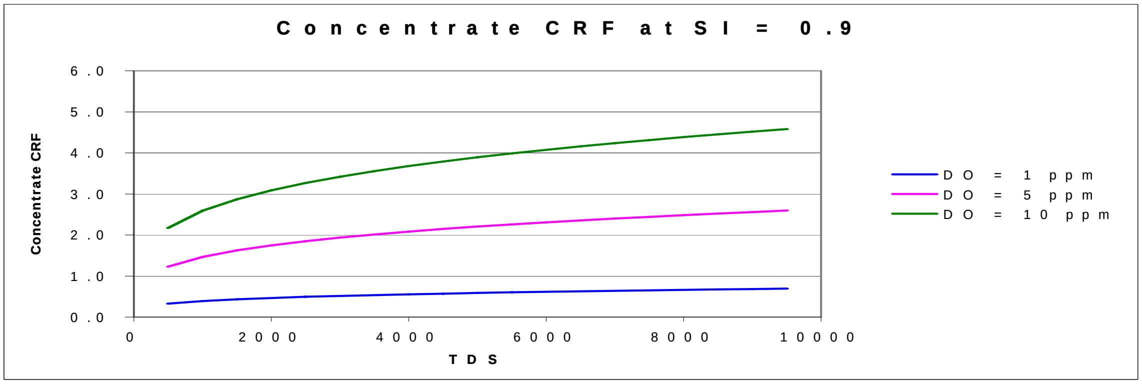


Figure 8. Concentrate CRF at SI = 0.9 and baseline SI = 0.0

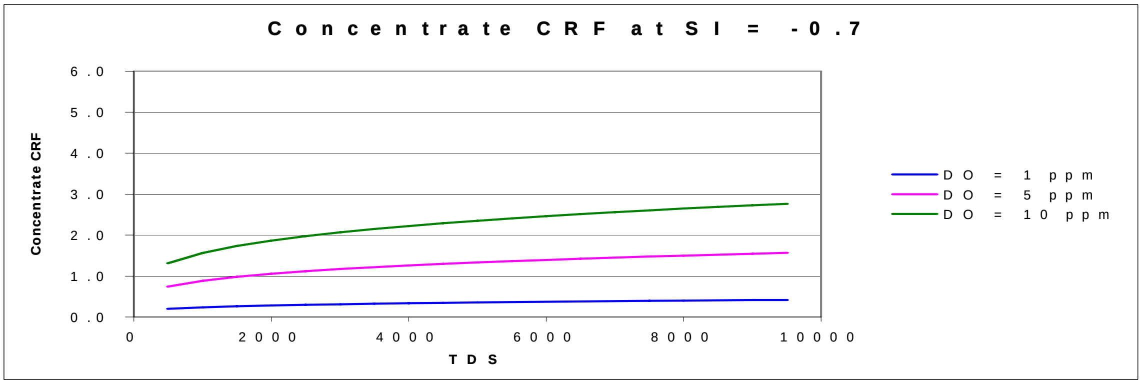


Figure 9. Concentrate CRF at SI = -0.7 and baseline SI = 0.9

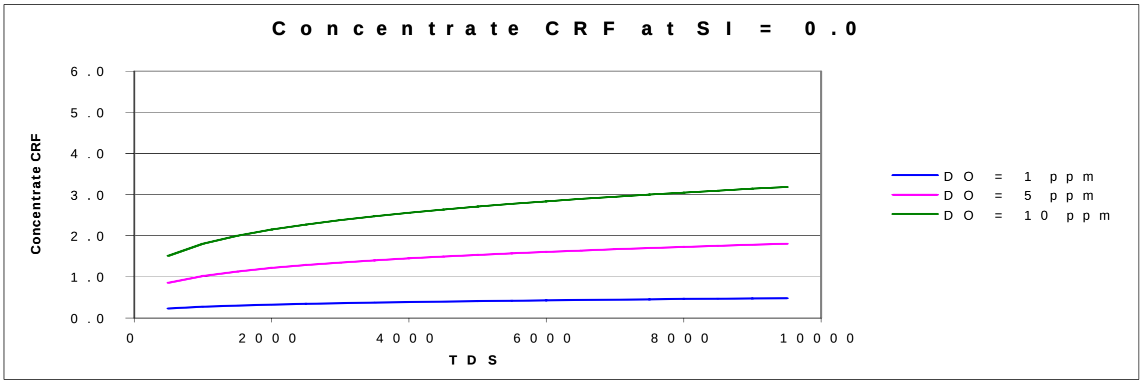


Figure 10. Concentrate CRF at SI = 0.0 and baseline SI = 0.9

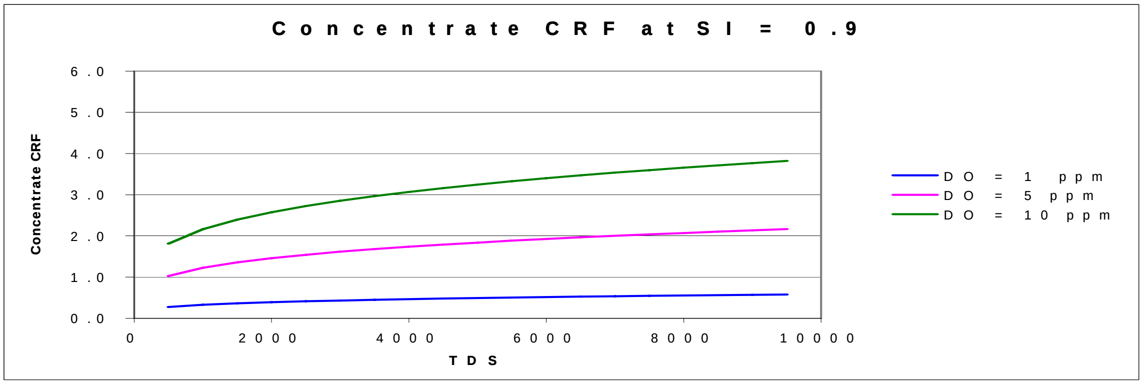


Figure 11. Concentrate CRF at SI = 0.9 and baseline SI = 0.9

Figures 3 – 11 demonstrate the significance of dissolved oxygen on corrosion rates.

TDS Calculations

The graphs in Figures 12-17 represent surfaces created by varying dissolved oxygen content. The surfaces indicate the TDS that produces a CRF of 1.5, as a function of the baseline and concentrate SI. These graphs can be used to calculate the maximum permissible TDS to achieve a 30-year life for carbon steel injection well materials.

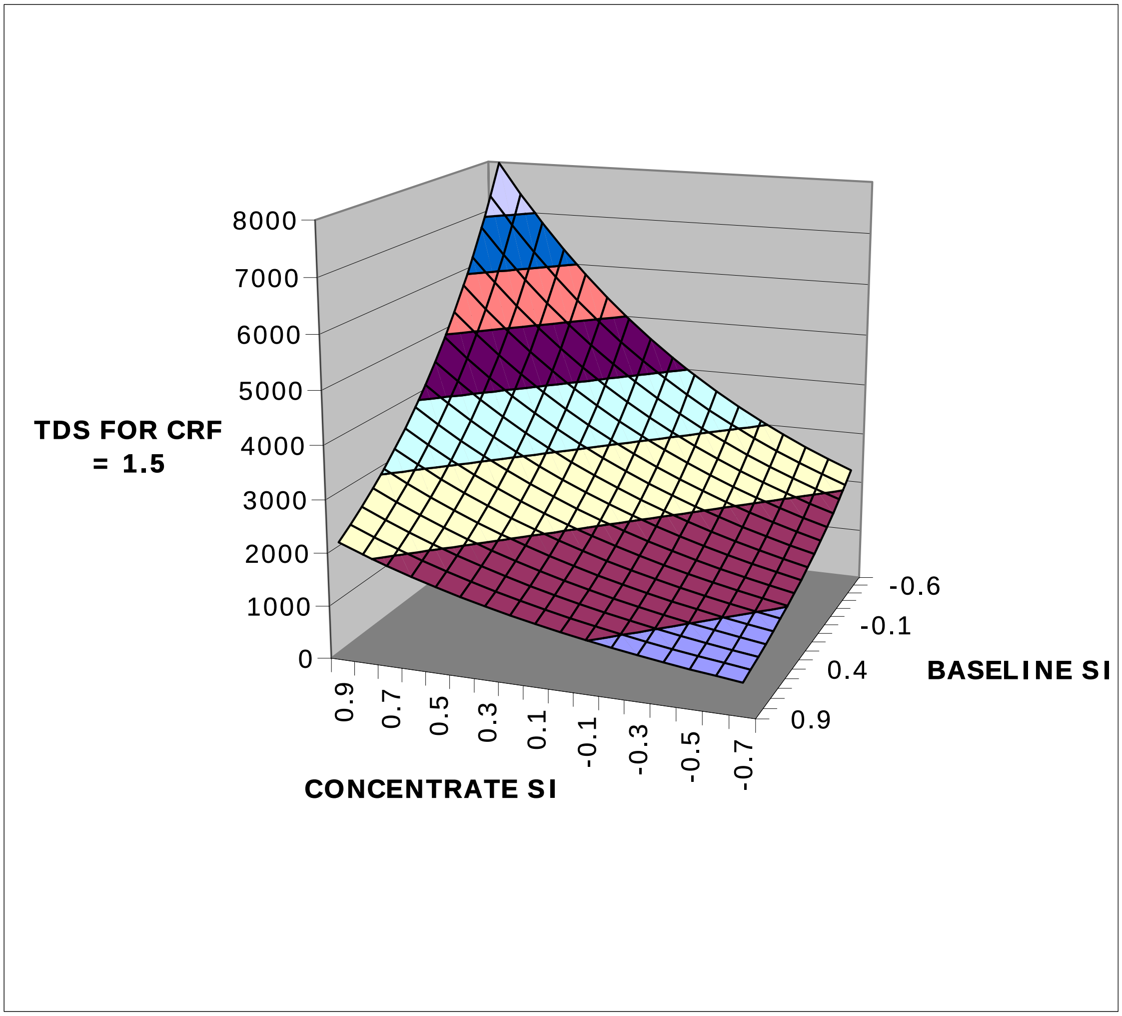


Figure 12. Calculated TDS values vs. baseline SI and concentrate SI, CRF = 1.5, concentrate DO = 5 ppm

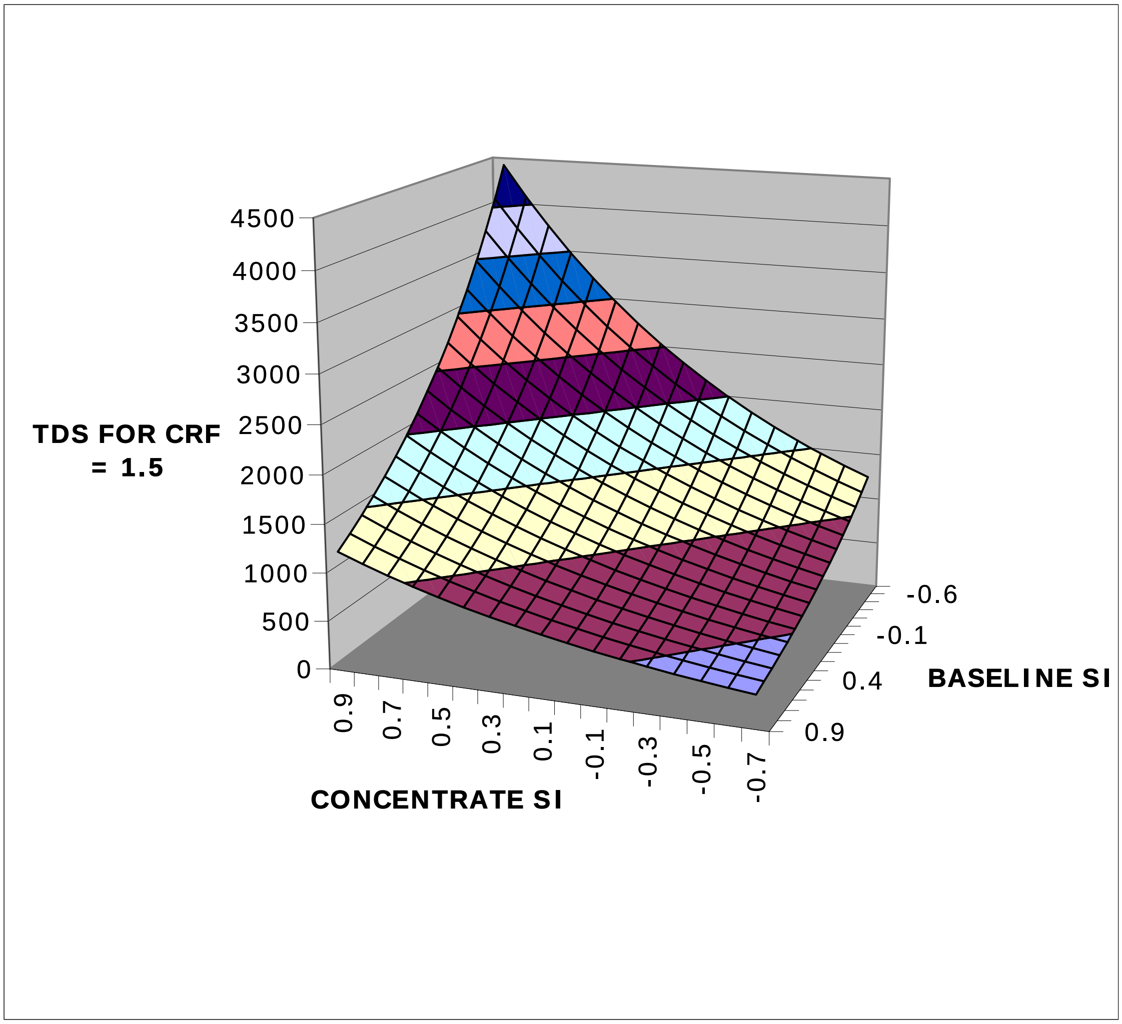


Figure 13. Calculated TDS values vs. baseline SI and concentrate SI, CRF = 1.5, concentrate DO = 6 ppm

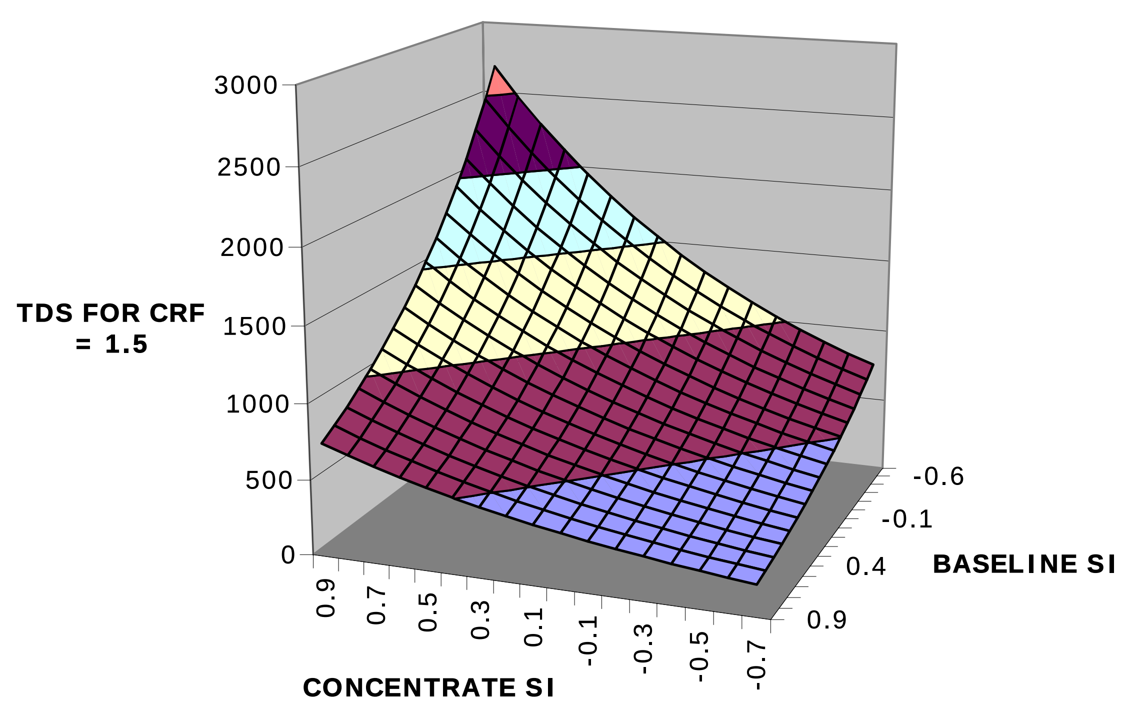


Figure 14. Calculated TDS values vs. baseline SI and concentrate SI, CRF = 1.5, concentrate DO = 7 ppm

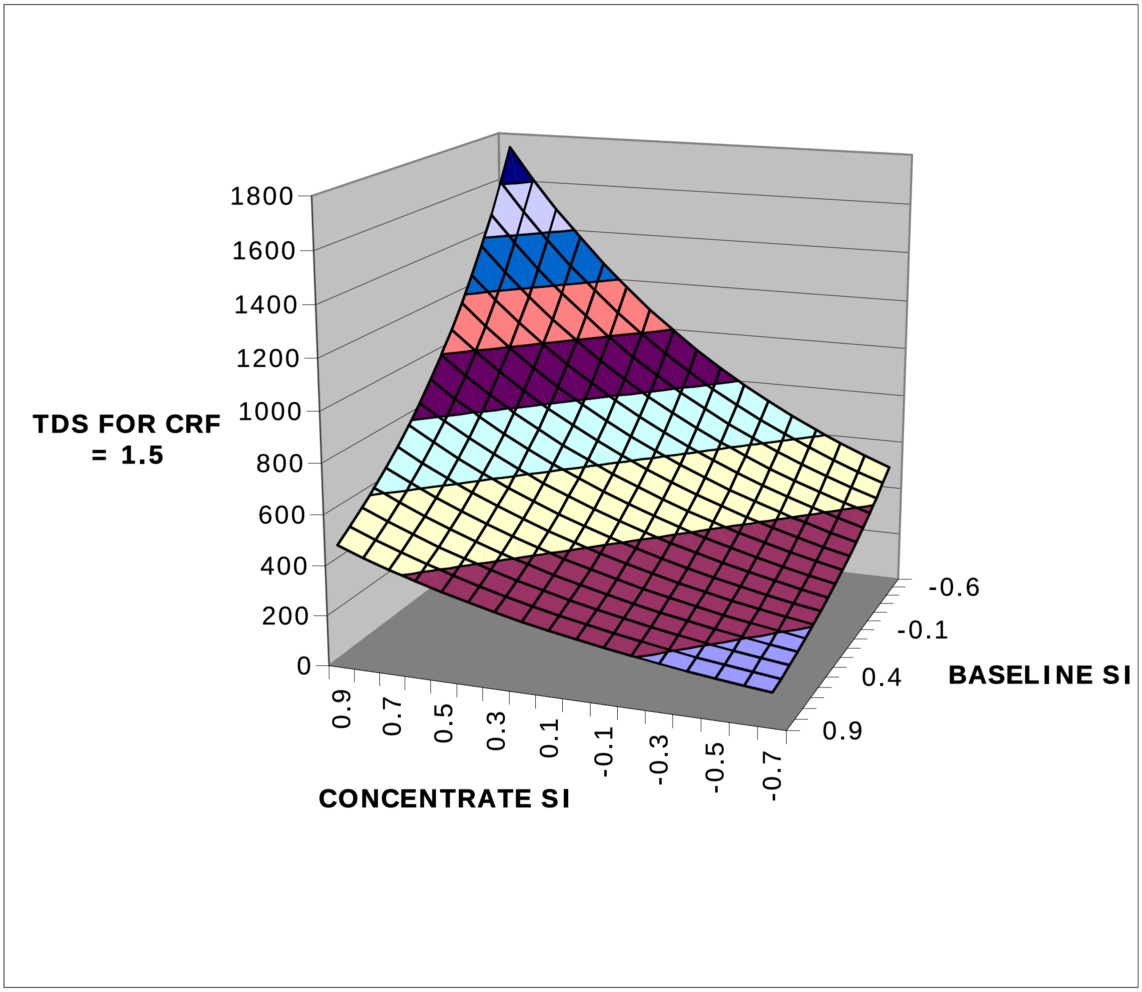


Figure 15. Calculated TDS values vs. baseline SI and concentrate SI, CRF = 1.5, concentrate DO = 8 ppm

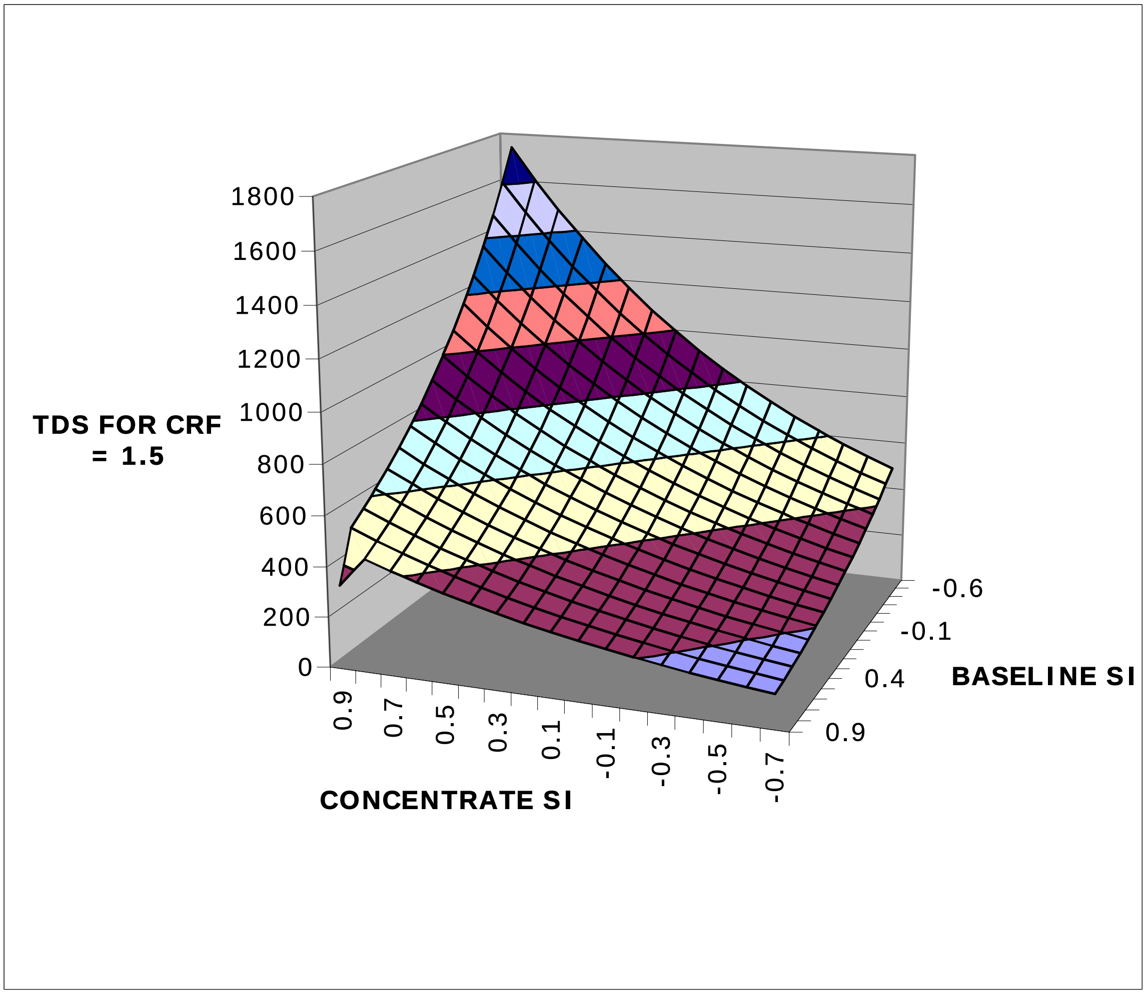


Figure 16. Calculated TDS values vs. baseline SI and concentrate SI, CRF = 1.5, concentrate DO = 9 ppm

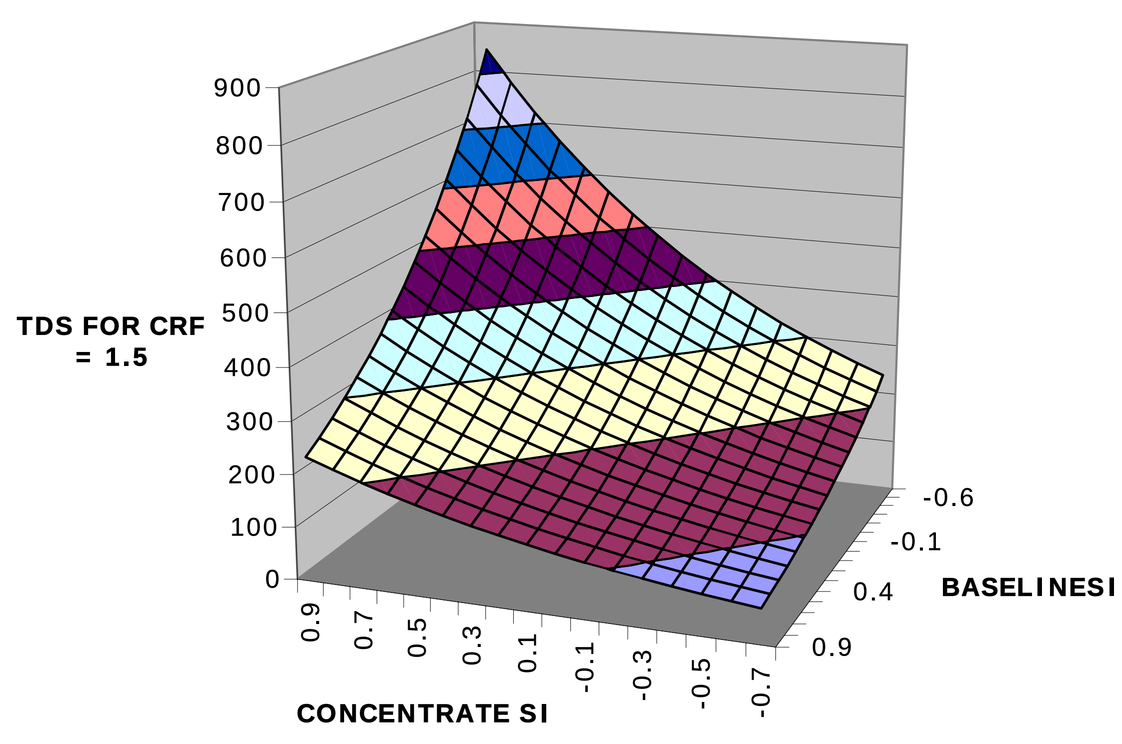


Figure 17. Calculated TDS values vs. baseline SI and concentrate SI, CRF = 1.5, concentrate DO = 10 ppm

PROPOSED CORROSIVITY EVALUATION METHODOLOGY

There are alternative methods to manage demineralization concentrate. The appropriateness of these alternatives should be considered when making decisions concerning management of demineralization concentrate. This section presents a methodology, which can be employed on a case-by-case basis to make rational decisions regarding the technical and economical feasibility of injection well disposal of demineralization concentrate, given case-specific factors. Figure 18 presents a concentrate decision tree that illustrates the recommended methodology. Following is a step-by-step description of how this methodology can be implemented.

Step 1 – Demineralization Concentrate Characterization

The initial step is to characterize the demineralization concentrate based on those parameters that are critical to its corrosivity. This is done either by testing the actual concentrate (if samples are available), or evaluation of the raw water source and projection of the concentrate characteristics based on the source water characteristics and expected RO performance.

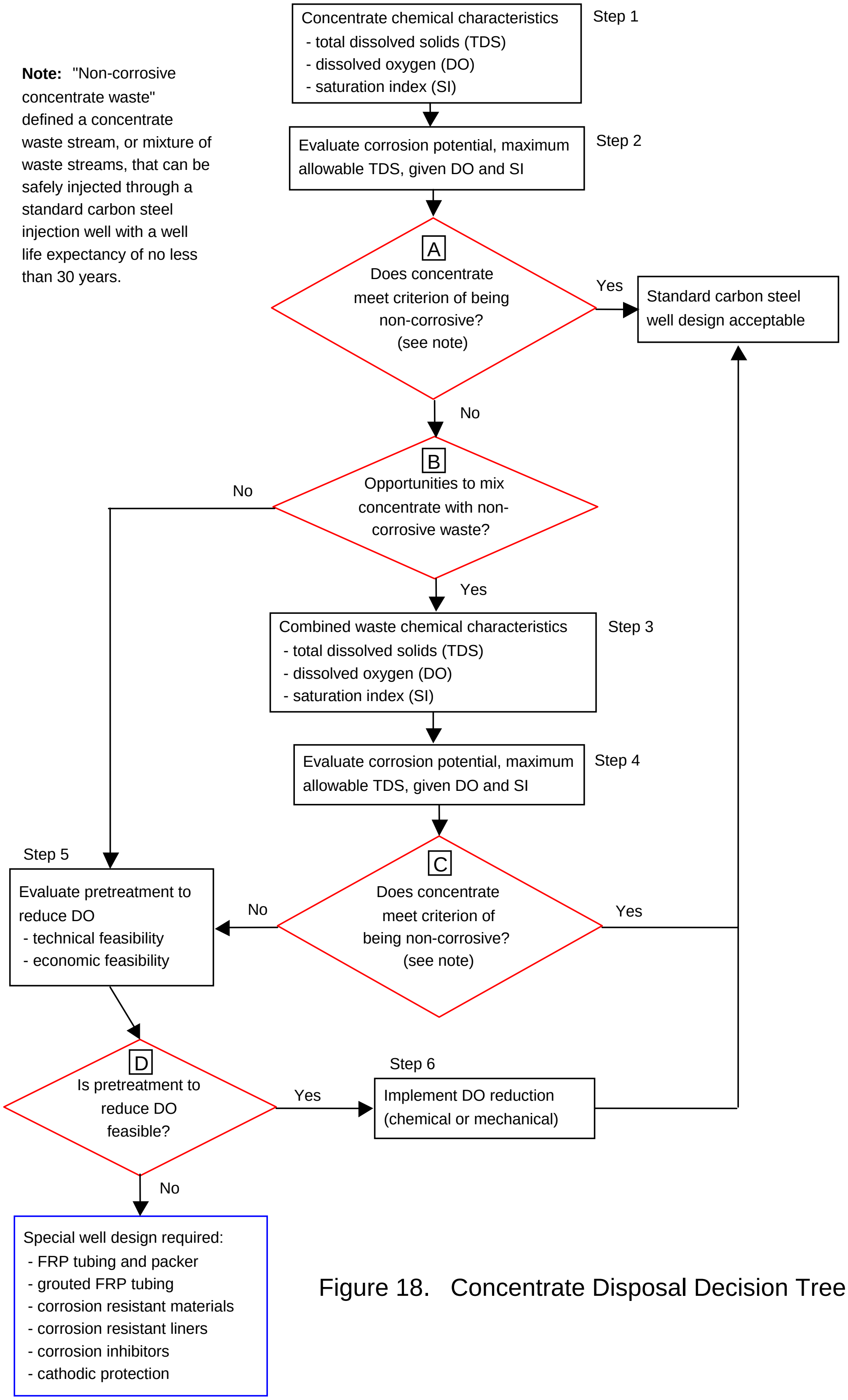
The parameters required to evaluate corrosion potential are:

- Dissolved oxygen concentration (DO)
- Total dissolved solids concentration (TDS)
- Saturation index (SI), which requires the concentration of carbonate, bicarbonate, sulfate, chloride, iron, calcium, magnesium, and sodium ions

Step 2 – Evaluation of Corrosion Potential (CRF) of the Concentrate

The corrosion potential of a given concentrate waste can be established given the TDS, DO and SI parameters as discussed previously.

For example, for a concentrate with DO = 5 mg/L, SI = 0.1 and TDS = 3,500 mg/L, the CRF will exceed the allowable value of 1.5. Referring to Figure 12, the maximum allowable TDS (given these DO and SI conditions) is in the range from 1,100 to 4,100 mg/L, depending upon the baseline SI.



Note: "Non-corrosive concentrate waste" defined a concentrate waste stream, or mixture of waste streams, that can be safely injected through a standard carbon steel injection well with a well life expectancy of no less than 30 years.

Figure 18. Concentrate Disposal Decision Tree

Decision Point A - Non-Corrosive Demineralization Concentrate

The definition of a "non-corrosive concentrate" for the purposes of this evaluation is a waste that can be safely discharged into an injection well of standard construction with a projected usable well life of no less than 30 years. Standard construction is defined as uncoated carbon steel casing with 0.5-inch wall thickness.

For a given case, if the results of the corrosion potential evaluation (Step 2) indicate that the waste meets the criteria of a non-corrosive concentrate (i.e., CRF = 1.5), then it is acceptable to discharge the waste into an injection well of standard construction. If not, then further evaluation is undertaken.

Decision Point B - Opportunities for Mixture with Other Waters

At this point in the decision process, it has been determined that the demineralization concentrate under consideration does not meet the non-corrosive criteria. In some instances there will be options for mixing the concentrate with other waters that will yield a mixture that does satisfy the non-corrosive criteria, most commonly a treated municipal wastewater effluent. If this possibility exists, then the evaluation of the mixture is undertaken (Step 3). If not, then analysis of pretreatment to reduce DO is undertaken (Step 5).

Step 3 – Mixed Demineralization Concentrate and Wastewater Characterization

For the purposes of this discussion, it is assumed that the concentrate will be mixed with treated municipal wastewater effluents. Concentrate mixtures with other types of effluent would require the tubing and packer well design.

This step in the decision process is similar to Step 2, except the characteristics of the combined water stream are evaluated. This can be performed by physically mixing representative samples of the demineralization concentrate with wastewater effluent (in proper proportion) and performing laboratory analysis. As an initial evaluation, or if samples of the wastestream(s) are not available, the parameters of the mixture can be calculated given the individual wastestream characteristics. For example:

Demineralization Concentrate: Flow = 0.6 MGD, TDS = 4,200 mg/L

Wastewater effluent: Flow = 3.3 MGD, TDS = 700 mg/L

Calculate the TDS concentration of the combined stream:

$$\text{Combined TDS} = \frac{(0.6 \text{ x } 4{,}200) + (3.3 \text{ x } 700)}{0.6 + 3.3} = 1{,}238 \text{ mg/L TDS}$$

Combined flow = 0.6 + 3.3 = 3.9 MGD

The combined DO can be calculated in similar fashion. The SI of the combined stream can be estimated by calculation of the concentrations of the individual components that are used to establish the SI.

Step 4 – Evaluation of Corrosion Potential (CRF) of the Mixed Stream

As in Step 2, the corrosion characteristic parameters are used to evaluate the CRF of the combined stream under consideration.

Decision Point C - Non-Corrosive Mixture

In a given situation, if the results of the corrosion potential evaluation (Step 4) indicate that the combined stream meets the non-corrosive criteria, then it is acceptable to discharge the combination into an injection well of standard construction. If not, then further evaluation is undertaken.

Step 5 – Evaluate Pretreatment to Reduce DO

The corrosivity of water treatment concentrates of various strengths is dependant on DO, because oxygen is involved in the primary cathodic reaction. Demineralization concentrates (of any strength) without oxygen are non-corrosive. Corrosivity increases with DO concentration and is diffusion limited (corrosion rate depends on the rate at which DO can diffuse to the steel surface). In the case of flowing demineralization concentrates, as in an injection well, the diffusion rate is very high because the shear stress created by the water flow produces a very thin laminar layer on the steel surface and corrosion rates can be significant. The type of carbon steel involved is a minor variable.

There are two basic options for controlling DO concentration as follows.

Chemical Deaeration

Chemical deaeration can be accomplished by injecting a catalyzed oxygen scavenger upstream of the injection well. Oxygen scavengers are reducing agent chemicals that react with DO (usually sulfite salts such as sodium sulfite, sodium bisulfite, etc.). A catalyst is required or the reaction rates are too slow for practical use. The best catalysts are divalent metal cations, like cobalt or nickel (Co^{+2} and Ni^{+2}). The reaction requires a few minutes to complete, so a mixed reaction vessel upstream of the well is required. Lab testing is suggested to determine the best and most economical oxygen scavenger, and dosage required on a case-by-case basis. Chemical deaeration is relatively low in capital expenditure, but on-going chemical costs are an economic consideration.

Mechanical Deaeration

Deaeration equipment can be installed. Examples are vacuum or gas towers to deaerate demineralization concentrate streams prior to injection. The capital costs for mechanical deaeration equipment can be high. Annual costs can be substantial to operate and maintain the vacuum pumps or provide a constant flow of oxygen-free gas to the tower.

Decision Point D - Pretreatment to Reduce DO - Cost Effectiveness

Once the most appropriate method of DO concentration reduction is established for a given application, the economics must be evaluated to determine cost feasibility. The following is an example of an economic feasibility evaluation for chemical DO removal for a concentrate stream, which is projected to average 600,000 gallons per day (gpd) during its first 10 years of operation; 800,000 gpd during its second 10 years; and 1,000,000 gpd during its third 10 years. The stream is expected to have an average DO concentration of 5.5 mg/L throughout its operating life. The system’s designer has determined that, if the DO concentration can be reduced to 1.5 mg/L or less, the waste stream will meet the criteria for a non-corrosive waste and a standard-construction carbon steel well can be used for injection. If not, a more expensive FRP tube and packer well will be required.

	YR 1-10	YR 10-20	YR 20-30
BASIS OF DESIGN			
AVERAGE FLOW - MGD	0.6	0.8	1.0
DO mg/L	5.5	5.5	5.5
TARGET EFFLUENT DO mg/L	1.5	1.5	1.5
DO REMOVED mg/L	4.0	4.0	4.0
DO REMOVAL - PPD	20	27	33
CHEMICAL TREATMENT			
SODIUM SULFITE			
USAGE RATIO LB CHEM/LB DO	7.90	7.90	7.90
EXCESS DOSE	5%	5%	5%
CHEMICAL USAGE - DRY PPD	166	221	277
CHEMICAL COST - $/DRY LB	$0.52	$0.58	$0.64
ANNUAL CHEMICAL COST	$31,500	$46,800	$64,600
ECONOMICS			
PRESENT WORTH OF CHEMICAL COSTS	$243,000	$221,000	$188,000
RATE OF RETURN	5%		
CAPITAL COST FOR CHEMICAL STORAGE & FEED EQUIPMENT	$40,000		
TOTAL PRESENT WORTH	**$692,000**		

Table 2. Example of an economic feasibility evaluation for chemical dissolved oxygen removal

The present worth of future chemical costs plus the capital expenditure for chemical storage and injection equipment in this example are $692,000. Thus, if the installation cost difference between a standard carbon steel well and a tubing and packer well is greater than $692,000, then chemical treatment to remove DO is cost justified and standard well construction can be used (Step 6). If not, then it is more cost effective to spend the extra capital to install the more expensive tubing and packer well and avoid the recurring chemical costs.

At this point in the decision process, it has been determined that (1) the concentrate stream does not meet the definition of a non-corrosive waste, (2) mixture opportunities do not exist or are not adequate to produce a non-corrosive waste mixture, and (3) DO removal is not feasible. Thus alternate methods or injection well construction techniques are required to handle a corrosive waste. These are addressed in the Section of this document titled Options for Managing Corrosive Demineralization Concentrate.

OPTIONS FOR MANAGING CORROSIVE DEMINERALIZATION CONCENTRATES

This section provides an overview of corrosion control options for managing demineralization concentrates that do not meet the non-corrosive waste criteria. Options examined include:

- Use of protective linings
- Use of cathodic protection
- Use of corrosion inhibitors
- Use of alternate construction materials
- Use of current design alternatives

Use of Protective Linings

Protective coatings or linings can be applied to metal (carbon steel in the case of injection wells) to minimize or prevent corrosion. Protective linings control corrosion by three mechanisms:

1. Barrier protection: Barrier protection is based on separating the metal from the corrosive environment (exposure to the corrosive concentrate stream).

2. Inhibitive protection: Chemical corrosion inhibitors added to the lining can disrupt the cathodic or anodic reactions, or both. However, use of inhibitors is most commonly implemented to control atmospheric corrosion, as their use in immersion service often leads to problems of blistering.

3. Sacrificial protection: Linings such as zinc or aluminum can afford a degree of cathodic protection.

The use of a lining on the interior of the well string is problematic, given the practical considerations of construction. The well consists of a series of pipe lengths, butt-welded at approximately forty-foot intervals. Thus, it would be difficult to establish a continuous protective barrier, as any applied coating would be damaged in the area of the weld. Welding and recoating each connection point as the pipe string is being installed would be impractical.

There are numerous organic, inorganic, and metallic linings available for control of internal corrosion of the well string. All these types have the common problem of coverage in the weld area. Cement mortar linings have been used extensively in the water/wastewater industries, although in this application bell and spigot connections are used instead of welding. Cement mortar linings in the well string would be susceptible to the build up of corrosion products between the lining and the pipe. Stresses imposed by this situation tend to lead to the sloughing off of the lining, exacerbated by the forces imposed by fluid velocity.

Metallic linings (sacrificial linings) are used in immersion service only where oxygen-induced corrosion is mild to moderate, and their use is most often beneficial in atmospheric service.

Therefore, the use of linings as a corrosion control method appears to be limited when dealing with demineralization concentrate injection wells.

Use of Cathodic Protection

Cathodic protection involves the imposition of an electric current to the surface of the protected metal, in effect forcing the metal to be the cathode in the corrosion cell. Cathodic protection systems can be either impressed (depending on an exterior source of current) or galvanic (depending on the use of more active metals such as zinc and aluminum). For injection well operations, cathodic protection is primarily used to control soil-side corrosion. Impressed current systems are impractical for the interior of a pipe string. Galvanic systems used inside the pipe involve spray application of metallic linings. Their efficacy in immersion is minimal in oxygen rich environments, and the defects induced at welds will further minimize their effectiveness.

Use of Corrosion Inhibitors

Many water systems (especially closed systems) employ chemical corrosion inhibitors. There are many organic and inorganic corrosion inhibitor chemicals available, many of which are considered toxic substances.

Inhibitors are commonly used for corrosion control within the annulus of tubing and packer injection wells (a closed system). Corrosion induced by oxygen in a saline environment of open systems cannot be effectively controlled with inhibitors (API 1958). Also, the flow-through nature of an injection well (as opposed to a closed-loop system) would require continual dose replenishment and chemical costs are expected to be prohibitive. Types of chemical inhibitors are sodium nitrate, sodium metaphosphate, sodium orthophosphate, sodium silicate, and potassium dihydrogen phosphate.

Use of Alternative Construction Materials

Carbon steel used in conventional well construction represents the most common material used in injection wells. The well-known structural properties, ease of manufacture and use, and low cost are important criteria for selection. There are more corrosion resistant metals and alloys available, including:

- Stainless steels
- Monels (Ni-Cu)
- Nickel-iron-chromium-molybdenum
- Aluminum
- Bronze
- Titanium

The selection of alternate metals and alloys requires an examination of the corrosive environment, as well as the physical requirements for the material. For oxygenated environments, where embrittlement is not a concern, metal selection should be based on control of metal loss. These metals are the more expensive alloys, such as stainless steel, nickel-based alloys and titanium. In addition to higher material costs, use of these materials will present challenges with welding. Any alternative material used for the construction of the wells would have to be approved by FDEP. It would need to be demonstrated that the material would not inhibit or interfere with the required geophysical logs such as the cement bond log, or with the required mechanical integrity testing.

Alternatively, nonmetallic corrosion resistant materials are available. There is a wide variety of non-metallic piping materials, including cementitious, ceramic, and plastics. The most extensively used materials are fiberglass pipes using epoxy resins.

Plastic materials are of two general types: thermoplastics and thermosets. Thermoplastic materials (e.g. PVC) may be resolublized in organic solvents. Thermosets involve catalyzed systems (e.g. epoxy) and are much more resistant to the effects of solvents. Both types of systems must be reinforced (filled with materials such as glass or graphite) to enhance properties such as strength.

Although immune to electrochemical corrosion (except for graphite reinforced materials), non-metallic materials exposed to a hostile environment can degrade by several mechanisms. The degradation of non-metallic materials can result in numerous failure mechanisms, including blistering, crazing, swelling, softening, and delaminations. In most cases the degradation leads to a loss of mechanical properties, especially strength. The concentrate environment typically would not have the organic solvent in sufficient quantities to adversely affect non-metallic materials, especially the thermoset materials. Thermoset materials include polyesters and epoxies. Epoxy coated steel has been used as an injection well material in Florida. Use of alternative construction materials will likely require alternative design or construction methods. Design and construction guidelines for use of these materials in Florida are not currently available.

Use of Current Design Alternatives

Injection wells can be constructed based on several different designs (Figure 19). The municipal well construction design is the most commonly used. Section 62-528.200 (45), *F.A.C.*, states that this design can only be used for wells injecting treated domestic wastewater. A telescoping method of casing installation is required. Normally a pit casing is installed to avoid sand caving into the borehole. The pit casing is often vibrated or driven into place, but in some areas is cemented. A surface casing is then installed through the silt and clay of the Hawthorn Group into the top of the Floridan aquifer system. The well drilling method for the surface casing is mud rotary circulation. An intermediate casing is normally installed to below the base of the underground source of drinking water (USDW). The drilling method employed to penetrate to this depth is reverse circulation or “reverse air.”

The surface and intermediate casing are required to be carbon steel with a thickness of at least 0.375-inch. The casings are required to be cemented into place with Florida Type II cement. The injection casing is installed to near the top of the injection zone. It is required to have a thickness of at least 0.50-inch and be seamless or an approved equivalent. The lower 200 feet of the injection casing is required to be pressure grouted in place using Florida Type II neat cement with no additives. The injection casing is then cemented to the surface.

Tubing and Packer Design

A tubing and packer design is required to be used for wells injecting wastewater that is considered corrosive or is nonmunicipal. The steel casings are required to be installed with the same methodology and requirements as the municipal well construction design. A tubing and packer is installed inside the 0.50-inch injection casing with the packer set near the top of the injection zone. The tubing is usually internally coated steel, stainless steel, acrylonitrile butadiene styrene (ABS), fiberglass reinforced plastic (FRP), or a similar material. The packers are normally positive seal with mandrel or equivalent. The annulus between the tubing and injection casing is filled with a corrosive resistant fluid (usually fresh water). The annulus is monitored continuously for pressure losses. This allows for continuous monitoring of internal mechanical integrity.

Fluid Seal Design

The fluid sealed annulus design is allowed for disposal of corrosive fluids. This type of design is commonly used in the petroleum industry but is not common in Florida. The surface, intermediate, and injection casings are installed just as in the municipal and tubing and packer well designs. The tubing is composed of a corrosion resistant material (internally coated steel, stainless steel, ABS, FRP, or similar material). No packer assembly is required, but the annulus is filled with light immiscible fluid (fuel oil, diesel, etc). The pressure in the annulus is monitored continuously providing for real-time internal mechanical integrity monitoring.

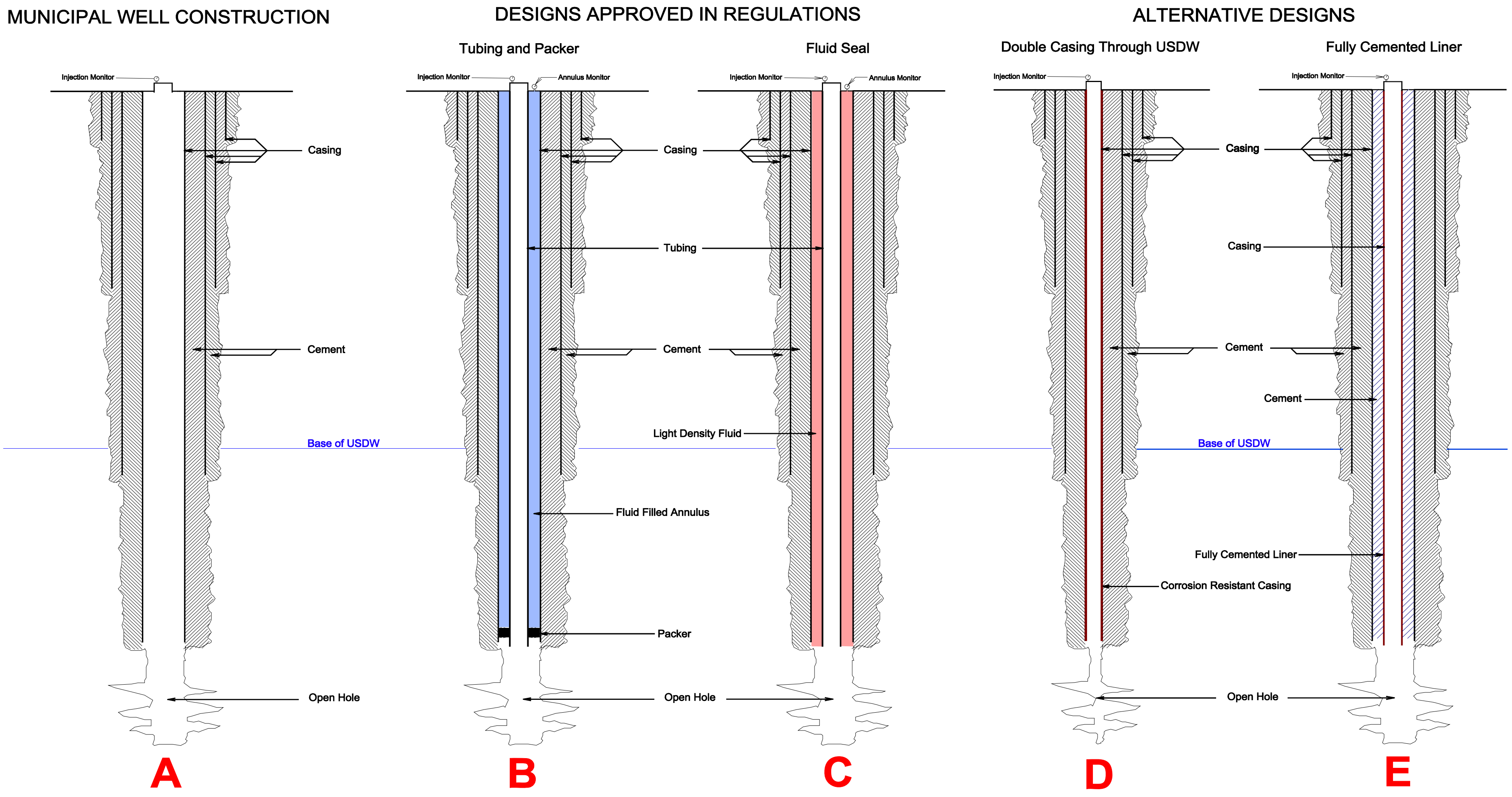
Double Casing Through USDW

The double casing through the USDW design has not been approved for any new injection wells in Florida. The surface, intermediate, and injection casings are constructed just as in the previous designs. A corrosive resistant casing is installed inside of the injection casing to the top of the injection zone. There is no fluid filled annulus so continuous monitoring of annulus pressure is not possible.

Fully Cemented Liner

The fully cemented liner design has been approved for several recently permitted demineralization concentrate injection wells. For this alternative design, the surface, intermediate, and injection casings are constructed as in the previously described alternative designs. The liner is composed of corrosion resistant material and extends to the top of the injection zone. A cement basket or disposable packer is set near the base of the liner and the annulus is cemented to the surface. Continuous monitoring of internal mechanical integrity is not possible and FDEP requires more frequent (interim) mechanical integrity tests (MITs).

Figure 19. Typical Class I injection well design options



SUMMARY

1. The tubing and packer requirement precludes many municipal injection well operators from utilizing existing domestic waste disposal wells for disposal of the by-product from demineralization of drinking water.

2. The corrosivity of demineralization concentrate (and mixtures of demineralization concentrate with municipal wastewater effluent), in terms of the ability to dispose of them in a standard-construction, carbon-steel injection well are case-specific and dependent on the chemical nature of the specific concentrate under consideration. In certain cases the disposal in standard construction wells would be acceptable based on projected corrosion rates, while in other cases more corrosion-resistant design would be appropriate to assure a 30-year life span of the well (e.g. FRP tubing and packer design). The FDEP injection rules, as currently written, are not adequate and appropriate to accommodate both cases. Currently the state regulations do not allow injection of a concentrate blend into a municipal well unless the concentrate is introduced into the headworks of the wastewater treatment plant

3. Neither the state nor the federal UIC regulations contain a specific definition of corrosive or non-corrosive waste. An appropriate definition of "non-corrosive waste" would be a waste that can be safely discharged into an injection well of standard construction with a projected well life of not less than 30 years.

4. Corrosion processes leading to the failure of steel casing and tubing used in injection wells are complex and not entirely understood. A number of factors appear to be important in causing corrosion and in controlling the rates of corrosion of steel materials used in injection wells. Significant factors include concentrations of dissolved oxygen and total dissolved solids, velocity of fluid movement, time of exposure, dissolved mineral saturation, and potentially biologically-mediated processes. Other factors such as temperature, the presence of electrical currents, and differences in salinity may also be important.

5. For the purposes of this evaluation the corrosion rate of carbon steel casing is generally proportional to the dissolved oxygen concentration of the injected demineralization concentrate. Higher dissolved oxygen

concentrations in demineralization concentrate cause higher corrosion rates.

6. Corrosion processes in steel pipes transmitting demineralization concentrate are extremely complex due to the range of possible oxidants and reductants, dependence of the reactions on localized conditions, and the complications arising from the formation of scales on the pipe surface.

7. The approximate upper TDS limits of demineralization concentrates to achieve 30-year lives for carbon steel injection well materials can be calculated (Figures 12-17).

8. Protective coatings can be applied to carbon steel injection well casings to minimize corrosion. However, it is difficult to establish a continuous protective barrier, as any applied coating can be damaged during periodic mechanical integrity testing of the well.

9. Cathodic protection and corrosion inhibiters in the effluent would have minimal effectiveness in inhibiting corrosion of carbon steel casing.

10. Currently, there is insufficient knowledge of well corrosion mechanisms and materials performance upon which to base any regulatory changes regarding well design.

CONCLUSIONS AND RECOMMENDATIONS

1. Current regulations allow co-disposal of municipal and non-municipal (e.g., demineralization concentrate) wastewaters only if they are combined prior to treatment at the headworks of the wastewater treatment plant (WWTP). It is recommended that the rules be modified to allow mixing of demineralization concentrate and treated wastewater effluents downstream of the WWTP discharge in specific circumstances, prior to discharge to the injection well. Key reasons for this recommendation are:

    - Treated effluent at most municipal WWTP facilities is reclaimed and distributed for irrigation. The high TDS from demineralization concentrate introduced at the headworks of the treatment plant may not be suitable for many irrigation practices.
    - Municipal WWTP primary and secondary treatment processes are not effective at removing contaminants typically found in demineralization concentrate (mostly dissolved salts and minerals). Thus these contaminants will pass through the WWTP processes largely untreated, which increases the hydraulic loading on the WWTP facilities without providing any appreciable benefit in terms of contaminant removal.
    - Most domestic WWTP facilities include one or more aerobic biological processes. Excessive dissolved solids concentrations (i.e. TDS) can have inhibitory or toxic effects on aerobic biological systems. Mixing of demineralization concentrate with domestic wastewater will increase the TDS loading on the WWTP's biological treatment systems.

2. Due to the lack of field data on corrosion rates and the associated physical, chemical, and biological conditions leading to corrosion, it is recommended that a statewide survey of existing injection wells be conducted to identify the occurrences (or non occurrences) of corrosion at each site, to assess the factors associated with corrosion, and to evaluate whether it may be possible to control corrosion by developing more specific guidance for the design of injection wells. This survey should include a literature search of corrosion management practices

in related engineering fields that involve disposal such as petroleum engineering, geothermal energy production, and thermal-flash distillation.

3. After completion of the statewide survey described in Conclusions and Recommendations Item 2 above, an inventory of operating wells should be developed and reviewed for the purpose of selecting wells for additional testing and analysis based on well construction materials age, effluent quality, and operational history.

4. Effluent water quality testing and material testing with a corrosivity meter (LPR) should be conducted at the wells selected as per Conclusions and Recommendations Item 3 above, to establish a direct correlation between concentrate chemistry and corrosion rates. Site-specific corrosion rates should be established for these wells and corrosion rate nomograms should be developed based on well construction materials and effluent corrosivity.

5. Develop an algorithm that could be used for design of new well systems. The algorithm should be designed to select appropriate well construction materials based on input of key baseline parameters including injectate chemistry and expected operational dynamics.

6. For municipal design wells, consider modifying existing UIC regulations to require direct corrosion rate measurements of carbon steel casing during the required mechanical integrity testing.

7. Establish methodologies for in situ measurement of corrosion of carbon steel casings at existing and proposed injection well systems.

8. Design and construction guidelines for use of alternative construction materials such as fiberglass casings should be developed for Florida applications. These guidelines should consider life cycle cost comparisons for construction using alternative materials vs. the tubing and packer design.

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