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CORROSIVITY LITERATURE AND DATA REVIEW FOR DEMINERALIZATION CONCENTRATE MANAGEMENT STUDIES AND WELL COMPLETION DESIGN

ST. JOHNS RIVER WATER MANAGEMENT DISTRICT

CORROSIVITY LITERATURE AND DATA REVIEW
FOR DEMINERALIZATION CONCENTRATE MANAGEMENT
STUDIES AND WELL COMPLETION DESIGN

Prepared for:

St. Johns River Water Management District

Prepared by:

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EXECUTIVE SUMMARY

The 2005 District Water Supply Plan (DSWP) (SJRWMD 2006) developed by the St. Johns River Water Management District (SJRWMD) has determined that treatment of brackish and saline waters by membrane treatment is a valuable treatment technology for meeting the water demands in SJRWMD projected through year 2025. However, management of the demineralization concentrate (concentrate) has been identified as one of the primary impediments to gaining regulatory approval for these types of treatment systems.

The feasibility of demineralization of brackish and saline waters is controlled partly by the ability to dispose of the concentrated byproduct of demineralization. The disposal of concentrate by deep well injection is potentially a solution; however, the corrosivity of the fluid and its compatibility with the steel tubing that is typically used for such wells presents both technical and regulatory challenges.

Therefore, the following report was developed to assess corrosion rates in deep injection wells that dispose of concentrate from the demineralization of brackish water and to identify the well construction options available for the construction of these wells within SJRWMD. In order to accomplish this task, the following three tasks were performed:

1) A literature review was performed to develop a list of reference material addressing corrosion in injection wells. This literature search was also utilized to determine the impact of corrosion on the injection well industry and the solutions to corrosion problems that have been developed by the injection industry and other industries that are required to place pipe below land surface.

2) A survey was performed to establish the impact of corrosion on Class I concentrate disposal wells within the state of Florida and methods utilized within the state to mitigate or eliminate corrosion problems.

3) A review of currently utilized injection well designs was performed to establish the options available for the construction of Class I concentrate disposal wells. Specific designs were reviewed and evaluated based on the different materials that are currently utilized for construction.

The following information was obtained from the literature survey:

- Corrosion of mild steel in an injection well occurs at the walls of the tubing material in contact with the injected water. Corrosion on the outside wall of the tubing and the casing is rarely an issue.

- Corrosion rates of 2 mils per year (mpy) or less are recommended by the National Association of Corrosion Engineers (NACE 1985), but rates of 20 mpy can be acceptable in some applications. One thousandth of an inch is equal to one mil, therefore the loss of one thousandth of an inch in one year equates to a corrosion rate of 1 mpy.

- The use of corrosion resistant materials such as fiberglass, special alloy steels, and plastic coated pipe were effective at minimizing or eliminating corrosion.

- De-oxygenation of injected water has been effective at minimizing corrosion for the injection of brine water injected into oil and gas brine disposal wells.

The survey of the Class I injection wells disposing of concentrate in Florida showed that:

- Sixteen facilities, with 19 total wells, initially utilized mild steel tubing as the material of construction. Of these 19 wells, 11 have failed due to corrosion.

- The corrosion rate of mild steel tubing in the Class I wells ranged from 25 to greater than 500 mpy with an average value of 178 mpy and a median rate of 167 mpy for those wells known to have failed to meet mechanical integrity requirements in Florida.

- Based on the high corrosion rates observed for mild steel tubing, the Class I concentrate disposal wells in Florida are currently being constructed with corrosion resistant materials. Epoxy and plastic lined pipes were the first materials utilized in the state to circumvent the corrosion. Fiberglass is currently the most utilized material. A duplex steel alloy, known as 2205 duplex steel, has also been successfully utilized in the construction and operation of one well.

- The total dissolved solids content of the injected water does not have an overriding impact on corrosion. Wells have failed with similar corrosion rates although the total dissolved solids (TDS) levels in the injected water ranged between 400 milligrams per liter (mg/l) and 14,000 mg/l.

Potential methods to mitigate corrosion in concentrate disposal wells, including the use of corrosion resistant materials, de-oxygenation, chemical inhibitors and cathodic protection, are presented in this report. Cost and potential effectiveness were also discussed. Based on the reviewed information, the use of corrosion resistant materials appeared to provide the most cost effective method of combating corrosion. Well construction designs based on the use of corrosion resistant materials were reviewed and critiqued. The discussions provided in this report support the use of a liner completion based on:

- The reduced manpower required to operate and maintain a liner completion versus a tubing and packer type completion,

- The reduced number of points at which pressure losses (leaks) can occur that are not associated with a breach of the longstring casing,

- The added protection of the outer casing provided by the presence of cement sheaths on both the inner and outer surfaces of the final longstring casing, and

- The reduction in the magnitude of forces acting on a liner versus the magnitude of forces acting on the tubing in a tubing and packer completion due to seasonal temperature changes.

CONCLUSIONS

The following conclusions are based on the information developed during the preparation of this report:

1. Class I disposal wells, as with the vast majority of oilfield production and injection wells, have not experienced significant corrosion problems when using mild steel as the casing material. However, mild steel tubing is highly susceptible to corrosion in wells injecting concentrate from desalinization processes (concentrate) or a mixture of concentrate and water reclamation facility effluent.

2. While the corrosion rates for concentrate from desalinization and water reclamation facilities suggest that dissolved oxygen is the primary causative factor; the lack of data on dissolved oxygen levels did not allow a definitive conclusion of this relationship.

3. The median mild steel corrosion rate of tubing for wells in Florida injecting concentrate or a combination of municipal waste and concentrate is 167 mpy. Observed corrosion rates ranged from 25 mpy to greater than 500 mpy. All observed corrosion rates were far in excess of the NACE recommended maximum rate and the New Mexico target rate (NMWAIDS n.d.) of 2 mpy and are related to a pitting corrosion attack rather than uniform corrosion of the tubing material.

4. Of the 22 wells with reported total dissolved solids (TDS) data, 5 wells had TDS levels of less than 4,100 mg/l, 7 wells had TDS levels between 4,100 and 10,000 mg/l, and 10 wells had TDS levels greater than 10,000 mg/l. The data do not indicate that TDS has a large influence on the failure rate of the wells.

5. Corrosion resistant materials such as 2205 duplex steel, fiberglass, and plastic coated or lined pipe provide the best options for reducing or eliminating the negative impact of corrosion on tubing in Class I non-municipal injection wells.

6. PVC pipe can provide good service for shallow Class V wells utilized to inject concentrate in coastal areas authorized to use this type well by the Florida Department of Environmental Protection.

7. Liner completions offer a significant advantage over tubing and packer completions when constructed properly. Therefore, concentrate disposal wells should be completed using a liner made from fiberglass or 2205 duplex steel.

RECOMMENDATIONS

1. Based on a review of the corrosion rate data, it is recommended that a corrosion resistant material be utilized for the tubing or liner in a concentrate or combination concentrate/municipal waste disposal well.

2. The major choices of materials are:

- Fiberglass or 2205 duplex steel. The actual choice of 2205 duplex steel or fiberglass will ultimately be left to the preference of the engineer. However, in those cases when 2205 duplex steel can reduce the number of required wells, then 2205 duplex steel is the recommended material of construction.

- PVC for shallow Class V wells that do not require the use of a tubing and packer or liner is a viable option. PVC could also be considered as a liner material for shallow wells that do not exceed 500 to 800 feet in depth.

3. Based on current construction standards, it is recommended that Class I concentrate and concentrate/municipal waste disposal wells be completed using a liner rather than a tubing and packer type completion.

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1.0 INTRODUCTION

Background

The 2005 District Water Supply Plan (SJRWMD 2006) developed by the St. Johns River Water Management District (SJRWMD) has determined that treatment of brackish and saline waters by membrane treatment is a valuable treatment technology for meeting the water demands in SJRWMD projected through year 2025. However, management of the demineralization concentrate (concentrate) has been identified as one of the primary impediments to gaining regulatory approval for these types of treatment systems.

The feasibility of demineralization of brackish and saline waters is controlled partly by the ability to dispose of the concentrated byproduct of demineralization. The disposal of concentrate by deep well injection is potentially a solution; however, the corrosivity of the fluid and its compatibility with the steel tubing that is typically used for such wells presents both technical and regulatory challenges.

There are two classifications of wells authorized by the Florida Department of Environmental Protection in which concentrate from a demineralization process can be injected. In all cases, the receiving aquifer must have a total dissolved solids (TDS) content greater than 10,000 milligrams/liter (mg/l). The major classification is for deep injection wells that must be cased through aquifers containing less than 10,000 mg/l TDS. These wells are given the designation of Class I injection wells and they must have both a casing and an inner tubing or liner to conduct the injected water from the surface to the subsurface injection interval. The second type of well is a Class V, Group 4 well. This classification is utilized for injection of concentrate when no aquifers containing less than 10,000 ppm (parts per million) TDS lie within 0.25 miles of the wellbore. An aquifer containing less than 10,000 mg/l TDS is considered an underground source of drinking water (USDW).

SJRWMD, in coordination with the Florida Department of Environmental Protection (FDEP), conducted a preliminary evaluation to determine appropriate injection well design requirements for disposal of demineralization concentrate from systems that are designed to produce potable water. The chemical and physical characteristics of typical concentrate generated by membrane demineralization systems were used to determine acceptable corrosivity rates for carbon steel injection well casing. SJRWMD is seeking to develop more information regarding corrosion characteristics of concentrate and suitability of well casing materials in order to provide design guidance to assist water suppliers in developing acceptable concentrate disposal systems.

Purpose and Scope

There is a general lack of field data on corrosion rates that occur in injection wells disposing of membrane concentrate and the associated physical, chemical, and biological conditions that lead to corrosion. Of particular interest is determining whether there is adequate field data available to determine the relationship between dissolved oxygen levels in the concentrate and corrosion rates. The scope of work for this project included a survey of existing injection wells to identify the occurrences (or non-occurrences) of corrosion and assessment of the factors associated with corrosion. The work also included an evaluation regarding whether it may be possible to control corrosion by developing more specific guidance for the design of injection wells. This work primarily focused on Florida systems; however, injection well systems outside of Florida that have experienced corrosion are included where they provide important information.

Also included is a literature search of corrosion management practices in related engineering fields that involve similar circumstances related to the transmission of brackish and saline water such as occurs in water production, demineralization processes, wastewater treatment, petroleum engineering, and geothermal energy production.

In addition to the corrosion analysis and review, well completion design options that can be utilized for concentrate disposal wells were reviewed. This review was included based on discussions with the SJRWMD project management staff concerning well designs and the recent introduction of a packer that is designed and installed by a Florida based drilling company that specializes in the construction and repair of Class I injection wells in the state of Florida. Information is included that covers the FDEP basic well design requirements, and well design variations including available packer styles and connection types (threaded versus welded). A comparison between standard tubing and packer completions and alternate liner completions is also provided. The information in this report is an overview of the options in well construction that are available for constructing a Class I demineralization concentrate disposal well in the state of Florida and the advantages and disadvantages of these construction alternatives.

2.0 CORROSION IN CONCENTRATE DISPOSAL WELLS

There are two major variations of corrosion discussed in this section. These two variations in corrosion are generally described as uniform corrosion and pitting corrosion. Uniform corrosion, as the term suggests, relates to general corrosion over an entire surface. For this document, the second type of corrosion is pitting corrosion. For visualization purposes, uniform corrosion is inferred to mean direct contact between interacting chemical species in which electrons (e^-) are transferred directly between reactants. This type of chemistry is represented as completely balanced chemical equations as indicated below:

$$aA + bB \rightarrow cC$$

Pitting corrosion is associated with reactants that are spatially separated. These reactions require that electrons be transported through the material from one point to another. This reaction type is represented in this section by electrons being generated or consumed as indicated in the chemical half reactions represented below:

$$A + 2e^- \rightarrow A^{2-} \quad \text{(reduction)}$$

(reduction occurs at the cathode)

$$B \rightarrow B^{2+} + 2e^- \quad \text{(oxidation)}$$

(oxidation occurs at the anode)

The difference in these two types of corrosion reactions (uniform and pitting) is emphasized here since a previous report (Sims et al. 2005) focused on uniform corrosion and, based on the findings of this work, pitting corrosion is the major reaction path responsible for the failure of Class I injection wells in the state of Florida.

2.1 Definition of Corrosivity

The types of water being injected into Florida's concentrate disposal wells do not meet the United States Environmental Protection Agency's (EPA) definition of corrosive. The EPA definition of corrosive, as utilized by environmental agencies including state Underground Injection Control (UIC) programs, is presented in 40 CFR 261.22 and restated below:

"(a) A solid waste exhibits the characteristic of corrosivity if a representative sample of the waste has either of the following properties:

(1) It is aqueous and has a pH less than or equal to 2 or greater than or equal to 12.5, as determined by a pH meter using Method 9040 in "Test Methods for Evaluating Solid Waste, Physical/Chemical Methods," EPA Publication SW-846, as incorporated by reference in Sec. 260.11 of this chapter.

(2) It is a liquid and corrodes steel (SAE 1020) at a rate greater than 6.35 mm (0.250-inch) per year at a test temperature of 55 ^{o}C (130 ^{o}F) as determined by the test method specified in NACE (National Association of Corrosion Engineers) Standard TM-01-69 as standardized in "Test Methods for Evaluating Solid Waste, Physical/Chemical Methods," EPA Publication SW-846, as incorporated by reference in Sec. 260.11 of this chapter."

A fluid that does not meet the above characteristics is categorized as non-corrosive. However, as indicated in the EPA Technical Assistance Document, Corrosion, Its Detection and Control in Injection Wells" (EPA 1987), a pH of 4 is considered corrosive to mild steel. The EPA document also indicates that the presence of aggressive chemical species in the absence of scale formation can cause corrosion of carbon steel at pH levels of 5.5. A review of the data presented later in this report (Subsection 2.3) shows that the concentrate typically produced during the desalination process does not meet the EPA definition of corrosive nor do these injectates have pH levels below 5.5. However, as will be shown in this report, the concentrate injected into disposal wells in

Florida is sufficiently corrosive to commonly cause mild steel tubing in these wells to lose mechanical integrity within 2 to 10 years of installation. Loss of mechanical integrity means that the annulus between a tubing and packer cannot hold a pressure equal to 1.5 times the maximum injection pressure for a period of 1 hour within plus or minus 5% of the initial starting test pressure.

When a well looses mechanical integrity, the cause of the loss in mechanical integrity must be determined. Most often, the loss in mechanical integrity is due to a leak around the packer or a leak in the tubing. If the tubing is leaking, it must be replaced. If the packer is leaking, it may not need to be replaced if the leak can be repaired from the surface by adding a small amount of solid material such as barite or bentonite pellets. If the packer cannot be sealed from the surface using a method accepted by the FDEP, then both the tubing and packer will most often need to be replaced.

2.2 General Discussion of Corrosion Mechanisms

As indicated previously, reactions associated with the direct contact between two reactants are indicated by chemical equations that are balanced and show both the oxygenated and reduced species (chemical equations 1 through 4). These type reactions are most often associated with uniform corrosion over the metal surface.

Chemical reactions associated with electrochemical cells (pitting) show only the oxidation or reduction reaction and are represented by chemical half reactions (Chemical Equations 5 through 7). Those half reactions with electrons (e^-) on the left side of the equation indicate reduction. Half reactions with the electron (e^-) denoted on the right side of the chemical equation represent oxidation. This nomenclature is utilized to help distinguish between direct oxidation/reduction reactions due to direct contact and those reactions representative of pitting corrosion, crevice corrosion, chloride stress corrosion, or other types of corrosion associated with the generation of an electric current due to the formation of a galvanic cell (battery). Since pitting corrosion is the major controlling mechanism for corrosion in concentrate disposal wells, those reactions indicating that electrons are being transferred are the major reactions upon which to focus.

A third type of corrosion, not addressed in this document, is associated with the injection of low pH fluids, - i.e. fluids with pH levels below 4. This category is not addressed since the fluids injected into Florida's wells that were surveyed, with one exception, have pH levels above 6.0.

The fundamental reactions associated with the direct oxidation of steel by oxygen and chlorine (uniform corrosion) include:

1) $Fe + O_2 + H_2O \rightarrow Fe^{2+} + 2OH^-$

2) $Fe + ClO^- + H_2O \rightarrow Fe^{2+} + 2OH^- + Cl^-$

Chemical equation 1 represents the direct oxidation of elemental iron to Fe^{2+} by direct contact between the steel construction material and dissolved oxygen in water. The second reaction represents the direct oxidation of elemental iron to Fe^{2+} by direct contact of the steel construction material and aqueous chlorine (hypochlorite) in water. In the presence of either of these oxidants (hypochlorite or oxygen), the iron (II) in solution is rapidly oxidized to iron (III), which precipitates from solution as iron (III) hydroxide (reaction 3) or iron (III) oxyhydroxides (reaction 4).

3) $2Fe^{2+} + 1/2O_2 + 5H_2O \rightarrow 2Fe(OH)_3 + 4H^+$

4) $2Fe^{2+} + 1/2O_2 + 3H_2O \rightarrow 2FeO(OH) + 4H^+$

The second corrosion mechanism, which is the most relevant to the corrosion of the inside of the injection tubing, is associated with the development of an electrochemical cell. Types of electrochemical corrosion include:

- Pitting Corrosion
- Crevice Corrosion

- Stress Corrosion Cracking

Pitting corrosion generally is enhanced in the presence of mobile ions such as the chloride ion (Ahluwalia 2003). For this type corrosion, a difference in the potential on the inside surface of the pipe can occur due to the protection of one portion of the pipe from oxygenated water and the exposure of another portion of the pipe to oxygen or other oxidizing material. The overall reactions are similar to those specified previously, but in this case; the reaction occurs at different points in the pipe and requires that the pipe be able to conduct electricity (electrons) between the points where the reactions are taking place. This type reaction is most responsible for the high corrosion rates observed in the Florida concentrate disposal wells (Section 5).

The point in the pipe where reduction occurs is defined as the cathode. Equation 5 is the basic chemical half reaction indicating the reduction of oxygen, while equation 6 is representative of low pH solutions (acids) and the reduction of hydrogen ions to hydrogen gas.

5) $4H^+ + 4e^- + O_2 \rightarrow 2\ H_20$

6) $4H^+ + 4e^- \rightarrow 2\ H_2$

The point in the pipe where oxidation occurs is defined as the anode. The anode reaction represents the loss of iron from the pipe. Reaction 7 is representative of chemical oxidation of iron and is the fundamental half reaction representing corrosion of steel pipe:

7) $Fe \rightarrow Fe^{2+} + 2\ e^-$

It is important to note that reaction 5 and 7 or 6 and 7 must occur almost simultaneously so that a build-up of charge does not occur. The electrons, which are required to be exchanged between the cathode and the anode, are transported through the conductive metal pipe. When pitting corrosion occurs due to a defect or change in the surface of the metal pipe, the area which is less exposed to oxygen or the general fluid behaves as the anode (NMWAIDS n.d.). In the case of mild steel, the iron is oxidized and moves into the aqueous phase. The movement of the iron into solution causes a build up of a positive charge in the region near the anode surface. The build-up of charge can slow the corrosion reaction down. However, in solutions that contain mobile, negatively charged ions such as the chloride ion, the negatively charged ion will move into the positively charged area and neutralize the charge. The neutralization of the charge allows the pitting corrosion to continue at a high rate.

Crevice corrosion appears to operate very similarly to pitting corrosion in that the crevice, due to its lack of exposure to the main fluid stream, can act as an anode. Again, mobile anions, such as chlorides, will tend to reduce the build-up of charge in the crevice and therefore enhance the continued localized loss of iron in the crevice.

Stress corrosion cracking is similar to crevice corrosion in that there is an area of the pipe surface that is not exposed to the bulk waste stream. In addition, corrosion may occur along grain interfaces due to the specific chemistry of the metal at these surface point anomalies. The key to this corrosion verses crevice corrosion is that the metal must be under stress for this type corrosion to be identified as stress corrosion cracking. Again, mobile anions, such as chlorides, will tend to reduce the build-up of charge in the pits, crevices, and other surface anomalies and therefore enhance the continued localized loss of metal. Similar discussions with references are available in the EPA Technical Assistance Document, “Corrosion, Its Detection and Control in Injection Wells” (EPA 1987). Stainless steel (300 series) is susceptible to pitting, crevice corrosion, and stress corrosion cracking.

Since fiberglass is not readily reactive with oxygen, it is not susceptible to corrosion. Furthermore, fiberglass behaves like an insulating material (non-conductor), and it does not support pitting, crevice corrosion, or the types of oxidation/reduction reactions requiring the transmission of electrons from one location to another – i.e. fiberglass does not participate in the formation of galvanic cells.

2.3 Quality of Water Injected Into Concentrate Disposal Wells

There are two types of wells injecting concentrate into disposal wells in Florida. The first type well injects a combination of both demineralized concentrate and municipal waste. The second type well is designed to inject only concentrate from a demineralization process.

Table 1 provides data on total dissolved solids (TDS), chlorides, conductance, and pH for the desalination concentrates that are injected at several locations within the state of Florida. Dissolved oxygen levels are not normally measured as part of the monitoring protocol and therefore this constituent is missing from the data and could not be evaluated. The pH levels of the discharge waters ranged between 5.8 and 8.7 with a mean value of 6.8. As can be seen from the data, the reverse osmosis (RO) systems in the state of Florida discharge concentrate with TDS levels ranging between 400 and 38,000 mg/l with a mean value of 13,000 mg/l. The chloride levels in these wells range between 100 and 30,000 mg/l with a mean value of 6,300 mg/l. Conductivity values range between 1,142 and 51,600 microsiemens (μS/cm), with a mean value of 13,000 μS/cm. A review of Table 1 will show that there can be a variation in the salinity of water being injected in some of the wells. The most extreme example of this is provided by deep injection well (DIW) 7. Typically, a wide range of salinities is indicative of a well injecting both water reclamation facility (WRF) effluent and concentrate from a demineralization facility. The variation in salinity is typically seasonal. In the rainy season, an RO facility may be shutdown temporarily due to reduced water demand while the need to dispose of municipal waste increases due to the influx of storm water and low demand for irrigation water. In the dry season, disposal requirements are reversed. An RO plant is typically running near maximum capacity while the demand for re-use water is high, and therefore the need to dispose of the WRF wastewater is low.

TABLE 1

St. Johns River Water Management District
Deep Injection Well Water Quality Data
Class I Injection Wells

Deep Injection Well (DIW) Reference Number	Cl *	TDS*	Cond.*	pH*	Calculated Corrosion Rate For Steel Pipe	Observed Corrosion rate at point of failure
	mg/l	mg/l	uS/cm	S.U.	mpy ***	mpy
DIW 1	ND	ND	ND	ND	ND	ND
DIW 2	ND	ND	ND	ND	ND	approximately500
DIW 3	1,490	4,340	6,600	7.06	19.7	250
DIW 4	ND	ND	ND	ND	ND	167
DIW 5	100	2,400	2,500	6.1	16.9	167
DIW 6	290	2,150	2,910	6.1 - 6.7	16.4	250, 500**
DIW 7	225 - 19,500	680 - 30,400	1,142 - 50,000	6.5 - 8.7	32.2	53
DIW 8	7,033	14,300	22,166	6.6	26.6	56, 250**
DIW 9	7,033	14,300	22,166	6.6	ND	ND
DIW 10	ND	ND	ND	ND	ND	****NA
DIW 11	ND	ND	ND	ND	ND	****NA
DIW 12	2,500	400 - 1,500	6,000	6.5	15.2	250
DIW 13	351	2,400 - 2,800	2,900 - 3,400	5.8 - 6.3	17.1	25
DIW 14	570	4,600	5,000	7.0	20.0	45
DIW 15	ND	ND	ND	ND	ND	ND
DIW 16	2,800	7,212	10,700	7.7	ND	****NA
DIW 17	475; 70 - 2,900	1,530; 350 - 4,900	2,380; 830 -6,300	7.4; 6.9-8.2	20.3	****NA
DIW 18	ND	ND	ND	ND	ND	****NA
DIW 19	ND	ND	ND	ND	ND	****NA

TABLE 1 (Con't)

Deep Injection Well (DIW) Reference Number	Cl *	TDS*	Cond.*	pH*	Calculated Corrosion Rate For Steel Pipe	Observed Corrosion rate at point of failure
	mg/l	mg/l	uS/cm	S.U.	mpy ***	Mpy
DIW 20	Not in Operation	Not in Operation	Not in Operation	Not in Operation	ND	****NA
DIW 21	10,000	26,000	16,900	6.7	24.4	****NA
DIW 22	1,850	4,300	8,350	7.5	20.0	****NA
DIW 23	30,000	38,000	51,600	7.5	34.0	****NA
DIW 24	6,200 - 7,300	12,000 - 14,000	19,000 - 24,000	6.5 - 8.0	26.0	****NA
DIW 25	ND	ND	ND	ND	ND	****NA
DIW 26	Not in Operation	Not in Operation	Not in Operation	Not in Operation	ND	****NA
DIW 27	12,000	26,000	20,000	6.5 - 6.7	24.4	****NA
DIW 28	12,000	26,000	20,000	6.5 -6.7	24.4	****NA
DIW 29	Not in Operation	Not in Operation	Not in Operation	Not in Operation	ND	****NA
DIW 30	Not in Operation	Not in Operation	Not in Operation	Not in Operation	ND	****NA
DIW 31	ND	ND	ND	8.46	ND	****NA
DIW 32	ND	ND	ND	ND	ND	No Failure
DIW 33	215	2,044	2,545	6.8	16.3	No Failure
DIW 34	570	4,600	5,000	6.2	20.0	No Failure
DIW 35	450	2,950	3,600	6.0 - 6.8	18.5	No Failure
DIW 36	ND	ND	ND	ND	ND	No Failure
DIW 37	9,100	17,533	27,600	6.83	28.0	No Failure
DIW 38	9,100	17,533	27,600	6.83	28.0	No Failure

* WQ -Values are reported as an average, range, or average range. ND - No Data

** This site had two failures

*** Based on Equation presented by Sims et al.(2005)
TDS is only variable changed to calculate Corrosion Rate, SI = 0 and DO = 5 ppm

**** NA - Not Applicable – Fiberglass

2.4 Evaluating Corrosivity of Concentrates

A method for estimating the corrosion rate for mild steel was provided in Special Publication SJ2005-SP17 from the SJRWMD (Sims et al. 2005) and is provided below:

Equation 1

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

Where:

CR = Corrosion Rate in mpy
TDS = Total Dissolved Solids (ppm)
DO = Dissolved Oxygen (ppm)
SI = Langelier Saturation Index
TOE = Time of Exposure

The above corrosion rate calculation, which assumes a constant temperature, relates corrosion rate to four variables, TDS, DO, SI, and TOE. Of the four identified variables, TDS is the only parameter available from data sets typically provided to the FDEP and analyzed in this report. As noted previously, the dissolved oxygen concentration, which is arguably the most important parameter associated with corrosion, is not available. However, DO concentrations are anticipated to range between 1 and 6 ppm. It is important to note that the above equation applies to uniform surface corrosion. However, as the corrosion review in this study indicates, the critical corrosion path for the Florida wells is best described as pitting, a corrosion mechanism not addressed by Equation 1.

A comparison is made between the observed corrosion and calculated rates. The calculated rates were obtained using Equation 1 and assuming that TDS is the only changing variable (Table 1). The dissolved oxygen concentration was assumed constant at 5 ppm. As indicated by reviewing Table 1, the calculated corrosion rates are less than the observed corrosion rate at the point of failure and are, in many cases, more than 10 times less than the observed rates. The primary reason for this difference is that Equation 1 is based on uniform corrosion and the observed corrosion is associated corrosion at a single point.

As discussed in Section 6.0, and suggested by Equation 1, it might appear that there is a major opportunity for reducing corrosion rates of the concentrate waste streams by mixing concentrate with effluent from a water reclamation facility. However, as discussed in Section 6, the blending of these waters has not led to a successful mitigation of corrosion.

2.5 Field Example of Concentrate Corrosion Rates

A representative example of tubing corrosion is provided by reviewing the case history for city of Marco Island's injection well, IW-1 (Water Resource Solutions 2002a). At this site, the corrosion rate of an injection stream was determined after a 92 day test period using mild steel coupons and 2205 duplex steel coupons. The coupons, as shown in Figures 1 and 2, were approximately square with edge lengths of approximately 3 inches. The width of each coupon was approximately three-eighths of an inch. The injection stream was a mixture of RO concentrate and varying amounts of municipal waste as indicated by the chloride, conductivity (measured in micromhos/cm - μmhos/cm), and TDS concentrations (Table 2). The average TDS concentration over the test period was approximately 10,000 mg/l. Over the historic operational period of this well, the average TDS concentration was approximately 14,000 mg/l and ranged between 680 mg/l and 30,400 mg/l.

The purpose of this coupon test was to verify the corrosion rate of mild steel tubing in the injected water and compare the corrosion rate of mild steel to the corrosion rate of 2205 duplex steel under operating conditions. The experiment was conducted by lowering four coupons of mild steel and four coupons of 2205 duplex steel alloy into the well on a 1-inch diameter, schedule 80 PVC pipe. The duplex and mild steel coupons were mounted on opposite sides of the pipe using nylon bolts (Figure 1). The coupons were placed in the flow stream and hung vertically in the well. The coupons were left in the well for 92 days. As the data in Table 3 indicate, the corrosion rate for the mild steel was approximately 43 mpy.

Water Resource Solutions	PROJECT NAME: SJRWMD	DWG. NUMBER: 1143707mp1
	PROJECT NUMBER: 1143707	DATE: 07/17/07

FIGURE 1. COUPONS ATTACHED TO COUPON HOLDER AFTER 92 DAYS IN IW−1 INJECTION WELL STREAM.

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	PROJECT NUMBER: 1143707	DATE: 07/17/07

FIGURE 2. COMPARISON OF 2205 (ALSO MARKED 2202) COUPON AND MILD STEEL COUPON CORROSION AFTER 92 DAYS IN IW–1 INJECTION STREAM.

TABLE 2

Monthly Waste Stream Analyses Data

Date	pH (std. units)	Temp. (deg. C)	Conductivity (µmhos/cm)	Chloride (mg/l)	SO_4 (mg/l)	TDS (mg/l)	NO_3 (mg/l)	NO_2 (mg/l)	NH_4 (mg/l)	TKN (mg/l)
Jul-95	6.78		18,710	2,620	1,110	1,160	10	<0.01	0.169	1.35
Aug-95										
Sep-95	7.8	26.1	1,142	225	167	792	12.2	0.03	<.06	0.76
Oct-95	6.7	28.3	10,690	3,474	672	7,667	8.8	<.01	0.048	0.42
Nov-95	7.8	27.8	30,900	14,872	3,340	25,010	0.07	<.01	0.55	0.78
Dec-95										
Jan-96	7.3	28.3	40,100	10,800	2,240	27,000	<0.02	7.18	1.24	1.32
Feb-96	7.3	28.3	13,500	4,150	790	7,730	<.02	8.52	4.56	6.26
Mar-96	7.5		16,000	3,550	901	5,610	<0.02	6	5.23	0.32
Apr-96	7.5	28.9	46,500	17,800	3,070	30,400	<0.02	<0.02	1.14	1.21
May-96	7.3	28.3	25,600	8,700	1,820	17,600	<0.02	<0.02	1.31	1.52
Jun-96	7.7	28.9	2,170	824	160	1,510	<0.02	5.49	1.83	<0.05
Jul-96	7.5	28.3	21,400	7,990	1,560	11,866	<0.02	0.11	0.62	0.74
Aug-96	7.5	28.9	36,600	12,500	2,240	24,100	0.27	<0.02	0.84	<0.05
Sep-96	7.6	28.9	18,800	4,860	1,180	11,400	0.97	<0.02	0.03	0.03
Oct-96	7.1	28.9	1,420	534	137	784	<0.02	<0.02	1.72	3.25
Nov-96	7.1	26.7	23,300	8,020	1,520	13,097	<0.02	<0.02	0.74	1.32
Dec-96	7.6	28.9	42,000	18,800	2,440	25,840	<0.02	<0.02	0.26	<0.05
Jan-97	7.3	27.7	30,300	11,200	2,160	17,700	<.02	<.02	0.98	1.05
Feb-97	7.5	28.3	10,200	3,820	669	5,254	<.02	<.02	5.18	6.65
Mar-97	7.3	28.9	13,800	4,170	988	7,710	4.17	<0.02	5.64	8.49
Apr-97	6.9	29.4	31,900	13,200	2,220	19,712			0.98	0.92
May-97	7.1	28.3	31,100	12,700	2,260	16,100			1.22	0.11
Jun-97	7.1	33.3	29,700	11,700	2,130	18,800	0	0	1.34	<.05
Jul-97	6.8	28.9	10,200	3,270	674	5,940	7.12	<0.02	2.75	2.89
Aug-97	6.6	29.4	34,600	14,700	2,460	22,100	<.02	<.02	1.68	0.07
Sep-97	6.6	30.4	40,100	19,500	3,240	25,900	<.02	<.02	1.12	1
Oct-97	6.6	27.6	38,600	10,300	1,987	24,300			1.07	1.57
Nov-97	6.7	27.8	14,600	4,290	831	8,820	<0.02	<0.02	1.67	2.28
Dec-97	6.6	27.2	45,000	16,000	2,700	30,000	<.02	<.02	1.2	1.70
Jan-98	6.8	25.9	13,000	4,400	930	7,200	6.9		9.6	10.00
Feb-98	7.07	26.6	9,400	3,400	670	5,600	0.032		1.5	
Mar-98	7.3	29.8	38,000	14,000	2,500	27,000	ND	ND	1.2	1.40
Apr-98	7.18	27	14,000	4,300	890	9,900	0.1	1.6	5.7	6.4
May-98	6.5	30.9	44,000	18,000	2,900	30,000	<.02	<.005	1.1	1.40
Jun-98	7.4	31	42,000	18,000	3,000	28,000	<.02	<.005	1.4	1.5
Jul-98	7.0	32	1,300	18,000		680			3	4.10
Aug-98	6.7	32.3	2,600	740	160	2,600	<.02	9.5	4.2	5.00
Sep-98	7.1	30.2	27,000	9,700	1,500	20,000	<.02	<.02	0.58	0.81
Oct-98	7.0	29.7	14,000	3,900	640	8,500	3.2		6.2	5.0
Nov-98	6.68	28.9	14,000	5,400	940	9,100	0.77		7.1	7.8
Dec-98	7.4	25	7,800	2,000	360	4,800	<.020	15	2.6	3.00
Jan-99	8.7	26.5	14,000	5,300	910	8,500	0.093	4.9	5.7	5.6

TABLE 2 (Con't)

Monthly Waste Stream Analyses Data

Date	pH (std. units)	Temp. (deg. C)	Conductivity (µmhos/cm)	Chloride (mg/l)	SO_4 (mg/l)	TDS (mg/l)	NO_3 (mg/l)	NO_2 (mg/l)	NH_4 (mg/l)	TKN (mg/l)
Feb-99										
Mar-99	6.7	27.3	33,000	12,000	1,900	21,000	0.036	0.12	7.3	9.30
Apr-99	6.8	29	19,000	7,900	1,400	15,000	1.8	0.06	2.9	2.7
May-99	6.9	28.3	50,000	470	110		0.065	2.7	2	2.60
Jun-99	7.6	30.8	8,700	2,500	460	5,300		13	0.36	1.3
Jul-99	7.7	28.7	24,000	8,000	1,500	18,000	<.02	<.02	1.00	1.50
Aug-99	7.3	28.2	12,000	4,600	750	7,900	<.02	<.02	0.24	1.10
Sep-99	6.98	29	6,800	2,400	400	8,800	<.02	6.9	1.6	2.5
Oct-99	7.2	28.2	17,000	5,300	960	11,000	3.9	0.14	2.9	3.40
Nov-99	7.7	28.8	25,000	13,000	2,100	22,000	0.04	<.02	0.95	1.5
Dec-99	6.6	27.2	45,000	16,000	2,700	30,000	<.02	<.02	1.2	1.70
Jan-00	6.7	25.8	21,000	8,300	1,400	13,000	0.12	0.46	9.7	10
Feb-00	6.81	26.4	19,000	6,400	1,100	11,000	1.3	1.3	7.4	7.7
Mar-00	6.8	27.5	30,000	9,600	1,700	20,000	0.14	0.13	6.5	7.10
Apr-00	7.4	28.7	20,000	6,300	960	12,000	1.7	0.075	6.1	6.00
May-00	8.6	34	34,000	12,000	1,600	23,000	<.02	0.02	0.86	1.50
Jun-00	7.9	27.3	8,800	3,200	440	5,600	7.5	<.02	1.7	2.6
Jul-00	7.9	32.5	24,000	7,600	1,000	17,000	0.52	<.02	0.9	1.80
Aug-00	7.6	30.2	1,300	240	150	800	<.02	15	.05U	1.10
Sep-00	7.25	31.7	1,500	320	150	810	<.02	7.8	.05U	1.2
Oct-00	6.9	27.3	28,000	9,400	1,400	18,000	<.02	<.02	0.91	1.30

TABLE 3

Coupon Corrosion Rate Test Results

Specimen Number and Type	Total Specimen Surface Area (in^2)	Initial Weight (Grams)	Weight After 92 Days (Grams)	Net Weight Change (Grams)	Corrosion Rate (mpy)
1 SS*	14.923	281.90	283.15	1.25	***
2 SS*	15.157	282.53	284.20	1.67	***
3 SS*	15.005	282.00	283.60	1.60	***
4 SS*	14.903	280.95	282.70	1.75	***
1 MS**	14.848	275.20	253.90	-21.30	43.8
2 MS**	14.763	274.80	254.20	-20.60	42.6
3 MS**	14.862	275.18	254.80	-20.38	41.8
4 MS**	14.958	275.32	254.40	-20.92	42.7

* SS is used to indicate coupon was 2205 Duplex Steel

** MS is used to indicate coupon was constructed from mild steel

*** Measurements show a gain in weight and therefore no valid corrosion rate was determined. The weight gain, after consultation with industry experts, is assumed to be due a film build-up on the coupons.

It is known that a thumb size hole appeared in the tubing for this well after approximately 9.5 years of operation. The local corrosion rate at the point of tubing failure was at least 53 mpy based on the 9.5 years of operation and a pipe wall thickness of 0.5inches. The test coupons were located within 15 feet of the tubing failure point. Figure 2 provides a visual comparison of the mild steel and the 2205 duplex steel coupons once they were removed from the well. It is relevant to note that most of the injection tubing, upon removal from the well, had uniformly lost approximately 0.25 inches of wall thickness over the entire length of pipe. The tubing wall losses correlate to a uniform corrosion rate of approximately 26 mpy, which is actually 6 mpy less than the 32 mpy calculated using the corrosion equation. Figures 3 and 4 provide visual evidence of the corrosion of the tubing recovered from the failed well. It is also relevant to note that these pictures show a thick layer of iron rich scale on the inner wall of the tubing. The combined thickness of the iron rich scale and the remaining steel wall is approximately 0.50 inches. Thus, a normal caliper evaluation that might be conducted to evaluate casing integrity would not indicate that any loss in wall thickness had occurred.

Prior to the initial construction of the example well, a corrosion study was performed to evaluate four different materials that could be utilized as the tubing material for the injection well (Harco Technologies 1990). The alternative choices listed for this well were mild carbon steel, carbon steel with a PTFE (Teflon) liner, stainless steel (AL6XN), and Hastelloy C. Harco Technologies (1990) experts determined that mild steel, at the time, was the best choice based on cost and the ability and estimated cost to replace the tubing when it failed. Harco Technologies (1990) estimated that the corrosion rate of the mild steel would be approximately 50 mpy, in good agreement with actual corrosion failure rate of 53 mpy and the estimated corrosion rate of 43 mpy from the corrosion coupon testing performed on this well after the tubing failure. The experience at the above site suggests that the life expectancy of mild steel tubing in a municipal/concentrate disposal well would be anticipated to be on the order of 10 years or less under typical Florida conditions.

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FIGURE 3. CORROSION ENCRUSTED TUBING AFTER 9.5 YEARS SHOWING 0.25 INCHES OF WALL THICKNESS REMAINING.

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FIGURE 4. CORROSION ENCRUSTED TUBING AFTER 9.5 YEARS OF OPERATION.

2.6 Dissimilar Metals

A slightly different form of galvanic corrosion can occur when dissimilar metals are in contact with each other. When this occurs, a galvanic current can be set-up, which causes the less noble material (anode) to corrode faster, and the more noble metal to corrode slower. Stainless steel is more noble than mild steel (1010 steel as an example). This means that when stainless steel (300 series stainless steel or 2205 duplex steel) is in contact with mild steel, the mild steel is anticipated to corrode and inhibit the corrosion of the stainless steel.

This issue has some relevance if 2205 duplex steel is utilized as the tubing or liner material (See Section 5) or if stainless steel ends are used with fiberglass to connect the fiberglass string to the mild steel casing, which is not uncommon for Class I wells. In either case, the contact between the stainless steel and the mild steel will occur. For incidental contact between the stainless steel and the mild steel, it is argued that the mild steel will ultimately corrode at the point of contact. The corrosion point will rust, and this rust will inhibit further deterioration of the casing (Roscoe Moss Company 2007). Corrosion due to incidental contact can be further reduced by using non-conducting centralizers to minimize contact between the casing and the tubing and then to cement the fiberglass tubing in place so that the free movement of water in the tubing/casing annulus is eliminated.

For stainless steel connections on the fiberglass tubing, it is suggested that if the ratio of the surface area of the mild steel is 10 times the surface area of the stainless steel, then galvanic corrosion due to dissimilar metals should be small (ASSDA n.d). Thus, the use of stainless steel to make connection with a packer or the casing at the bottom and top of the casing is not anticipated to result in significant corrosion. However, cementing the fiberglass tubing in the casing should substantially reduce any impact due to dissimilar metals.

3.0 TYPICAL WELL CASING PROGRAMS FOR CONCENTRATE DISPOSAL WELLS

Before proceeding with the discussion of corrosion in Class I concentrate disposal wells, a brief discussion is provided that outlines the casing construction designs for these wells. A typical Class I concentrate disposal well is constructed with four different casing strings. These casing strings are known by a variety of names. However, the following discussion provides the specific names utilized in this document to describe each casing string (Figure 5).

Subsection 3.8 provides a brief description of a general Class V well that could be permitted and constructed for concentrate disposal in regions where no USDW is present or where the USDW lies below the target disposal zone.

3.1 Conductor Casing

The first casing string is commonly named the conductor or pit casing. In Florida, this casing string is typically set to a depth of 100 feet or less below the surface. This casing string is constructed from 0.375-inch wall spiral welded steel casing meeting Spiral Weld ASTM A139 Grade B standards. The actual length of this casing string is commonly selected by the drilling contractor.

3.2 Surface Casing

The second casing string is typically set at a point below the depth where formation sand production is no longer considered a problem. Typically, this casing marks the point at which the drilling technique switches from conventional mud rotary drilling to reverse air drilling. This second casing, which will be called the surface casing, is typically constructed from 0.375-inch wall, spiral welded steel casing meeting Spiral Weld ASTM A139 Grade B standards.

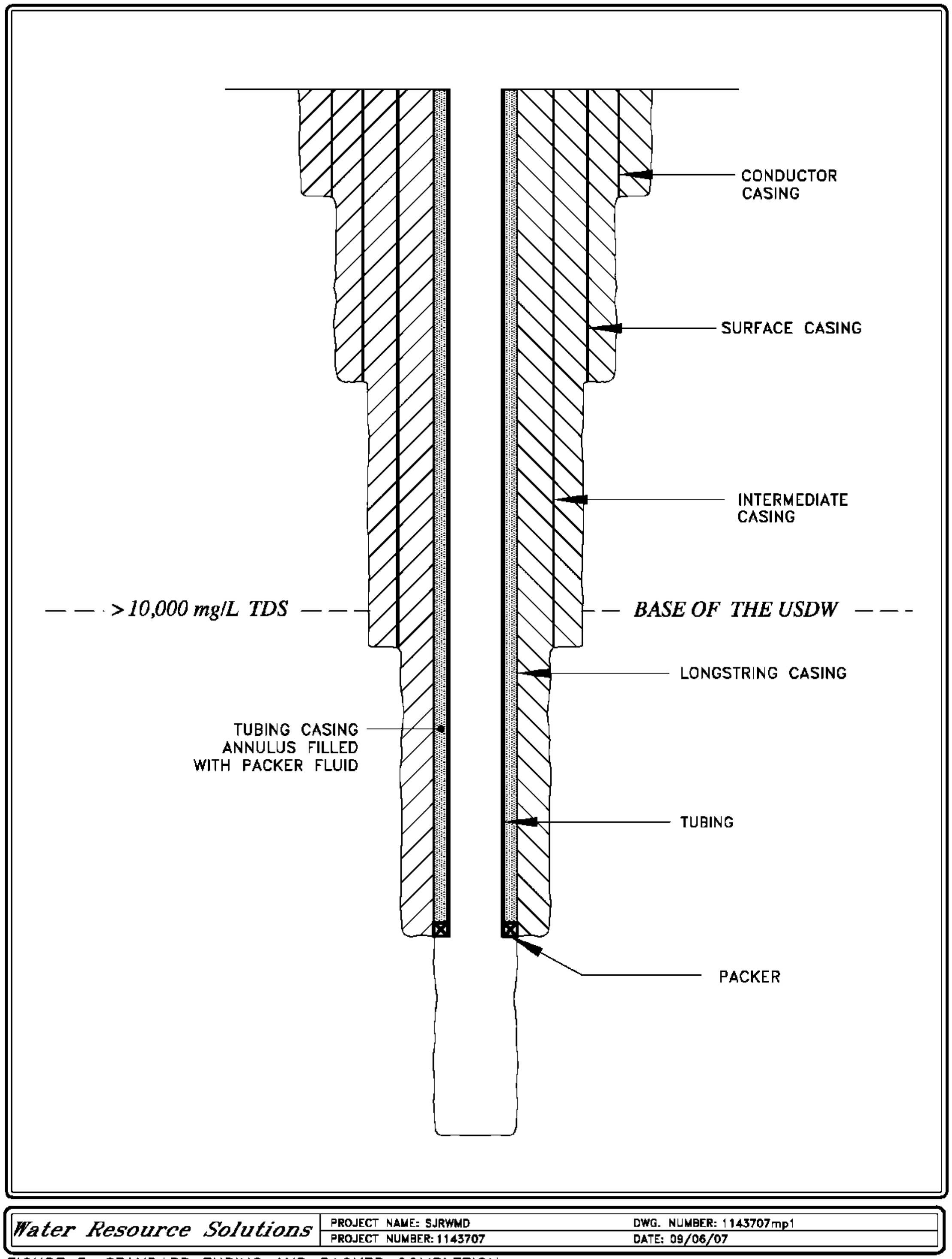

FIGURE 5. STANDARD TUBING AND PACKER COMPLETION.

3.3 Intermediate Casing

The third string of casing is commonly called the intermediate casing. This casing is placed to a depth below the base of the lowermost underground source of drinking water (USDW). A USDW is defined as an aquifer containing less than 10,000 ppm total dissolved solids. The specific purpose of this casing is to provide an additional cement and steel barrier to protect water resources behind this casing and to prevent the invasion of more saline water into or above the lowermost USDW during operation or drilling activities. The surface casing is typically constructed from 0.375-inch wall, spiral welded steel casing meeting Spiral Weld ASTM A139 Grade B standards. All casings to this depth have a cement sheath isolating both the inside and outside of the casing when the well is finally completed (Figure 5). The cement sheaths reduce the rate for corrosion in these casing strings (Michie and Associates 1988).

3.4 Longstring Casing

The fourth and final casing string, as stated in 62-528.410, *Florida Administrative Code* (*F.A.C.*) is required to be "seamless mild steel pipe having a minimum of 0.500-inch wall thickness. An applicant who proposes to use pipe composed of other than 0.500-inch wall seamless mild steel for the final casing shall demonstrate that the proposed material and thicknesses will not compromise the integrity or operation of the well." Seamless mild steel casing conforming to API 5L Grade B or ASTM A53 Grade B standards meet these requirements and has been the longstring casing material of choice for Class I injection wells in Florida. This casing string is often called the longstring casing.

In addition to the different casing strings, concentrate disposal wells are also required to have a tubing and packer type completion (Figure 5), a fluid seal (Figure 6), or a liner type completion (Figure 7). A liner type completion requires a special review by the FDEP since it is not formally authorized in the regulations (62-528.410(1)(e)1, *F.A.C.*).

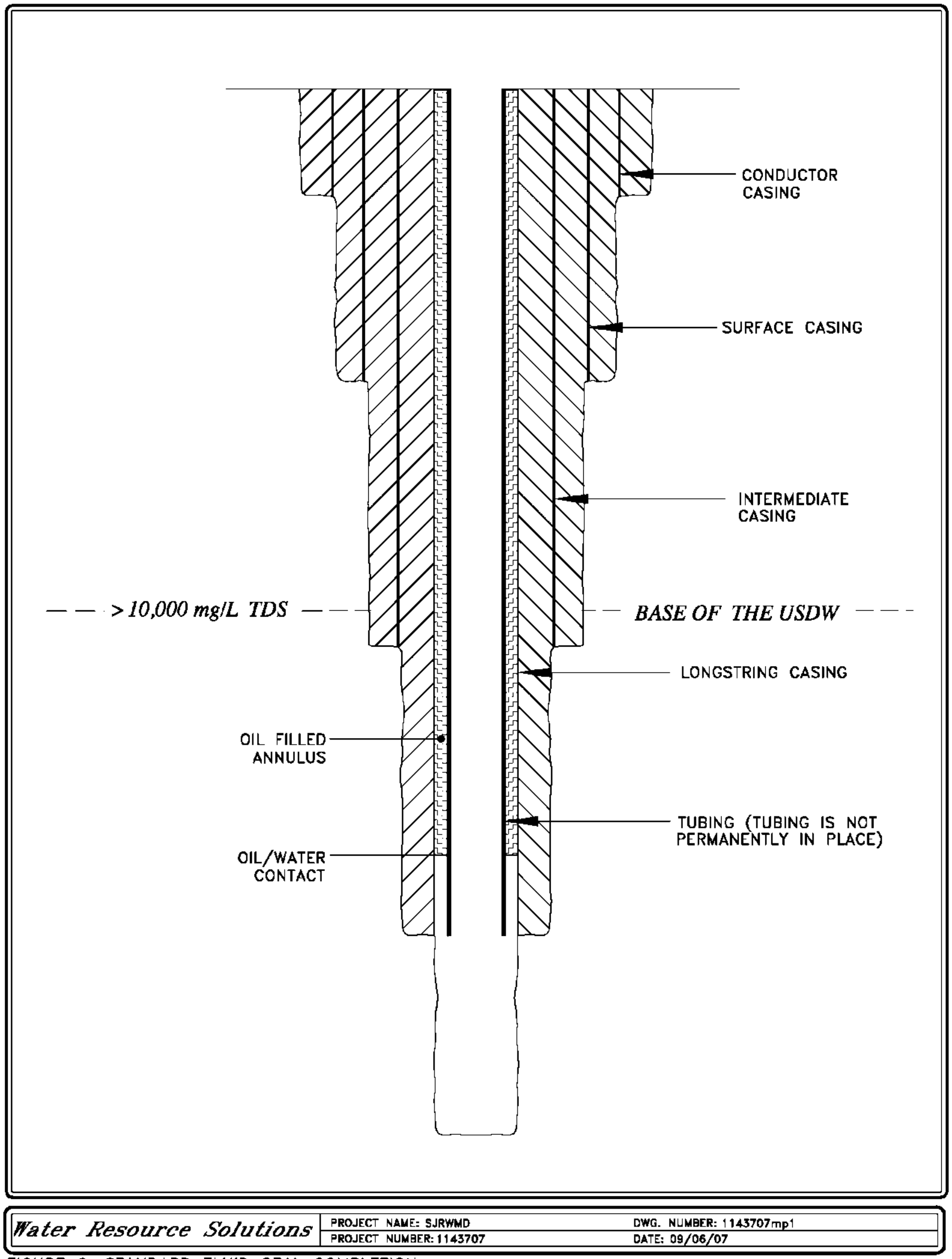

FIGURE 6. STANDARD FLUID SEAL COMPLETION.

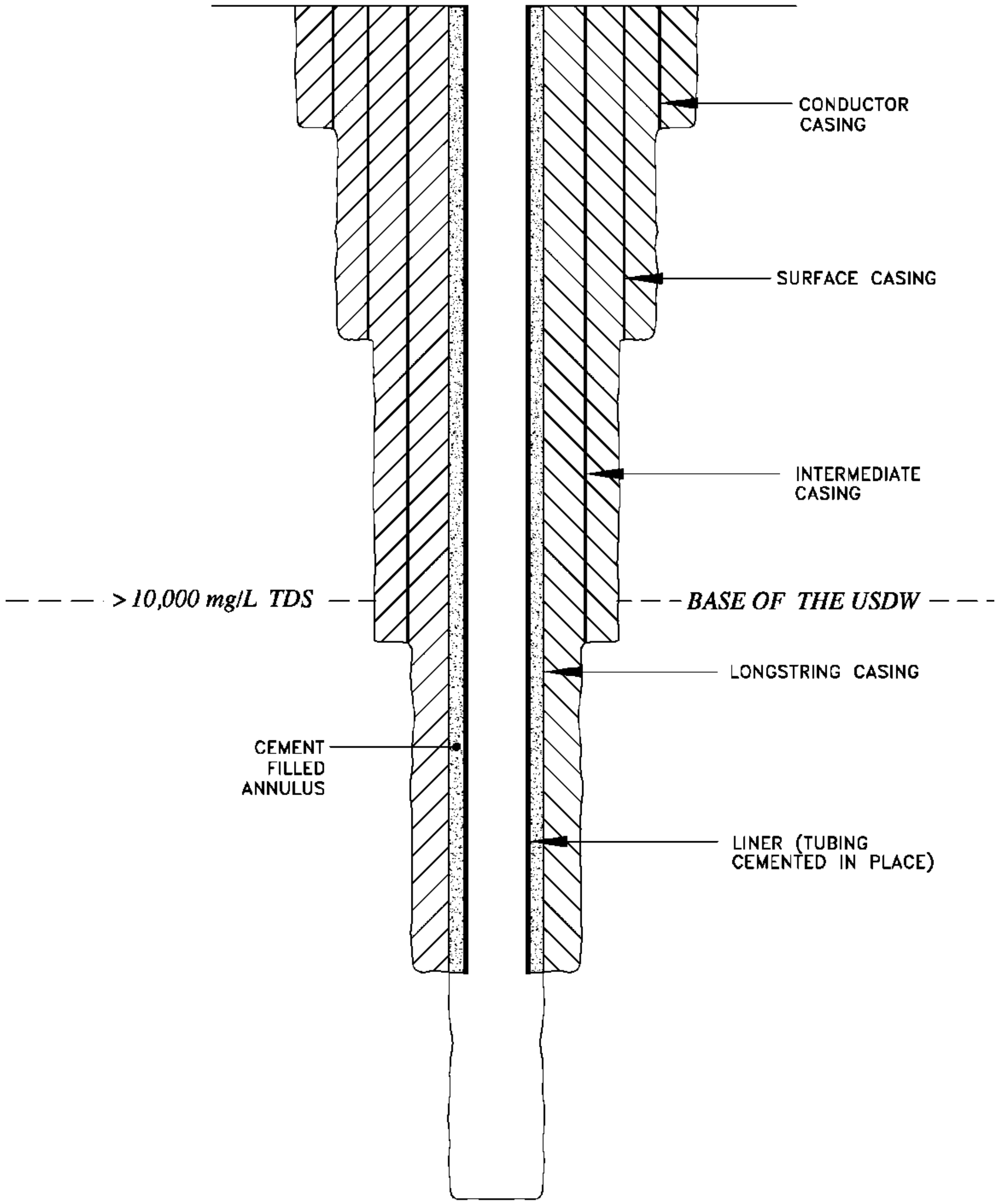

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FIGURE 7. STANDARD LINER COMPLETION.

3.5 Injection Well Tubing and Packer Completion

A tubing and packer completion requires that another pipe string, identified as tubing, be placed inside the longstring casing. The term tubing is used to indicate that the pipe is not permanently installed in the well and that it can be removed. The tubing prevents the injected fluid from contacting the casing. The bottom of the annulus between the tubing and casing is sealed using a packer (Baker Hughes 2006; Whalen 1979). The top of the annulus between the casing and the tubing is sealed at the surface using a variety of techniques. Most commonly, a flange is welded to the top of the tubing and this flange is bolted onto the wellhead to seal the tubing/casing annulus.

A solution containing a corrosion inhibitor is placed in the annulus between the casing and the tubing. This inhibited fluid is commonly called a packer fluid. The tubing and packer completion is designed to protect the longstring casing from corrosion due to contact with the injected fluid. The pressure in the annulus between the casing and tubing is required to be monitored continuously (62-528.415(1)(e)1, *F.A.C.*). The FDEP currently requires that the pressure between the casing and tubing be held at a higher pressure than the injection pressure. This requirement ensures that if a leak in the tubing occurs, water will flow from the casing/tubing annulus into the injection stream. In addition, the leak will be recognized very rapidly as a loss of pressure in the casing/tubing annulus. The pressure in the annulus is maintained by a well annular monitoring system (WAMS). The tubing and packer completion allows the early detection of leaks from the casing/tubing annulus. The pressure in the casing/tubing annulus is also impacted by temperature changes in the injected water. These pressure changes can influence the short-term interpretation of the annular monitoring system data. If the tubing is mild steel, it will conform to API Grade B or ASTM A53 Grade B specifications. Mild steel tubing generally meets the requirement, including wall thickness, as required for the longstring casing. Formal material specifications for the non-mild steel tubing and liner materials are provided in Section 6 where these materials are discussed in more detail.

3.6 Injection Well Tubing and Fluid Seal Completion

The tubing and fluid seal type completion has no mechanical seal between the tubing and the casing at the base of the tubing. The annulus is filled with a non-corrosive, lighter than water organic fluid such as mineral or diesel oil. The density difference between the organic fluid and the water causes the column of oil to be pressurized and therefore an increase in annular pressure at the surface is observed. The pressure at the surface is monitored for changes that would indicate a leak.

Since the organic fluid is lighter than water, there would always be a positive force upwards in the annulus due to the hydrostatic head of the water in the injection formation. In addition, injection would cause the column of oil to be further pressurized during injection.

Although the organic fluid seal is authorized in the FDEP rules, it is unlikely to be utilized for the following reasons:

1) Organic fluids are generally considered to be contaminants. Therefore, if a leak in the casing were to occur below the surface, oil would move into the formations that were originally to be protected.

2) The ability to identify a leak with this system is not as easily accomplished as with a tubing and packer completion. Changing temperatures due to injection and fluctuating injection rates translate into fluctuating pressures at the surface. These fluctuations are not readily interpreted (EPA 1987).

3) Leaks in the casing below the oil/water contact level cannot be detected without performing a packer test. The packer test can either be performed on the casing by: a) removing the tubing and the oil, or b) by setting the packer at a point below the base of the tubing. Setting the packer below the tubing requires that the packer have a smaller diameter than the tubing and an extended diameter that is larger than the casing inside diameter (I.D.) In addition, the packer must hold an

additional 100 or more psi force acting downward at its setting depth without leaking to pass the packer test. Finally, the packer must uniformly deflate so that the packer can be retrieved through the tubing. Mechanically, the above operations can be very difficult to accomplish.

4) Finally, the oil presents a continuous risk of contaminating the surface environment if the wellhead seal were to leak.

3.7 Injection Well Liner Completion

A liner completion is very similar to the tubing-and-packer or fluid-seal completions in that an additional pipe is run inside the casing. However, in this case, the internal pipe is commonly called a liner because it is cemented in place along the entire length of the longstring casing. The liner and the cement now provide the primary protection of the longstring casing against contact by the injected fluid. The liner completion is unable to provide information about the development of downhole leaks, and therefore the FDEP requires that this type completion undergo an additional pressure test 2.5 years after each routinely scheduled mechanical integrity test is performed. An advantage of the liner completion is that it has fewer potential points of leakage than a tubing and packer type completion. Also, the liner completion is not affected by temperature changes during injection since the liner is cemented to the casing rather than being suspended from the wellhead.

The objective of each of the above well construction types is to protect the underground sources of drinking water from injected fluid. The primary line of defense against fluid leaking into the formations above the injection zone and especially the USDW's is the liner or tubing. This liner/tubing string is the first major barrier and therefore attention should be paid to the selection of the tubing/liner material to prevent or minimize corrosion (See Section 6). The longstring casing, the second line of defense, is protected by a cement sheath on the outside and either by a corrosion inhibiting packer fluid or a cement sheath on the inside of the casing. Finally, the last line of defense against direct fluid movement from the well into a USDW is the intermediate casing. The inner and outer surface of this pipe is protected from corrosion and excessive contact with formation fluids by cement.

3.8 Class V Concentrate Disposal Wells

Along the coastline of Florida there are potential locations where shallow wells could be constructed to inject concentrate from a demineralization facility. The requirements for the construction of these wells can be far less complex than those required for a Class I injection well. The reason that the well construction requirements may be reduced is due to the absence of a USDW. The FDEP should be consulted in all cases where a Class V well will be requested to be authorized for concentrate disposal.

When a Class V well is an option for disposal of concentrate, the following construction design can be utilized.

3.8.1 Conductor Casing

Typically, the driller will be requested by the project engineer to set a conductor casing. This casing string is generally constructed from 0.375-inch wall spiral welded steel casing meeting Spiral Weld ASTM A139 Grade B standards. The actual length of this casing string is commonly selected by the drilling contractor. The purpose of this casing is to prevent hole collapse and allows the driller added control of the hole. This casing should be set deep enough to reduce the potential for undermining of the drilling pad.

3.8.2 Longstring Casing

The next string of casing will typically be the longstring or injection casing. This casing can be constructed from PVC or fiberglass. The selection of the material will be based on the mechanical nature of the formation. Since fiberglass is generally stronger mechanically, it may be a better choice where beach or land erosion is more likely to occur around the well. However, PVC is the material most utilized for Class V well construction for the disposal of concentrate. Generally, these wells will be shallow (30 to

100 feet deep) and will be required to be completed as a screened well if the final injection interval is composed of sand. The wall thickness of the casing material should be 0.5-inches and the borehole will likely require a 10-inch overdrill as required for a Class I well. However, there is some potential that the FDEP will relax this requirement depending on site-specific circumstances.

Figure 8 provides generic schematics for two types of Class V disposal wells. The schematics are based on a 6-inch well, but the actual diameters might range between 4 inches to approximately 10 inches in diameter. These wells are generally required to meet the pressure test requirements of the mechanical integrity test, but radioactive tracer tests are not typically required for the shallower wells. Actual well construction will be based on site geology and injection capacity. Also, since injection pressure may cause mounding of the injected water, the injection pressure may be limited to gravity flow.

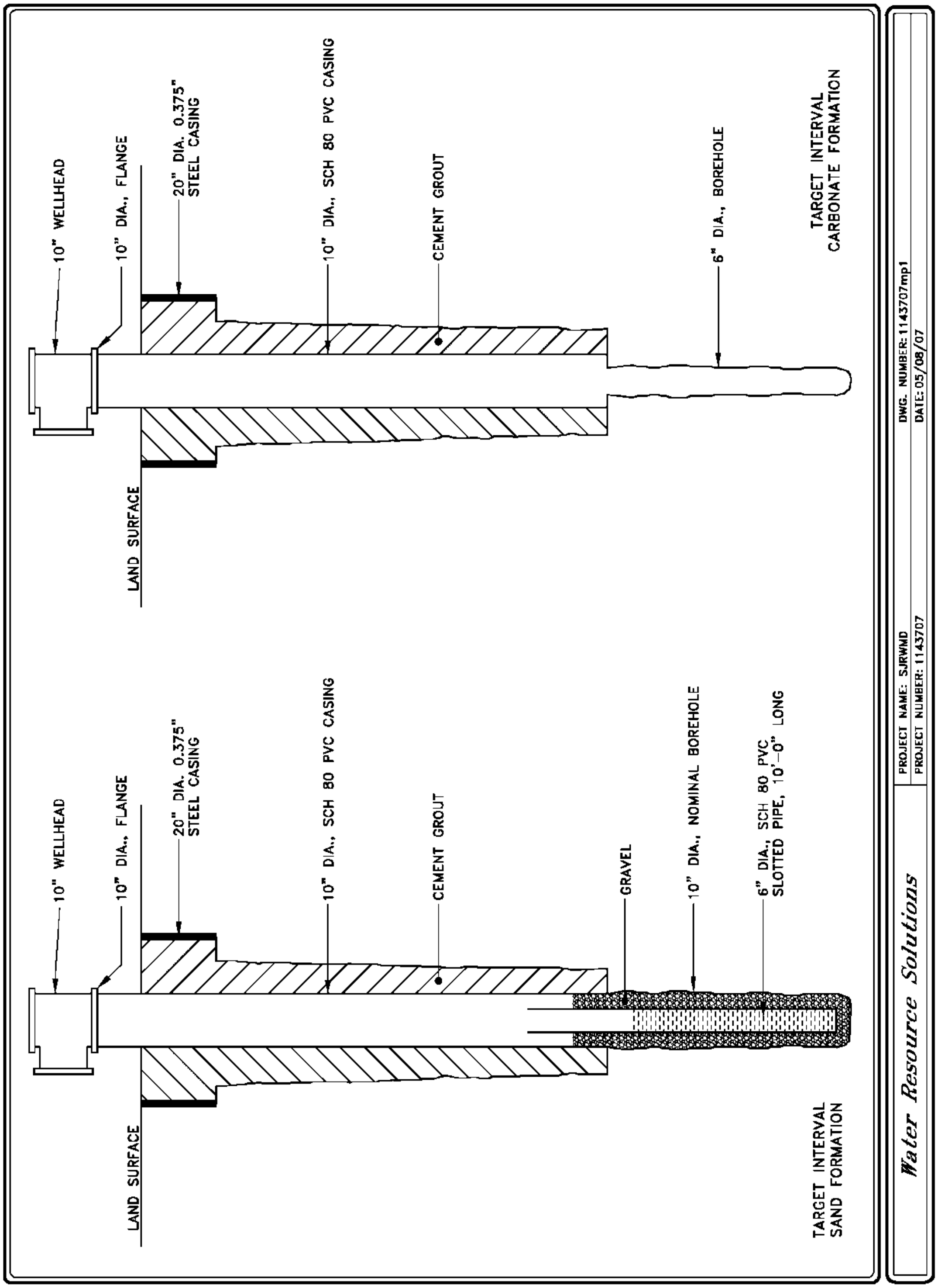

FIGURE 8. SHALLOW CLASS V CONCENTRATE DISPOSAL WELL SCHEMATICS.

4.0 LITERATURE REVIEW

A literature survey was conducted to develop a list of reference material addressing corrosion in concentrate injection wells. Specifically, the goal was to locate documents that would provide corrosion rate information applicable to concentrate disposal wells in Florida. However, most of the publicly available documents focus on the causes of pipeline failures that occur due to a variety of mechanisms including corrosion. Most commonly, pipeline data were developed, for or by, the U.S. Department of Transportation. A lesser amount of injection well data is available, although the oil and gas industry has addressed corrosion in saltwater disposal wells (Brown and Dubreuil 1979) and in oil field enhanced recovery wells. The most specific information on corrosion rates for Florida concentrate injection wells is provided in Section 2.5 of this report and in Section 5.

There are three general sources of information available on corrosion. These sources include the National Association of Corrosion Engineers (NACE), the Ground Water Protection Council (GWPC), and the U.S. Department of Transportation. In addition, the International Gas Union (IGU) is developing an international incident database for natural gas transmission lines that provides additional information on pipeline construction and failures (Bolt 2006). Once completed, the information developed in the databases should provide additional insight into the long-term performance of mild steel pipe within the subsurface.

A review of the NACE document, “Corrosion Data Survey,” indicates that materials with corrosion rates of 2 thousandths of an inch per year (mpy) or less are “recommended” for service (NACE 1985). This same low level of corrosion is the target level recommended by the New Mexico Water and Infrastructure Data System (NMWAIDS n.d.). Practical experience shows that corrosion rates on the order of 20 mpy can be acceptable in some applications where a 20 year life is anticipated prior to replacement and replacement is possible. For the purposes of this report, a corrosion rate of 2 mpy will be utilized as a benchmark for recommending materials of construction.

Since specific corrosion rate data were not readily available, the literature was reviewed for articles or sources of information that would provide a broad base of general information. A major source of information on corrosion in oilfield brine injection wells was compiled for the American Petroleum Institute (Michie and Associates 1988). Mr. Troy Michie's review, entitled "Oil and Gas Industry Water Injection Well Corrosion" is currently available from the Ground Water Protection Council located in Oklahoma City, Oklahoma. Major conclusions provided in this paper that are applicable to the construction of RO concentrate disposal wells include:

- Eliminating oxygen and inhibiting biological activity are commonly utilized to eliminate corrosion in the casing/tubing annulus.

- The use of corrosion resistant materials such as fiberglass, special steel alloys, plastic coated steel pipe, and cement lined steel pipe were effective at reducing corrosion during concentrate injection.

- Longstring casing/tubing annulus corrosion is minimal if a packer fluid is placed in the annulus between the casing and tubing and the packer fluid contains a corrosion inhibitor and biocide. More importantly, corrosion remains minimal as long as the annulus is isolated from the environment to exclude oxygen. It is relevant to note that most packer fluids utilized in the oil industry are saturated or close to saturated solutions of sodium chloride, potassium chloride, or calcium chloride. The solutions contain high salt contents since these fluids were utilized for the installation of the tubing and packer and are needed to control well pressure at the surface during installation. The presence of these fluids is also required when the tubing needs to be pulled for maintenance. Therefore, the heavy brines are not removed from the wells, but are left in place. The lack of significant corrosion of the inner surface of the casing and the outer surface of the tubing in the absence of oxygen reinforces the basic importance of oxygen to the overall corrosion process. A review of Figures 3 and 4 shows that little actual corrosion has occurred on the outside of the mild steel tubing whereas the inside of the tubing has been significantly corroded. This observation provides visual support for Mr. Michie's conclusions concerning internal annulus corrosion.

Extensive reference lists are available from the GWPC website and are provided in Appendix 1 of this document. The references address the performance of Class II oilfield saltwater disposal wells and water injection wells associated with enhanced oil recovery, and a broader set of references for all types of injection wells including hazardous and general non-hazardous wells. Not all references are relevant to the topic of injection well corrosion.

In the course of developing the information for this document, the potential differences between the corrosion of longitudinally welded pipe and seamless pipe were reviewed. This portion of the project was undertaken due to the significant difference in the cost of seamless versus welded pipe and the restriction against using a welded pipe in Class I well when both pipe types meet the same ASTM and API standards. The literature suggested that longitudinally welded pipe manufactured after the 1970's was more corrosion resistant to selective seam corrosion (SSC) than pipe manufactured prior to that time (DOT 2005). However, experience, as expressed in the literature, appeared to indicate that improvements in manufacturing and testing program of the welded pipe have had a major impact on actual pipe performance. It is relevant to note that as of 2001, no welded pipeline constructed during the 1990's had experienced a pipe defect or pipe seam failure (Kiefner and Trench 2001).

Although the FDEP does not currently allow the use of welded casing based on an apparent failure of spiral-welded casing in the 1970's, it is likely the FDEP may eventually authorize the use of longitudinally welded pipe. If this approval occurs, an increased emphasis on quality control and testing of longitudinally welded pipe may need to be developed beyond the ASTM and API specifications to ensure that the maximum life of the longstring casing is ensured.

5.0 SURVEY RESULTS FOR FLORIDA'S CLASS I CONCENTRATE DISPOSAL WELLS

As part of this project, a survey was taken of all current Class I concentrate disposal wells in the state of Florida. This survey provides a review of the history and performance of concentrate disposal wells in the state of Florida. The survey identifies the types of material used in the construction of these wells and the performance of these materials. Table 4 provides a copy of the survey. Table 5 provides a summary of the results that were obtained during this survey. A well is indicated to have failed a mechanical integrity test in a tubing and packer completion when the annulus between the tubing and packer is unable to remain within +/- 5% of the site established test pressure for a period of one hour without adding or removing fluid. The test pressure is defined as 150% of the maximum injection pressure requested by the site. A well is indicated to have failed a mechanical integrity test for a liner completion when the liner is pressured to 150% of the maximum injection pressure requested and this pressure is unable to be sustained within +/- 5% of the established test pressure for a period of one hour without adding or removing fluid.

A well could also fail a mechanical integrity test if fluid was indicated to be moving upwards outside the longstring casing during a radioactive tracer test. However, a failure of this type is rarely observed and is not associated with the choice of casing material.

5.1 Preliminary Assessment

The state of Florida has 114 Class I injection facilities encompassing 171 wells. The initial information concerning these facilities was obtained from the Florida Department of Environmental Protection (FDEP) well inventory database (FDEP 2003a). This database includes the total number of wells for each facility, the status of the wells (active, permitting/under construction, or plugged/inactive), and a location map (FDEP 2003b). Additional research was conducted to obtain facility information such as responsible entity and contact information.

TABLE 4

INJECTION WELL PERFORMANCE QUESTIONNAIRE
THE ST. JOHNS RIVER WATER MANAGEMENT DISTRICT

Facility ______________________________

Question 1: Approximately how long has your site been in operation? _________ years.

Question 2: If the well utilized a packer and tubing completion, what material was utilized for the tubing when the well was first installed? (Please circle the appropriate choice.)

a) Mild steel
b) Plastic coated mild steel pipe
c) Fiberglass
  i. Tubing & Packer
  ii. Cemented Liner
d) PVC, ABS or other plastic pipe
e) Corrosion Resistant Alloy
  304 Stainless Steel
  316 Stainless Steel
  2205 Duplex Steel

Question 3: Are you continuing to utilize the original completion or did the original completion lose mechanical integrity at any time during operation? (Please circle the appropriate choice.)

a) Continuing to use the original completion, no loss in mechanical integrity.
b) Continuing to use original completion, but added barite or other materials to stop a packer leak.
c) Original completion lost mechanical integrity due to:
  1) Un-repairable packer leak
  2) Hole in tubing due to corrosion
  3) Failure of threaded connection
  4) Other ________________________

If your well has not lost mechanical integrity, please proceed to question 15.

TABLE 4 (Con't)

INJECTION WELL PERFORMANCE QUESTIONNAIRE
THE ST. JOHNS RIVER WATER MANAGEMENT DISTRICT

Question 4: How long was the well in operation before it lost mechanical integrity? _______

Question 5: If the first tubing and packer completion failed and required replacement, how was the well re-completed? (Please circle the most accurate answer.)

a) Continued to utilize original completion type and materials.
b) Re-completed the well using alternate materials for tubing with a packer.
c) Re-completed the well using alternate materials for tubing and an alternate design that did not require a packer.
e) Other, please indicate ______________________________

Question 6: What material was utilized for the tubing replacement? (Please circle the appropriate choice.)

a) Mild steel
b) Plastic coated mild steel pipe
c) Fiberglass
   i. Tubing & Packer
   ii. Cemented Liner
d) PVC, ABS or other plastic pipe
e) Corrosion Resistant Alloy
   304 Stainless Steel
   316 Stainless Steel
   2205 Duplex Steel
f) Other ____________________

Question 7: Has the repaired well maintained mechanical integrity?
Yes
No

Question 8: How many years has/was the first re-completion been in service? ________

Question 9: If the first repair of the well lost mechanical integrity, how many years after it was repaired did it lose mechanical integrity? ________________

If your well has maintained mechanical integrity since the first re-completion please proceed to question 15.

TABLE 4 (Con't)

INJECTION WELL PERFORMANCE QUESTIONNAIRE
THE ST. JOHNS RIVER WATER MANAGEMENT DISTRICT

Question 10: The first repair of the well lost mechanical integrity due to:

1) Un-repairable packer leak
2) Hole in tubing due to corrosion
3) Failure of threaded connection
4) Other ______________________

Question 11: If the first repair of the well eventually failed the mechanical integrity testing and required replacement, how was the well repaired the second time? (Please circle the most accurate answer.)

a) Continued to utilize original completion type and materials.
b) Re-completed the well using alternate materials for tubing with a packer.
c) Re-completed the well using alternate materials for tubing and an alternate design that did not require a packer.
e) Other, please indicate ______________________________

Question 12: What material was utilized for the first tubing replacement? (Please circle the appropriate choice.)

a) Mild steel
b) Plastic coated mild steel pipe
c) Fiberglass
   i. Tubing & Packer
   ii. Cemented Liner
d) PVC, ABS or other plastic pipe
e) Corrosion Resistant Alloy
   304 Stainless Steel
   316 Stainless Steel
   2205 Duplex Steel
f) Other ____________________

Question 13: How many additional times, if any, has your tubing and packer failed? ________

Question 14: Was the well completion design changed after the additional failures? Yes No

TABLE 4 (Con't)

INJECTION WELL PERFORMANCE QUESTIONNAIRE
THE ST. JOHNS RIVER WATER MANAGEMENT DISTRICT

Question 15: What tubing material is currently being utilized in your well?

a) Mild steel
b) Plastic coated mild steel pipe
c) Fiberglass
  i. Tubing & Packer
  ii. Cemented Liner
d) PVC or other plastic pipe
e) Corrosion Resistant Alloy
  304 Stainless Steel
  316 Stainless Steel
  2205 Duplex Steel

Question 16: What is the diameter of the casing? ________

Question 17: What is the typical/average water quality of the injected concentrate?

Chloride (mg/L) _________

Total Dissolved Solids (TDS) ___________

Conductivity (uS/cm) ___________

pH (std. units) ___________

TABLE 5
Saint Johns River Water Management District
Survey Answers - Class I Injection Wells

DIW Reference	Question 1	Question 2	Question 3	Question 4	Question 5	Question 6	Question 7	Question 8	Question 9	Question 10	Question 11	Question 12	Question 13	Question 14	Question 15	Question 16
DIW 1	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
DIW 2	5	Plastic coated	D. coating defective and FRP installed	< 1	B.	FRP - T&P	Yes	5	--	--	--	--	--	--	FRP - T&P	ND
DIW 3	20	Mild Steel	C. #2 Hole	2	C.	FRP - Cement	Yes	18	--	--	--	--	--	--	FRP - Cement	16
DIW 4	16	Mild Steel	C. #2 Hole	3	E.	F. Tubing could not be removed	--	--	--	--	--	--	--	--		ND
DIW 5	13	Mild Steel	C. #2 Hole	10	C.	Fiberglass	Yes	3	--	--	--	--	--	--	FRP - Cement	13.5
DIW 6	16	Mild Steel	C. #2 Hole	2	A.	Mild Steel	No	1	1	2. Hole	C.	Mild Steel	1	Yes	FRP - Cement	10.7
DIW 7	15	Mild Steel	C. #2 Hole	9.5	C.	E. 2205 Duplex Steel	Yes	--	--	--	--	--	--	--	2205	16
DIW 8	14	Mild Steel	C. #2 Hole	9	A.	Mild Steel	No	ND	2	2. Hole	B.	Mild Steel	1	Yes	FRP - Cement	16
DIW 9	3	Mild Steel	C. #2 Hole	10	A.	Mild Steel	No	ND	3	2. Hole	B.	Mild Steel	2	Yes	MS	16
DIW 10	12	Mild Steel	C. #2 Hole	ND	B.	Fiberglass	Yes	ND	--	--	--	--	--	--	FRP	ND
DIW 11	12	Mild Steel	C. #2 Hole	ND	B.	Fiberglass	Yes	ND	--	--	--	--	--	--	FRP	ND
DIW 12	7	Mild Steel	C. #2 Hole	2	B.	FRP - T&P	Yes	5	--	--	--	--	--	--	FRP - T&P	14
DIW 13	22	Mild Steel	C. #2 Hole	20	B.	Will be Fiberglass	NA	--	--	--	--	--	--	--	FRP - Cement	18
DIW 14	12	FRP - T&P	C. #1 Leak	Will be FRP - Cement	E.	Removing packer	NA	0	--	--	--	--	--	--	Plan to go to FRP -	12
DIW 15	8	Mild Steel	C. #1 Leak	ND	A.	Mild Steel	--	--	--	--	--	--	--	--	MS	ND
DIW 16	13	FRP - T&P	A.	9	A. Upgraded casing size	FRP - T&P	Yes	4	--	--	--	--	--	--	FRP - T&P	4.5
DIW 17	24	Epoxy Coated	A.	--	--	--	--	--	--	--	--	--	--	--	Epoxy	16
DIW 18	1	Fiberglass	A.	--	--	--	--	--	--	--	--	--	--	--	FRP	9.625
DIW 19	1	Fiberglass	A.	--	--	--	--	--	--	--	--	--	--	--	FRP	12

NA - Not Applicable; ND - No available Data
Question 17, of the survey, is presented in Table 1.

1 of 2

TABLE 5
Saint Johns River Water Management District
Survey Answers - Class I Injection Wells

DIW Reference	Question 1	Question 2	Question 3	Question 4	Question 5	Question 6	Question 7	Question 8	Question 9	Question 10	Question 11	Question 12	Question 13	Question 14	Question 15	Question 16
DIW 20	0	Fiberglass	A.	--	--	--	--	--	--	--	--	--	--	--	Fiberglass	ND
DIW 21	21	FRP - Cement	A.	--	--	--	--	--	--	--	--	--	--	--	FRP - Cement	16
DIW 22	5	FRP - Cement	A.	--	--	--	--	--	--	--	--	--	--	--	FRP - Cement	10
DIW 23	4	FRP - Cement	A.	--	--	--	--	--	--	--	--	--	--	--	FRP - Cement	6.625
DIW 24	6	FRP - T&P	A.	--	--	--	--	--	--	--	--	--	--	--	FRP - T&P	12
DIW 25	3	FRP - T&P	A.	--	--	--	--	--	--	--	--	--	--	--	FRP - T&P	14.5
DIW 26	1	FRP - T&P	A.	--	--	--	--	--	--	--	--	--	--	--	FRP - T&P	12
DIW 27	< 1	FRP - T&P	A.	--	--	--	--	--	--	--	--	--	--	--	FRP - T&P	18
DIW 28	< 1	FRP - T&P	A.	--	--	--	--	--	--	--	--	--	--	--	FRP - T&P	18
DIW 29	< 1	FRP - T&P	A.	--	--	--	--	--	--	--	--	--	--	--	FRP - T&P	12
DIW 30	2	FRP - T&P	A.	--	--	--	--	--	--	--	--	--	--	--	FRP - T&P	16
DIW 31	2	FRP - T&P	A.	--	--	--	--	--	--	--	--	--	--	--	FRP - T&P	12
DIW 32	10	Mild Steel	A.	--	--	--	--	--	--	--	--	--	--	--	MS	ND
DIW 33	7	Mild Steel	A.	--	--	--	--	--	--	--	--	--	--	--	MS	10.75
DIW 34	5	Mild Steel	A.	--	--	--	--	--	--	--	--	--	--	--	MS	16
DIW 35	5	Mild Steel	A.	--	--	--	--	--	--	--	--	--	--	--	MS	14
DIW 36	5	Mild Steel	A.	--	--	--	--	--	--	--	--	--	--	--	MS	ND
DIW 37	4	Mild Steel	A.	--	--	--	--	--	--	--	--	--	--	--	MS	20
DIW 38	4	Mild Steel	A.	--	--	--	--	--	--	--	--	--	--	--	MS	20

NA - Not Applicable; ND - No available Data
Question 17, of the survey, is presented in Table 1.

Facility operation managers were contacted directly to help ensure the recovered information was accurate and current.

For the purposes of this study, only wells injecting concentrate or a combination of municipal waste and concentrate were included in the data review. Based on the FDEP database, there are 54 wells within 44 facilities listed as desalination facilities. After additional facility information was gathered, it was determined that 33 facilities with 38 injection wells met the criteria established for this study – i.e. all or a portion of the waste stream was concentrate. All facilities were contacted, and all showed some interest to participate. Ultimately, three facilities did not return well construction details, and 11 facilities did not return water quality data.

The South Florida Water Management District (SFWMD) database and FDEP personnel assisted in providing survey information not provided by the facilities directly. In house records were also utilized to provide more detailed information when possible. In the end, data were obtained for the 38 wells in the survey. Although information on four of the injection wells remains incomplete, information relevant to this project was obtained for these wells.

5.2 Industry Survey Results

The results of the industry survey are divided into groups based on tubing or liner material utilized. The data provided in this document clearly show that the industry has moved towards using an alternate material for the tubing or liner. Most new completions are using fiberglass, and one well was re-completed using 2205 duplex steel. One well, originally completed with epoxy-coated pipe, has been in service for 24 years.

5.2.1 Mild Steel Tubing

Sixteen facilities, encompassing 19 wells, initially utilized mild steel tubing as the well completion material. Of these 19 wells, a total of eleven wells have failed due to a loss of mechanical integrity. Failures occurred within 1 to 10 years for all but one well (DIW 13, Table 5). Four wells failed within three years and four wells failed within 9 to 10 years. The time to failure for two wells was not specified. All reported failures, except one due to a leaking packer, were due to corrosion. The time in service prior to failure for three of the wells is unknown.

Of the eight wells using mild steel that have not failed, six have been in service for five or less years. One well has been in service after 7 years, and one well has been in service for 10 years.

Two of the above 11 wells that failed were re-completed with mild steel. One of these wells also failed again due to corrosion in less than two years. This brings the total number of completions using mild steel that failed due to corrosion to twelve with six of these failures occurring within three years.

Eight of the wells that failed have now been re-completed using fiberglass. One facility used 2205 duplex steel for the installation of a liner, and another well utilized mild steel. The original tubing in one well could not be removed, and the well was eventually plugged and abandoned.

The observed corrosion rate in the mild steel wells can be determined by dividing the tubing wall thickness of 0.5-inches by the years in service prior to failure. The observed corrosion rates range from 45 and to more than 500 mpy, with an average corrosion rate of 178 mpy and a median value of 167 mpy. These high corrosion rates are likely associated with pitting type corrosion.

5.2.2 Fiberglass Tubing

Sixteen of the thirty-eight wells utilized fiberglass tubing in the original completion and eight wells, originally completed with mild steel, have been re-completed with fiberglass. These wells have been in service for an average of 4 years. Operational life ranges from less than 1 year to 21 years. The median operational life is four years. So far, only one of the fiberglass wells has lost mechanical integrity. The loss of mechanical integrity in this well was due to a packer leak. The packer in this case was a conventional, tension set packer. The FRP casing appeared to be in good condition based on video logs.

5.2.3 Plastic Coated Tubing

Two of the 37 wells were initially completed with either plastic or epoxy-coated pipe. The plastic coated pipe failed mechanical integrity in less than one year. Apparently, the plastic failed to bond to the pipe leading to exposure of the mild steel pipe and accelerated corrosion. The epoxy-coated pipe appears to have been in operation for 24 years without loss of mechanical integrity.

5.2.4 2205 Duplex Steel Tubing

One tubing and packer completed well, which failed due to corrosion, was re-completed with a 2205 duplex steel liner. This material was selected for the following reasons:

1) High recommendation by several independent corrosion consultants for the disposal well environment based on chloride concentration, TDS concentration, and temperature,

2) Coupon testing in the field demonstrated that the 2205 duplex steel material was not impacted by the brackish to saline environment (Water Resource Solutions 2002b).

3) Extended period of use predicted for the duplex steel,

4) Ability to install liner and cement in place using the tremmie method.

5) Availability of the duplex steel tubing (16 to 30 week delivery),

6) Ability to be installed by more than one drilling contractor due to thinner wall and lighter weight. Thus, a competitive price was obtained for removing the old tubing and installing the new tubing.

Of interest is that after five years in service, the condition of recompleted 2205 Duplex Steel tubing appears similar to when it was first installed.

5.3 Injected Water Quality Information

Deep injection wells either inject a combination of municipal waste and concentrate or solely concentrate. As a result of these two injected effluent types, water quality values vary considerably. Water quality data were also requested from the participating facilities. Requested data included chlorides, total dissolved solids, specific conductivity, and pH. Water quality values supplied from plant operators are provided in Table 1 as previously indicated. DO data were not available.

Chloride data ranges from approximately100 to 30,000 mg/l, with an average of approximately 5,700 mg/l. Total dissolved solids ranges from 400 to 38,000 mg/l, with a mean of approximately 11,000 mg/l. Conductivity values range between approximately 1,150 and 51,600 μS/cm, with a mean value of approximately 12,700 μS/cm.

The pH levels of the discharge waters ranged between 5.8 and 8.7 with a mean value of 6.9. The neutral range of the pH values indicates that pH does not significantly contribute to the observed corrosion rates for the concentrate disposal wells.

6.0 CORROSION PREVENTION

There are basically two approaches that can be taken to eliminate or reduce corrosion in an injection well. One method is to use corrosion resistant or non-corroding materials for all materials in contact with the corrosive water (Knowles and Boytim 1995). The second approach is to reduce or inhibit the corrosive nature of the injection fluids.

6.1 Corrosion Resistant Materials

Until recently, mild steel was often the material of choice for the injection tubing in a concentrate disposal well. However, by the year 2000, the cost of replacing mild steel tubing had increased to over $1,000,000 per well. The high cost of tubing replacement means that the use of corrosion resistant materials for the tubing provides a more economical approach for long-term well operations.

In order to address the broader issue of corrosion during injection, information from the larger brine injection industry literature, including those that inject oilfield brines, was used to identify the available options utilized in the industry to limit corrosion in an injection well. The major options identified by this study included the use of corrosion resistant materials such as plastic coatings on mild steel, fiberglass pipe, and special metal alloys and the removal of the corrosive elements from the injected brines. The materials of construction that are reviewed in this section include:

- Plastic coated mild steel tubing (Coated Pipe)
- Fiberglass Reinforced Pipe
- 300 series stainless steel
- 2205 Duplex Steel
- Hastelloy C

6.1.1 Plastic Coated Pipe and Similarly Constructed Pipe Liners

Carbon based products (plastics, epoxy, and Teflon), in general, are highly resistant to chemical attack by salt water. Therefore, the piping industry developed several alternatives for the construction of both brine disposal wells and oil and gas wells.

One of the first alternatives was provided by the development of techniques to coat pipe with plastic and epoxy. This type pipe appeared to offer a significant advantage to the oil and gas industry. Plastic and epoxy coated steel pipe provided the corrosion resistance of plastic without requiring any changes of the pipe handling equipment on a typical drilling rig. This pipe was found to perform well as long as the plastic coating remained continuous. However, once the plastic coating was damaged and the underlying metal was exposed, rapid corrosion at the point of damage was observed (Harco Technologies 1990; Beavers and Thompson 2006). Plastic coating is currently available, but the maximum diameter of pipe that most manufacturers are currently willing to coat appears to be limited to around 16 inches I.D. Plastic and epoxy coated pipe have been utilized at three sites within the state of Florida. At the first site, the plastic coating failed to adhere to the mild steel casing and well failure occurred in less than one year. The epoxy-coated tubing at the second site has been in service for over 24 years and has not yet shown signs of failure. Epoxy coated pipe was installed at the third site, but this well has not yet been in service for five years and therefore the well has not undergone a mechanical integrity test since installation. It is relevant to note that fusion bonded epoxy (FBE) coated pipe has performed well in segments of pipeline for over 30 years (Fore and Varughese 2006).

A conceptually similar type pipe, Duoline designed by Rice Engineering, has been available for over 20 years (Duoline Technologies n.d.). In an effort to overcome the problems with damaging the plastic lining, Rice Engineering developed liners made from fiberglass or PVC. The liner is cemented into a mild steel pipe, which can be new or used. This process provides the benefits of a fiberglass or PVC resistant interior and the use of normally available rig tools for installation. The maximum outside diameter for this pipe is currently limited to 10.75-inches. The I.D. of this pipe, after installing the liner, is approximately 9.75 inches. This pipe also requires special coupling elements to seal the pipe at the threaded connections so that the pipe joints are not exposed to the corrosive nature of the injected fluids.

The potential size for these types of tubing allow an overall maximum injection rate of 9,000 gpm (13 mgd) for 16-inch I.D. coated pipe and approximately 2200 gpm (3.2 mgd) for the 9.75-inch I.D. Duoline pipe. Actual maximum size of the coated pipe depends on the manufacturer and the type of coating being applied.

6.1.2 Fiberglass Pipe

In recent years, fiberglass pipe has become the industry's tubing of choice. Years of use have demonstrated that fiberglass (API 15TR) is an excellent material that is highly resistant to saltwater environments (Future Pipe Industries 2003) and can be used in geothermal well applications where high temperatures and brine salinity can be an issue (van Strien 1999). Fiberglass is also a material capable of operating at temperatures far above the temperatures that are encountered in Florida's subsurface to a depth of 3500 feet or more. Fiberglass, a threaded product, has been successfully used to inject saline water into the subsurface for more than two decades. However, fiberglass installation typically requires special handling equipment to prevent damaging the fiberglass during installation and the use of a specialized procedure called torque-turn. The torque-turn method is used to maximize the potential that a threaded joint is connected properly. When fiberglass joints are screwed together, there is an optimum torque-turn relationship. If the torque is outside the optimum torque range (either high or low), the connection is not acceptable and one or both pipe joints may need to be replaced. The manufacturer of the fiberglass pipe should be consulted on proper pipe connections and it is recommended that a pipe manufacturer representative be present on site to assure that the pipe is installed properly. It is recommended that this requirement be written into the specifications.

Currently, the maximum size of fiberglass available has an outside diameter (O.D.) of 20-inches and a nominal I.D. of 18 inches. The O.D. of the coupling required to join this pipe is 24 inches. This pipe size requires a longstring casing diameter of 26 inches, which appears to be the largest O.D., 0.5-inch wall seamless pipe manufactured in the world at this time.

The next largest fiberglass pipe has an O.D. of 18 inches, and an I.D. of 16.60 inches. The coupling O.D. is 22.30 inches. The 16.6-inch I.D. fiberglass pipe is the maximum size pipe that can be installed inside of a 24.0-inch O.D., 0.5-inch wall steel pipe. One manufacturer indicated somewhat smaller couplings may be available depending upon the application. The inside diameter of this pipe limits the normal operating rate to 6,745 gpm based on current FDEP regulations requiring fluid velocities to be less than 10 feet per second (62-528.415(1)(f)2, *F.A.C.*).

6.1.3 300 Series Stainless Steel

Although stainless steel materials have demonstrated good resistance to a variety of environments, a review of the NACE DATA Survey (NACE 1985, p. 114) and other reports (Harco Technologies 1990; AZoM.com 2000) indicates that the 300 series stainless steel are susceptible to chloride stress cracking and pitting in sodium chloride and saltwater solutions in the range of concentrations that are typically injected into the concentrate disposal wells. These stainless steels also suffer similar attacks from seawater. The expense of this material plus the potential for corrosion makes this a less attractive alternative.

6.1.4 2205 Duplex Steel

The 2205 duplex steel (ASTM A928 HTO, UNS S32205 or S31803) is well known for its resistance to both chloride stress corrosion cracking and to pitting corrosion (Sand Mayer Steel Company n.d.) in the type of environments encountered in concentrate disposal wells. This steel is considered to provide good resistance to corrosion, pitting corrosion, and chloride stress cracking under the conditions observed for Florida Class I concentrate disposal wells where temperatures are below 120^{o}F and chlorides are typically below 20,000 mg/l (Corrosionsource.com 2000). This pipe has been used successfully at one Florida site. A video survey performed 2.5 years after the initial installation indicated that the condition of the pipe was similar to when it was first installed. Since the connections on this pipe are welded, it is possible to use this tubing with a 20-inch O.D. in the standard 24-inch longstring casing to obtain injection rates up to 9,200 gpm (13.2 mgd). In general, the welded joint allows larger pipe to be used with smaller I.D. longstring casing. However, the major advantage occurs with the 24-inch longstring casing since this is the largest, readily available seamless pipe. The 2205 duplex steel has been investigated and shown to be applicable to service in western Canada brine disposal wells (Chitwood and Coyle 1994) and has been tested for use in geothermal hypersaline brines (Moeller and Cron 1998).

6.1.5 Hastelloy

Hastelloy is a nickel-based alloy that is extremely resistant to salt water corrosion. Hastelloy tubing and casing material were utilized in the construction of the 16,000 foot deep disposal well constructed by the U.S. Bureau of Reclamation in the Paradox Valley of Colorado near the town of Bedrock. This well was constructed to dispose of essentially saturated salt water that seeps into the Doloris River and ultimately impacts the chloride content of the Colorado River (USBR 2007). Although the Hastelloy alloys are extremely corrosion resistant, the cost of this material is not cost competitive with any of the other materials. Table 6 provides comparative costs obtained for these different materials in December of 2006.

6.1.6 Comparison of Corrosion Resistant Materials

Table 7 provides a list of advantages and disadvantages for the construction materials that offer the most potential for use in Class I concentrate disposal wells.

TABLE 6

Estimated Cost for 24-inch Casing and for Corrosion Resistant Tubing and Liner Material

Type Material	Pipe Size	Maximum Flow Rate (10 ft/sec)	Approximate Cost per foot
Casing Material			
Seamless Pipe	24-inch, O.D. 0.5-inch wall		$190
Mild Steel			
Longitudinal Welded Pipe	24-inch, O.D. 0.5-inch wall		$85
Mild Steel			
Tubing/Liner Material			
Fiberglass	16.3-inch I.D., FRP 1250	6,400 gpm / 9.3 mgd	$260
316 Stainless Steel	20-inch O.D., 0.312-inch wall	9,200 gpm / 13.2 mgd	$300
2205 Duplex Steel	20-inch 0.D., 0.312-inch wall	9,200 gpm / 13.2 mgd	$475
Hastelloy C	20-inch O.D., 0.312-inch wall	9,200 gpm / 13.2 mgd	$4,000*
* Cost estimated based on pipe weight/ft by manufacturer			

TABLE 7

Product Advantages and Disadvantages

Advantages	Disadvantages
Plastic Coated Pipe	
• Least expensive option for corrosion resistance. • Only requires normal rig equipment to thread joints together. • Suitable product for tubing and packer completions. Not recommended for a liner type completion. • Sufficient weight to set in YBI packer (See discussion in Section 7).	• Mechanical support provided by mild steel, which is relatively prone to corrosion in a concentrate injection well. • Once steel is exposed, corrosion is accelerated • Potential limits of available size.
Fiberglass Pipe	
• Corrosion resistant. • Limitation of pipe size only relevant if flows greater than 6,750 gpm are required on a routine basis. • Well connections can be monitored when connections are being made to maximize quality of connections.	• Threaded connection requires large couplings. Large coupling size restricts the maximum flow to 6,750 gpm (9.7 mgd) if a 24-inch long string casing is utilized. • Light weight requires additional compressive forces if using YBI packer for a tubing and packer completion. • Delivery can be in excess of 25 weeks after an order is placed. • Moderately expensive. • Requires special equipment to connect threaded joints.
2205 Duplex Steel Pipe	
• Welded connections, no couplings. • Each welded connection can be inspected using x-ray techniques to verify that the joint is welded properly and meets the proper specifications. • Can be provided in standard sizes. • Good corrosion resistance for Florida's concentrate disposal environment. • Can be utilized with the YBI packer without requiring additional compressive force being applied from the surface.	• Special welding techniques are required to put pipe together, • Most expensive option for tubing designs requiring less than 9.7 mgd. • Long lead times of 30 or more weeks may be required for delivery.

All of the above materials are considered to be satisfactory materials for an appropriate completion design as discussed in Section 7.

6.2 Reduction of Corrosivity

There are a variety of actions that can be taken to reduce the corrosivity of the water. The methods to reduce corrosivity include mixing with effluent from a water reclamation facility, physical de-oxygenation of the injected water, and chemical treatments.

6.2.1 Mixing Concentrate with Water Reclamation Effluent

Mixing of concentrate with effluent from a water reclamation facility could be beneficial based on a reduction in the TDS as suggested by the CR calculation provided in Section 2.4. However, the actual reduction in TDS depends on the relative volumes of fluids generated and the potential need for the effluent for reuse applications. In addition, mixing with the effluent can raise the oxygen content of the solution and introduces chlorine used for disinfection. It is not clear from the available data collected for this report that mixing is beneficial. Wells with mixed injection streams appear to have failed in similar time frames as those wells that only inject concentrate.

6.2.2 De-oxygenation of the Injected Water

The oil and gas industry has been utilizing de-oxygenation of their brine disposal wells for some time, and, in Saudi Arabia, it has become the principal method utilized to reduce the corrosivity of seawater (Brown and Dubreuil 1979). Discussions with vendors indicate that the de-oxygenation systems are utilized in offshore locations (United States Filter 2004). De-oxygenation of a water solution is currently performed utilizing a membrane system coupled with nitrogen gas, which can either be generated on-site or purchased in bulk. Current de-oxygenation systems utilized by the oil and gas industry cost approximately $1,000,000 per 1 mgd. De-oxygenation systems, which will likely be used to de-oxygenate water injected into an ASR well in the state of Florida, are estimated to cost approximately $150,000 to 400,000 per 1 mgd. Operating costs for a de-oxygenation system similar to one utilized for an ASR system to remove oxygen from the injected water is estimated to be over $100,000 per 1 mgd of capacity per year for a system operating 24 hours per day, 365 days per year. Yearly operating costs for a de-oxygenation system to handle a 5 mgd system (approximately $500,000) would equal the cost of installing a corrosion resistant liner within one to two years. This analysis indicates that, although feasible, operating costs over the life of a well would greatly exceed the cost for the installation of a corrosion resistant tubing or liner.

6.2.3 Chemical Treatments

The basic chemical treatments available include oxygen scavengers (chemical de-aeration) and corrosion inhibitors. In addition, corrosion inhibitors are broken down into organic and inorganic type corrosion inhibitors.

6.2.3.1 Oxygen Scavengers

Oxygen scavengers have been proposed for the removal of dissolved oxygen and chlorine from ASR wells and for water injected into Class I disposal wells. As indicated in the previous SJRWMD Corrosion Report (Sims et al. 2005), commonly proposed oxygen scavengers include sodium sulfite and sodium bisulfite. Also, as indicated by Sims et al. (2005), the reaction rate is slow in the absence of a catalyst such as nickel or cobalt. In addition to having a slow reaction time, laboratory experiments performed on water being injected into an ASR well suggested that 3 times the stoichiometric concentration of bisulfite was required to reduce the dissolved oxygen to less than 2 ppm. The cost of chemicals for was determined to be approximately $138 per million gallons of treatment capacity (Water Resource Solutions 2004). These data indicate that the use of the sulfite or bisulfite ion to remove oxygen is not efficient or cost effective.

6.2.3.2 Corrosion Inhibitors

Corrosion inhibitors in general reduce the corrosion rate, but do not eliminate corrosion. Corrosion inhibitors can be based on either inorganic or organic chemistry. The water industry is most familiar with mixtures of orthophosphates and polyphosphates. The corrosion resistance provided by these type materials, as with most inhibitors, is based on the film forming ability of these compounds (Sweetwater Technologies 2006). In order for these type inhibitors to be effective, the water chemistry needs to be consistent and the chemicals need to be added fairly continuously for the films to remain in tact. It is suggested that polyphosphates role is to sequester metal ions that would otherwise react with the orthophosphate, which is most responsible for film formation (Sweetwater Technologies 2006). The large concentration of multivalent metal ions in the concentrate would suggest that this type of inhibitor would not be suited for use in a concentrate disposal well. Other type of inorganic inhibitors includes metal nitrites such as sodium nitrite, chromates, and zinc oxide. It is also worth noting that film formation (precipitation) could impact injectivity of wells that inject into formations in which the porosity is not vugular in nature.

Organic inhibitors are often quaternary amines, hydrazine, and other nitrogen containing organic compounds; aldehydes and related compounds, and organic acids such ascorbic acid (NMWAIDS n.d.). These type inhibitors rely on their film forming ability and the stability of these films (Petroleum Technology Transfer Council 2002). Typically, these inhibitors need to be added continuously at low concentrations if they are to resist corrosion. The volumes of water injected into a typical disposal well would make the use of these compounds cost prohibitive. In addition, some of these chemicals are both toxic and carcinogenic, which makes the care and handling of these materials of concern.

It is also relevant to note that there is little use of corrosion inhibitors in oilfield injection wells, which is also indicative of the lack of cost effectiveness of this approach to corrosion reduction in injection wells.

6.3 Cathodic Protection

Cathodic protection is a commonly used technique to prevent corrosion of underground pipelines and has been used to protect the longstring casing in certain areas where underground currents are generated between subsurface layers. Cathodic protection requires that an electric current be carried between two electrodes (Beavers and Thompson 2006). Therefore, there must be a conductor for current to flow between the cathode (the negative electrode) and the anode (the positive electrode). When cathodic protection is applied to a well, the longstring casing becomes the cathode, and a sacrificial anode is used as the anode. The dissolved minerals in the water bearing soil are utilized to conduct the current between the cathode and the anode in the subsurface. This procedure can help protect the longstring casing from external corrosion (Michie and Associates1988). However, the tubing is located inside the outer casing and cannot be protected by this method due to the physical isolation of the tubing from the soil.

As reported by Michie, the cement surrounding the outside of the casing is most often sufficient to minimize corrosion of the outer surface of the longstring casing, and therefore, cathodic protection of the outer casing is rarely required. In addition, as further reported by Michie and previously stated in Section 4, corrosion of the tubing and inner surface of the casing is minimal when oxygen is eliminated from the packer fluid, even though the packer fluid may be extremely saline. From a practical perspective, this also means that corrosion is minimal in the tubing/casing annulus once the small amount of oxygen has reacted with the casing and no further oxygen is added. Since cathodic protection offers little potential to protect the inside of the injection tubing and liner, and since the outer and inner casing walls and inner tubing wall are not observed to be corroding at a significant rate, cathodic protection is not recommended.

7.0 INJECTION WELL DESIGN ALTERNATIVES

The two most viable completion options available for a concentrate disposal well are:

- Tubing and Packer Completion
- Liner Completion

The advantages and disadvantages of each type of completion are addressed at the end of this section. This discussion also includes a discussion of the materials that are available for the tubing and the basic types of packers that are available.

7.1 Tubing and Packer Completion

There are a number of issues that need to be considered when selecting a completion type for a concentrate disposal well. One important issue is the relationship between the forces acting on a tubing and packer system and temperature. One interaction that can be readily understood is the impact that a change in temperature has on the length of tubing suspended in a well from the top. This issue is important since changes in tubing length can affect the forces acting on the packer assembly at the base of the casing and potentially compromise the annular seal. In this case, the tubing weight does not change, but the length of the tubing can change as indicated by the following equation (Dean 1979):

Equation 2

$\Delta L = \alpha L \, \Delta T$

Where:

ΔL = Change in length of the tubing
α = Coefficient of linear expansion
L = Length of the tubing at the reference temperature
ΔT = Change in temperature from the reference temperature

For steel, α is equal to 6.0 $\times 10^{-6}/^{o}F$

For fiberglass, α is equal to1.2 x10^{-5}/^{o}F

The change in temperature required to change the length of a 2,500 foot-long tubing by 6 inches is 33^{o}F for steel and 17^{o}F for fiberglass. The potential expansion and contraction of the tubing with respect to temperature is important for the design of a tubing and packer type completion. Historically, there were only two types of packer designs and both contain a unit called a polished bore receptacle that is an integral part of the packer body. The tubing is equipped with a device called a stinger. The stinger, which contains several sealing devices, is set inside the polished bore receptacle. The seals are spaced inside the bore so that the tubing can move freely up and down as the length of the tubing changes with temperature without moving outside of the polished bore receptacle.

The second design allows the tubing to be latched into the packer. If the tubing is latched into the packer, then the tubing is no longer able to move. The restricted movement improves the life of the seal, but requires consideration of the changing forces acting on the packer and at the top of the casing.

For a free moving tubing system, all of the weight of the tubing is held at the top of the casing and all the mechanical attention is focused on the strength of the wellhead to support the tubing weight. For a packer with a latching device, the tubing is commonly latched into a previously set packer body mechanically attached to the well casing. The tubing is set in tension by latching into the packer body and then pulling upwards on the tubing in order to put tension on the tubing. This tension on the tubing places an additional downward force on the wellhead. For this system, the packer body is set in tension during the installation and the tension on the tubing helps maintain the mechanical set of the packer. In the case of a packer set in tension, a decrease in the average tubing temperature due to injection of a colder fluid causes an increase in the upward force on the packer and the downward force on the wellhead. Alternatively, if the temperature of the tubing increased by the injection of a warmer fluid, then the tubing increases in length and the tension on the tubing string and packer is reduced.

The change in force acting on the wellhead and the packer due to temperature variations can be calculated using the following equation (Arthur and Fenster 1969):

Equation 3

$F = EA\ \alpha\Delta T(^oF)$

Where:

F = Force in Pounds
E = Young's Modulus of Elasticity
A = Cross Sectional Area of the Pipe
α = Coefficient of Linear Expansion (carbon steel) = 6.0 $x10^{-6}/^oF$ for carbon steel
$\Delta T(^oF)$ = Temperature change

The following values are used to estimate the change in force due to a change in temperature of 10 ^oF for a 20-inch diameter, 0.5-inch wall steel pipe.

E = 30 $x10^6$ psi for steel
A = 30.6 in^2 for a 20-inch diameter, 0.5-inch wall steel pipe.
α = 6.0 $x10^{-6}/^oF$
ΔT = 10 ^oF

For the above values, the change in force is 55,100 lb. for steel tubing.

The weight of a 20-inch diameter, 0.5-inch wall, mild steel tubing string that is 2,500 feet in length is approximately 222,000 lb. in the hole due to the buoyancy of water. In air, the same string would weigh approximately 255,000 lb. Thus, the calculated force change of 55,100 lb. is equal to approximately 25% of the tubing weight.

The largest fiberglass pipe capable of fitting inside a 24-inch casing has an I.D. of 16.60 inches and an O.D. of 18.11 inches. The couplings for this pipe have an O.D. of 22.3 inches. The weight of a 16.6-inch I.D. fiberglass tubing string in air is 75,000 lb. The same tubing string in water weighs approximately 30,000 lb. If a similar calculation is performed for this fiberglass string, the change in force for a 10^oF change in temperature is calculated to be 10,000 lb.

Although the above information is part of the standard consideration for tubing and packer completions, the use of a new packer system developed by the Youngquist Brothers, Inc. (YBI) is gaining popularity throughout the state. The YBI packer is designed around a metal-to-metal seal that is created by inserting a specially tapered connection on the tubing into a similarly shaped profile permanently installed near the base of the longstring casing. The seal is energized by setting a portion of the tubing weight on the connection. For this system, there may be concern that the tubing will shrink if the temperature of the tubing is reduced and the seal between the casing and packer could be compromised.

Therefore, when the YBI packer is utilized, there are two issues that need to be considered. First, the minimum amount of force required establishing the seal between the packer and the casing needs to be known. Second, a realistic estimate of the maximum temperature change that could be experienced while injecting water needs to be determined.

Total Force (Weight) Placed on Packer	=	Force Required To Seal Packer	+	Force Required To Counteract Pipe Shrinkage Due to 10°F Temp. Decrease

For the purposes of demonstration, it is assumed that a minimum of 30,000 lb. of compressive force is needed to positively seal the YBI packer. The manufacturer needs to be consulted for the actual sealing force required. If it is also assumed that a 10 degree Fahrenheit decrease in temperature can occur at some point during the winter, then, for steel tubing the total force on the packer must be:

Total Force (Weight)	=	30,000 lb.	+	55,000 lb.
Placed on Packer	=	85,000 lb.		

A similar calculation performed for fiberglass indicates that a total compressive force of 40,000 lb is required.

A review of the weight of the fiberglass pipe will show that the 40,000 lb. exceeds the weight of the fiberglass tubing of 30,000 lb. in water. In this case, 10,000 lb. of downward force is required to be placed on the fiberglass tubing to ensure the seal between the tubing and casing is not lost during colder periods of the year. This also means that the tubing must be pushed into the well with 10,000 lb. of force. In response, the tubing will be pushing upward with a force of 10,000 lb. on the wellhead once the wellhead is installed in accordance with Newton's third law of motion.

Seasonally or otherwise, when the temperature of the injected water rises, the tubing string will lengthen. If the average temperature of the tubing string were to increase by 10 degrees Fahrenheit, then an additional force of 10,000 lb. of force would be available to enhance the seal at the packer for the fiberglass tubing. An additional 10,000 lb. of upward force would also exist on the wellhead. For steel pipe, theoretically an additional 55,000 lb. of downward force would be placed on the packer, while the hanging weight on the wellhead would be reduced by 55,000 lb. In reality, some of the additional forces that arise due to the lengthening of the tubing are picked up by the walls of the casing as the tubing begins to bend and contact the casing. Therefore, not all of the acting forces are necessarily transferred to the wellhead or to the packer.

It should be recognized that wells injecting both municipal waste and concentrate will undergo larger changes in temperature than would occur in wells that dispose of concentrate alone. The larger temperature change is due to the storage of municipal waste in surface ponds exposed to surface temperatures prior to injection.

7.1.1 Well Annular Monitoring System

In addition to the change in the length or force acting on the tubing, the injection of colder water can also impact the pressure in the annulus between the tubing and the casing. This issue is relevant from the perspective that the annular pressure between the casing and the tubing must remain higher than the injection pressure. For a closed system (constant volume), the change in pressure as a function of temperature can be calculated using the following equation (Levine 1978):

Equation 4

$\Delta P = \alpha/\beta \ (\Delta T)_v$

Where:

ΔP	=	System pressure change in psi due to a temperature change at constant volume
α	=	Coefficient of cubical expansion (9.7×10^{-4} /^{o}F)
β	=	Coefficient of compressibility (3×10^{-6} /psi)
$(\Delta T)_v$	=	Temperature change (^{o}F) at constant volume
α/β	=	32 psi/^{o}F

The above equation indicates that a significant drop or increase in annular pressure can occur when water at different temperatures is injected into a well. Annular monitoring systems must be able to adjust to these changes within a time period that is acceptable to the FDEP. A reasonable time period should range between 10 to 15 minutes. For an annular volume of 15,000 gallons, a change in temperature of 3^{o}F will cause an approximate pressure change of 96 psi in a closed system filled completely with water. The annular monitoring system must be able to compensate for these changes. In order to maintain the annular pressure during injection into a tubing and packer type well completion, a well annular monitoring system (WAMS) is required. The WAMS system needs to be able to respond to changes in temperature fairly rapidly. Although the theory behind operating these system is very basic, actual operation can prove to be more problematic. Commonly, a tank is connected to the well annulus. The tank is filled with both a gas and water. The gas, which is typically nitrogen, is used to control the pressure in the tank. Fifty percent of the tank is filled with water that is in direct communication with the well annulus. The tank is then fitted with inlet valves to allow nitrogen in from a nitrogen supply system when the pressure drops and a high-pressure release valve to allow nitrogen to escape to the atmosphere when the pressure gets too high. As temperatures fluctuate throughout the day, nitrogen is either being released as daily temperatures rise or being filled from the nitrogen bottles when temperatures decline at night. A 10 degree Fahrenheit daily change can mean that the nitrogen utilized per week can be on the order of one or more standard nitrogen bottles. In addition, the movement of the water level in the WAMS tank must also be followed to determine if water is being lost from the system. The monitoring of the amount of water in the system can also be difficult if the temperature of the injected water is changing. As operators become proficient with a WAMS unit over time, they become more confident in their ability to interpret the readings and identify if the well is actually losing fluids. The time required for an operator to gain this confidence typically takes at least one seasonal cycle.

7.1.2 Thread Performance

Another issue that can impact mechanical integrity associated with threaded pipe is the changing forces on threads (Gator Hawk n.d.). Many pipe threads are designed to hold pressure in (Colder Products n.d.) and the seal is actually energized when the pipe is pressurized (Gator Hawk n.d.). When a higher pressure is placed on the outside of the pipe than on the inside of the pipe, the thread can lose some ability to seal. In addition, for those pipes that require thread sealant (American Petroleum Institute 1992); changes in stress can result in the loss of sealing capacity of the thread (Gator Hawk n.d.). Therefore, for packer and tubing completions, the thread lubricant/sealant needs to be appropriately selected. The need to consider threaded pipe is only an issue for fiberglass pipe and for lined, mild steel pipe.

Historically, fiberglass has been set in tension as per manufacturer's recommendations. However, the YBI packer requires that the tubing be set in compression. In order to address this issue, the setting requirements for fiberglass in compression have been revised for many of the wells currently constructed in Florida (Future Pipe Industries 2003). It is therefore recommended that the manufacturer of the fiberglass pipe be contacted for additional information concerning setting their pipe in compression.

7.2 Liner Completions

Potential disadvantages of the liner type completion are that it does not provide the real time leak detection provided by the tubing and packer completion and it does not offer the replacement opportunity that is provided by the tubing and packer completion.

However, if the liner is properly selected – i.e. the liner will not corrode in the injection well environment and there are no other sources of leaks, then there are several advantages to the liner completion including:

1) Cement provides a second protective layer for the longstring casing.

2) A liner completion is not susceptible to temperature changes and therefore changing forces on wellheads, packers, threaded joints, length of tubing in the wellbore, or moving seals are of no concern since the condition of each is fixed by the cement. Long-term concern about leaks through the threads is significantly reduced.

3) A liner completion reduces the compressive forces that would be imposed on fiberglass if a YBI packer was used.

4) Other sources of leaks in the casing-tubing annulus are eliminated.

5) Significant operator time and operational concerns are reduced by not having to maintain a WAMS system.

The major disadvantage to the liner system is the regulatory requirement to perform a pressure test every 2.5 years on the tubing. If fiberglass pipe is to be utilized, then the available space between the couplings and the casing need to be considered if a tremmie pipe will be utilized in the cementing operation. If a 24-inch longstring casing is required, and the 16.6-inch I.D. fiberglass pipe is to be utilized, then the cementing of the fiberglass must be completed in one continuous stage. It must be done in one continuous stage because the outside diameter of the fiberglass coupling is approximately 22.1 inches and there is no room to run a tremmie pipe between the 23-inch I.D. casing and the 22.1-inch coupling. Although pumping a single stage is not necessarily a major issue, the reliability of the cement pumping arrangement, the surface injection pressure, the setting time of the cement, and the viscosity of the cement need to be considered since there is only one opportunity to bring the cement to the surface. Cement pumping pressure should not exceed the burst pressure of the pipe at the surface.

The information provided above indicates that:

1. When coated, mild steel tubing is used, a tubing and packer type completion must be utilized since failure of the coating could result in failure of the injection tubing. A liner type completion does not allow for removal and replacement of the liner.

2. Fiberglass, due to temperature consideration, may be best suited for a liner type completion when using an YBI type packer. The use of a standard packer type and setting the tubing in tension is also a viable alternative based on the long-term performance of large bore packers. Manufacturers should be consulted for specific completion designs for a given environment.

3. The use of 2205 duplex steel is best suited for a liner type completion.

8.0 CONCLUSIONS AND RECOMMENDATIONS

The following conclusions are based on the information developed during the preparation of this report:

8.1 Conclusions

1. Class I disposal wells, as with the vast majority of oilfield production and injection wells, have not experienced significant corrosion problems when using mild steel as the casing material. However, mild steel tubing is highly susceptible to corrosion in wells injecting concentrate from desalinization processes (concentrate) or a mixture of concentrate and water reclamation facility effluent**.**

2. While the corrosion rates for concentrate from desalinization and water reclamation facilities led us to speculate that dissolved oxygen is the causative factor; the lack of data on dissolved oxygen levels did not allow a definitive conclusion of this relationship.

3. The median mild steel corrosion rate of tubing for wells in Florida injecting concentrate or a combination of municipal waste and concentrate is 167 mils per year (mpy). Observed corrosion rates ranged from 25 mpy to more than 500 mpy. All observed corrosion rates were far in excess of the NACE recommended maximum rate of 2 mpy, and are related to a pitting corrosion attack rather than uniform corrosion of the tubing material.

4. Of the 22 wells with reported total dissolved solids (TDS) data, 5 wells had TDS levels of less than 4,100 mg/l, 7 wells had TDS levels between 4,100 and 10,000 mg/l, and 10 wells had TDS levels greater than 10,000 mg/l. The data do not indicate that TDS has a large influence on the failure rate of the wells.

5. Corrosion resistant materials such as 2205 duplex steel, fiberglass, and plastic coated or lined pipe provide the best options for reducing or eliminating the negative impact of corrosion on tubing in Class I non-municipal injection wells.

6. PVC pipe can provide good service for shallow Class V wells utilized to inject concentrate in coastal areas authorized to use this type well by FDEP.

7. Liner completions offer a significant advantage over tubing and packer completions when constructed properly. Therefore, concentrate disposal wells should be completed using a liner made from fiberglass or 2205 duplex steel.

8.2 Recommendations

1. Based on a review of the corrosion rate data, it is recommended that a corrosion resistant material be utilized for the tubing or liner in a concentrate or combination concentrate/municipal waste disposal well.

2. The major choices of materials are:

- Fiberglass or 2205 duplex steel. The actual choice of 2205 duplex steel or fiberglass will ultimately be left to the preference of the engineer. However, in those cases when 2205 duplex steel can reduce the number of required wells, then 2205 duplex steel is the recommended material of construction.

- PVC for shallow Class V wells that do not require the use of a tubing and packer or liner is a viable option. PVC could also be considered as a liner material for shallow wells that do not exceed 500 to 800 feet in depth.

3. Based on current construction standards, it is recommended that Class I concentrate and concentrate/municipal waste disposal wells be completed using a liner rather than a tubing and packer type completion.

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APPENDIX 1

EXTENDED LIST OF REFERENCES
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- **Class I Wells – General**
- **Class II Wells – General**
- **Class II Saltwater Disposal Wells**
- **Class III Wells – General**
- **Class V Wells**

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