SABINE RIVER WORKS
NO MIGRATION DEMONSTRATION

SECTION 4 - AREA OF REVIEW
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4.0 AREA OF REVIEW

4.1 SUMMARY

Non-Endangerment

Sixty-nine artificial penetrations were identified in the 2.5 mile radius Area of Review (AOR) (Appendix 4-4). The distribution of these 69 wells is as follows:

1. Forty-eight abandoned and plugged artificial penetrations

2. five active oil/gas wells (Artificial Penetrations 10, 11, 17, 24, 58),

3. five wells which do not penetrate the injection intervals (Artificial Penetrations 63, 65, 66, 69, and 75), and

4. eleven artificial penetrations which were modeled for non-endanderment evaluation (Artificial Penetrations 3, 4, 20, 22, 40, 41, 44, 47, 70, 72, and 74).

Forty-eight of the artificial penetrations (see Table 4-1) are plugged properly to satisfy the criteria for non-endangerment to underground sources of drinking water (USDWs). Please note that all Artificial Penetrations are not numbered consecutively. Properly plugged wells have a cement plug between the top of the injection zone and the base of the lowermost USDW. Twenty-one artificial penetrations do not meet this criteria (may be active, do not penetrate the injection intervals, or do not have cement plugs between the base of the USDW and the top of the injection zone) and have been evaluated to determine if they demonstrate endangerment (to USDWs) due to injection operations. The five active wells which are active will be properly plugged after production according to Texas Railroad Commission regulations which protect USDWs. Five abandoned boreholes do not penetrate any of the injection intervals and do not serve as potential conduit for movement of fluids from injection operations at the Sabine River Works. The remaining eleven wells were modeled to determine if pressure increases from injection operations would be sufficient to initiate the movement of fluids in the abandoned boreholes (Tables 4-2 and 4-3). To be conservative, evaluations were made in the 4600 ft J

sand (Table 4-3) because it is the uppermost injection interval and in the 5400 ft M sand (Table 4-2) because modeling (Section 2.1) has shown this sand to have the highest pressure build-up. Results of the evaluation indicate that there will be no threat to USDWs from the these eleven artificial penetrations within the AOR. Modeling projections were based on maximum permitted injection rates until the year 2000.

Analysis of the site included sensitivity analyses to address the communicative potential of faults A and D (Section 2.1.4.5) as they pass to the northwest and southwest of the plant. The throw on these faults at the dome is up to and over 1000 ft. Along their courses, their amount of throw diminishes to 50 ft or less at their closest point to the plant site. The presence of many fault traps which has provided reservoirs for oil production over Orange dome confirms the non-communicating nature of these faults at the dome. Close to the plant where the throw is much less, these faults are best treated as communicative across the fault plane where sand is juxtaposed against sand. Pressure matching of historical bottom hole pressure data confirms that the Sabine River Works is best modeled as a no-fault site. Thus, all pressure contour charts and pressure buildup evaluations in the AOR evaluation are based on this conservative case.

No-Migration

Artificial penetrations within the 10,000 year extent of the waste plume were evaluated to determine if they meet the no-migration of hazardous waste out of the Injection Zone criteria. Appendix 4-4 shows the location of the AOR, all artificial penetrations contained therein, and the maximum extent of the 10,000 year plume swath. See Section 3, Appendix 3-4 for structural controls on the plume and Section 2.1.4.4.1 for a discussion of plume boundary modeling.

Six artificial penetrations within the non-endangerment AOR were found to fall within the extent of the 10,000 year plume. These wells, APs 63, 64, 65, 66, 68 and 69 were individually investigated and modeled to determine the maximum distance waste would diffuse up the wellbore if allowed to enter. Records indicate (Appendices 4-3, 4-4, 4-5, 4-6), that APs 63, 65, 66, and 69 do not intersect the uppermost, J, sand. Therefore these could not be a conduit for upward movement.

The remaining wells, 64 and 68, were determined to contain drilling mud. Modeling of these wells showed that if injected material were allowed to enter these artificial penetrations at the present day, the maximum extent of the material above health based limits would be 310 feet. Diffusing up from the uppermost (worst case) injection sand, the J sand, the waste front will still be 500+ ft beneath the top of the Injection Zone.

Wells within the plume extent outside the non-endangerment AOR have been divided into two groups. The first is comprised of those few wells which lie to the west of the AOR and within the 10,000 year plume swath up to the fringe of Orange dome. These have been conservatively modeled assuming waste contact at the present day ignoring the time period required for the plume to reach each of the wells. The maximum distance the front may move up a mud filled borehole is 310 ft (Figure 4-26), and up a brine filled borehole is 440 ft (Figure 4-27). Added to the top of the uppermost J sand, this is still well within the Injection Zone.

The second group is made up of those wells drilled in Orange Field. Conservative modeling of density drift and dispersion of the plume indicate that the plume will reach Orange dome after approximately 3000 years. As shown in Figure 4-26, the maximum extent of any of the injected constituents above health based limits in a mud filled borehole at the dome would be 260 ft since the waste would be present at the dome for 7000 years in the 10,000 year time frame. Figure 4-27 shows the maximum extent of any of the injected constituents above health based limits in a brine filled borehole at the dome would be 375 ft. Therefore, no injected material will diffuse out of the Injection Zone above health based limits within the modeled period of 10,000 years.

Additionally, the site contains buffer aquifers that meet the siting criteria and provide an additional safeguard for any unknown improperly abandoned borehole or transmissive faults or fractures. A discussion of the faults mapped near the Sabine River Works is included in Section 3, Geology.

4.2 AREA OF REVIEW AND NO-MIGRATION DEMONSTRATION

The AOR refers to a specially-identified region around an injection site where the owner or operator must investigate all natural breaches (vertically transmissive faults or fractures) and artificial penetrations (abandoned boreholes) intersecting the confining and injection zones. According to the Federal AOR requirements (40 CFR 146.63, July 26, 1988) the AOR must address non-endangerment of USDWs by waste or formation brine. The long-term concerns associated with plume movement (no-migration demonstration) are addressed in 40 CFR 148.20. The EPA has stated that the standards of 40 CFR 148.20 and 40 CFR 146 are separate and must be addressed separately. The 40 CFR 146.62 requirement is designed to assure no endangerment of USDWs from injected fluid or from formation fluid, whereas 40 CFR 148.20 assures that no injected waste can leave the injection zone for as long as the waste remains hazardous. These requirements are addressed separately in this demonstration.

The **non-endangerment** requirement applies primarily to the time period during and immediately after injection has taken place, and the requirement has a broad set of regulatory controls. This is when pressure in the injection zone might be great enough to drive fluid through an artificial penetration into a USDW (assuming no transmissive faults or fractures are present).

Although both waste and formation brine are considerations in addressing non-endangerment, in practice, the primary concern is formation brine. This is because the waste plume is virtually always contained within the pressure front induced by injection operations:

> ...the area in which formation fluid could endanger USDWs is described by the pressure front induced by injection; the area in which injected fluid could move out of the injection zone, on the other hand, is described by the size of the waste plume. The pressure front is always larger--usually much more so--than the waste plume (40 CFR 146.62, preamble, July 26, 1988, p. 28134.)

Therefore, the determination of the AOR associated with non-endangerment will focus primarily on formation brine, although it will also automatically include the waste.

The determination of the region related to **no-migration** involves tracking the movement of the waste plume for 10,000 years. Depending on the velocity of the plume (density and natural horizontal drift), this region may extend beyond the non-endangerment AOR. Once the overall area for both non-endangerment and no-migration has been established, it is then necessary to evaluate all artificial penetrations within this area. The no-migration demonstration requirements are addressed in Section 4.6.2.

4.2.1 Non-Endangerment

This section (i.e., Section 4.2.1 and all associated subsections) uses the term AOR to refer to the area related to the non-endangerment requirement. It therefore does not include the portion associated with no-migration.

First, the concepts of ZONE OF ENDANGERING INFLUENCE and CONE OF INFLUENCE are discussed. Second, the Agency's explicit desire to limit the extent of AOR (to less than tens of miles from the injection well) is documented. Third, the basic requirements for modeling AOR are addressed. Fourth, a summary of the various historical approaches to identification of a worst case borehole scenario is presented, together with the results of field case studies and the historical approaches adopted by state regulatory bodies. It will be shown that the arbitrary requirement that AOR be based on the piezometric head of the injection zone and of the USDW is equivalent to specifying in advance a worst-case scenario in which the abandoned borehole contains formation brine. Such a requirement runs contrary to the Agency's frequently stated position that AOR be site-specific ("the Agency is not specifying particular methods of calculating an area of review..." and "The Agency ... does not believe that a single calculation, or a set of calculations, describes the universe of acceptable methods for determining area of review.").

4.2.1.1 Zone of Endangering Influence and Cone of Influence

In previous EPA underground injection control (UIC) regulations, the AOR was either (a) a fixed 1/4-mile radius of the well bore or (b) the calculated "zone of endangering influence" of the injection operation,

whichever was larger. The zone of endangering influence (ZOE) is defined as "that area the radius of which is the lateral distance in which the pressures in the injection zone may cause the migration of the injection and/or formation fluid into an underground source of drinking water." EPA has amended the AOR requirements for all Class I hazardous waste injection wells by modifying the area to be examined to either (a) a minimum fixed 2.0-mile radius from the injection well bore or, (b) at the discretion of the Director, the calculated "cone of influence" of the well. The cone of influence (COI) is defined as "that area around the well within which increased pressures caused by the hazardous waste injection well would be sufficient to drive fluids into an underground source of drinking water."

Whereas the definitions of the ZOE and COI appear very similar, there is a very subtle difference. The COI inherently ignores any initial underpressurization or overpressurization that may have existed in the injection formation; and, thus, assumes that the geological strata, down to the depth of the injection formation, were hydrostatic to begin with. The ZOE does not make this assumption, and is more realistic and appropriate for actual geological systems.

The basic difference between the two terms is that the former [ZOE]... includes the pressure of the formation, while the latter [COI] defines the area of review as the area described by the incremental increase in pressure caused by the injection well. The Agency believes the pressure of concern should be the increment over static conditions since that is the pressure resulting from the regulated activity. (40 CFR 146.63, preamble, p. 28134).

In this petition, we have used the COI because of the regulatory concerns about the increased pressure from background conditions (pre-injection activities). We also have applied the ZOE approach, which incorporates information about original formation pressures and the required additional pressure to lift drilling fluid in an abandoned borehole.

4.2.1.2 Agency's Explicit Desire to Limit Extent of AOR

It is interesting to review the Agency's underlying motivation in going from the ZOE approach to the COI approach, since this has a

bearing on the remainder of the present discussion. The Agency recognized that, under certain circumstances (such as initial overpressurization), the AOR calculated using the ZOE approach could turn out to be quite large or even infinite. They felt that such large AORs might place an undue burden on the owner or operator, without a commensurate increase in protectivness, and reasoned that the very existence of overpressurization might be an inherent indication of enhanced protectiveness.

The Agency also recognizes that calculations may result in an asymptote, or that in some physical settings the formation pressure will contribute to an AOR that extends over great distances. Under current State and Federally-implemented rules, the problem of infinite asymptotes has been addressed by setting cut-off points when the slope of the pressure curve flattens. It is not EPA's intent that operators "chase asymptotes" when no real potential endangerment resulting from the well exists. The physical settings which might result in calculated AORs in excess of 2 miles involve highly overpressurized formations. As noted in the proposal, overpressurization can be evidence that the formation is effectively a closed system. Where natural or man-made points of discharge exist, pressure will begin to equilibrate, and the excess pressure will tend to "bleed off." Absent such leaks, the system will retain excess pressure. (40 CFR 146.63, preamble, p. 28135).

The above arguments provide a clear-cut indication of the Agency's intent, by expressing both the expectation and the desire that the AOR not extend to great distances from the injection well (say, tens of miles), but rather, that it be confined to a reasonable distance. Distances greater than a few miles would place an undue burden on the owner or operator without a commensurate increase in protectiveness.

On the Gulf Coast of Texas and Louisiana, injection wells are at depths where formation pressures are hydrostatic. Even in these cases, the ZOE may extend for tens of miles. Certainly, the Agency was aware of this (40 CFR 146.63 preamble) and it was not their intent to have AORs extending vast distances. Thus, the AOR was redefined based on COI and induced pressure buildup. AORs greater than 2.0

miles are due to highly overpressurized formations, and this overpressurization may be an indication that the formation is a closed system. Injection sands in the Gulf Coast exhibit high permeability, and overpressurization of these sands is rare.

The AOR for Sabine River Works was determined to be the fixed 2.0-mile radius from the injection wells per the regulations. However, draft regulations (August 27, 1987) proposed a 2.5-mile radius, and our original studies for the AOR were based on the 2.5-mile radius. We have retained the 2.5-mile radius because data already had been gathered and was not a significant burden to incorporate. The COI for the Sabine River site was determined to be a 0.5-mile radius from the injection wells (see Section 4.4). The EPA noted that some wells outside the COI might have to be evaluated in the petition for a no-migration demonstration under 40 CFR 148--for example, where the formations are naturally overpressured or where there is significant flow. The no-migration demonstration satisfied 40 CFR 148.20 for the wells outside the AOR, and the results are presented in Section 4.6.2.

4.2.1.3 Historical Approaches to AOR

Thornhill et al. (1982, p. 33) and Engineering Enterprises (1985) have described a generic non-site-specific approach for determining the calculated AOR, applicable to any arbitrary location in the country. According to this approach, the AOR is determined by the region around an injection site in which the piezometric surface of the injection zone is above the piezometric surface of the USDW. This "piezometric surface" approach is inherently equivalent to assuming that the abandoned well contains formation brine and is open simultaneously to both the injection zone and the USDW. Such an extreme worst-case borehole description is much more stringent than necessary for many site-specific locations, such as on the Gulf Coast, where it can be demonstrated that far less conservative assumptions are valid. Moreover, any requirement that the AOR be universally calculated on the basis of the piezometric surface approach runs contrary to EPA's frequently-stated position that no one single method is to be specified for calculating AOR.

The Agency believes that ... guidance may be necessary to clarify the methods appropriate for establishing area of review, but does not believe that a single calculation, or a set of calculations, describes the universe of acceptable methods for determining area of review. Moreover, prescribing by regulation the appropriate method could preclude permittees from using more sophisticated methods which might become available at some future point. Therefore, the Agency is not specifying particular methods of calculating an area of review in this rule. (40 CFR 146.63, preamble, p. 28135)

Frequently, the calculated AOR determined using the piezometric surface approach is equated with the terms ZOE and COI. However, such an interpretation is not valid, except at sites where the abandoned well can actually be shown to contain formation brine. Moreover, regulations apply to pressures greater than background due to injection. Regulations do not require comparison of piezometric surfaces nor the drawdown of USDWs. It is important to remember that the COI is directly related to the increase in pressure over background, and is not a comparison of potentiometric levels. The Agency is aware that the natural position of the potentiometric level of the injection zone may be higher than the potentiometric level of the lowermost USDW by allowing the potentiometric surface of the fluid in the injection zone to be lower than the potentiometric surface of the lowermost USDW in the siting criteria.

It should also be mentioned that the piezometric surface approach neglects the effects of differences in fluid density between the injection zone and the USDW. Typically, the fluid in the injection zone has a higher density than that in the USDW, and this influences the calculated AOR. It is of interest to note, however, that the previous set of UIC regulations (40 CFR 146.6, July 1, 1986) presented an example in which the formula used to determine AOR included a proper correction for fluid densities. This correction involved multiplication of the piezometric head in the USDW by the specific gravity of the formation brine. This resulted in the use of a density-corrected head for the USDW in the AOR calculation. No density correction is required for the piezometric head in the injection formation.

In some instances, it has been suggested that the piezometric surface approach be used so that the drawdown is inlcuded when AOR is calculated. Even if the piezometric surface approach were valid for a given site, inclusion of the USDW drawdown would be inconsistent with the Agency definition of COI. It is obvious that drawdown of the USDW is equivalent in its effects on calculated AOR to initial overpressurization of the injection formation. According to the COI approach, initial overpressurization is to be explicitly ignored in determining AOR. (In any event, the present petition uses a combination of the more stringent COI and ZOE methodologies for AOR.)

Historically, AOR computational procedures for the Gulf Coast region have not used the piezometric surface method, because of the widespread recognition by regulators that the unknown abandoned wells in this locale contain drilling mud. Moreover, a wide variety of case studies have confirmed the validity and protectiveness of this assumption. Although many of the reports referenced refer to Gulf Coast conditions in Texas, the conditions in Gulf Coastal Louisiana are practically carbon copies of those in Texas, and the results would apply equally well.

Price (1971, see Appendix 4-7) published a Master's thesis in Civil Engineering at the University of Texas in Austin entitled "The Determination of Maximum Injection Pressure For Effluent Disposal Wells - Houston, Texas Area." In this thesis, he indicates that it was the common practice of the Texas Water Quality Board in the early 1970s to allow an injection zone pressure buildup of 10 psi/1000 ft of depth in determining the AOR. This allowance was based on an assumed abandoned borehole that was filled to the surface with drilling mud. An allowable pressure buildup of 10 psi/1000 ft of depth is equivalent roughly to an 8.66-lb/gal mud weight and a nominal Gulf Coast hydrostatic pressure gradient of 0.44 psi/ft. Price also commented as follows:

> This is a very low pressure tolerance since as can be expected, an unsupported earthen well bore will slough and heave with time and the likely pressure resistance to repressuring below may be as high as .2 or .3 psi per ft [200

> to 300 psi/1000 ft of depth]. The use of a tolerance of .01 psi per ft [10 psi/1000 ft of depth] is an arbitrary rule of thumb, but a better criteria for evaluating such situations does not presently exist (p. 72-73).

The Texas Water Commission (1977, see Appendix 4-8) later published a report stating that

> "... [a] rule of thumb [for calculating AOR] has been a pressure increase of 15 psi/1000 feet of depth. This is based on the pressure differential of a 9.5 lb. mud, normal Gulf Coast reservoir pressures (background pressure), and a considerable safety factor."

[Actually the safety factor used in this rule of thumb is extremely large. For a nominal Gulf Coast hydrostatic pressure gradient of 0.44 psi/ft and a 9.5 lb/gal mud weight, an allowable pressure buildup of 53.5 psi/1000 ft of depth would be calculated. Moreover, an additional margin of safety neglected is the effect of the mud gel strength.]

Both criteria have served to provide an unblemished record of preventing fluid movement from the injection zone to the USDW at waste injection sites over the past two decades.

Johnston and Greene (1979, see Appendix 4-9) issued an internal report at the Texas Department of Water Resources entitled "Investigation of Artificial Penetrations in the Vicinity of Subsurface Disposal Wells." In this report, they stated

> The critical pressure ... is the pressure required to displace 9 lb/gal mud in an unplugged well bore.

Barker (1981, see Appendix 4-10) completed a Master's thesis at the University of Texas at Austin entitled "Determining the Area of Review for Industrial Waste Disposal Wells". In this thesis, Barker was the first to document the development of the basic theoretical equation for calculating maximum allowable formation pressure at an abandoned borehole in terms of mud properties. This equation included the effects of both mud weight and gel strength. Barker performed

calculations for a reasonable worst case mud weight of 9 lb/gal and a minimal gel strength of 20 lb/100 ft^2. The Du Pont model for AOR is essentially the same as that of Barker, except the Du Pont model uses an assumed gel strength of zero for conservativeness.

Johnston and Knape (1986, see Appendix 4-11), on behalf of the Texas Water Commission, issued a report entitled "Pressure Effects of the Static Mud Column in Abandoned Wells". They indicated that the total pressure within the injection zone at an unplugged abandoned borehole should not exceed the hydrostatic head of the mud column contained in the borehole. They also suggested that a reasonable worst case abandoned borehole for the Texas Gulf Coast region would consist of a conduit filled to the surface with 9-lb mud. Johnston and Knape emphasized that this criterion ignores a number of factors that might add considerably to the safety of the injection operation, including mud gel strength and natural borehole closure.

Davis (1986, see Appendix 4-12) reiterated the methodology of Barker, by including both hydrostatic mud weight and gel strength in his analyses and calculations.

Collins (1986, see Appendix 4-13), in a report to the Chemical Manufacturers Association entitled "Technical Basis for Area of Review", stated that in order to properly model abandoned boreholes, it is important to use "...realistic values for mud and hole properties". Moreover, on the basis of a number of laboratory experiments on scale models of boreholes, he concluded that "... in most cases the contribution of the gel property [gel strength] to the critical pressure increase required for fluid entry into the well may be more significant than previously thought."

Warner et al. (1986, see Appendix 4-14) prepared a report for U.S. EPA Region V entitled "Confining Layer Study - Supplemental Report". In this report, they presented calculations using Barker's (1981) method to determine the static mud column pressure at an abandoned borehole. Warner (1988) in a study entitled "Abandoned Oil and Gas Industry Wells and Their Environmental Implications" stated that even an abandoned borehole has resistance to fluid movement. Drilling mud, partially effective cement or mud plugs, collapsed or sloughed formation, formations that have expanded into the borehole, and fish and junk lost in the hole would provide resistance to fluid movement.

Only in unusual circumstances would an abandoned well not contain some impediments to flow (e.g., a cable-tool well in competent strata). It is probable that, since this is normal drilling practice, all rotary-drilled, abandoned dry holes contain at least drilling mud.

Warner (1988, see Appendix 4-15) modeled the lower Tuscaloosa sand that had a permeability of 30 md, and an abandoned borehole that had a permeability of 40 Darcys (permeabilities for the borehole ranged from 40 to 4000 Darcys and made no observable difference in the results). Injection was into the lower Tuscaloosa and the pressure increase in the upper Tuscaloosa was 7.2 psi (through the middle Tuscaloosa and through the abandoned borehole). Above the upper Tuscaloosa, approximately 2040 ft of shale and chalk serve as confining strata for the Tuscaloosa. There was no pressure increase in the Wilcox above the shale and chalk. This simulation also confirmed the importance of the buffer aquifer concept because there was no flow up the abandoned borehole into the Wilcox. In another simulation, a 10-ft mud plug with permeability of 10^{-3} md (10^{-9} cm/sec) in the abandoned well across the middle Tuscaloosa showed no observable increase in pressure above the middle Tuscaloosa. Figures illustrating this model are contained in Warner's report, reproduced in Appendix 4-15.

Pearce (1989a) analyzed various abandoned borehole scenarios for the Gulf Coast region in attempting to arrive at a reasonable worst-case abandoned borehole for the AOR. His analysis included both cased and uncased wells, and wells containing either brine or drilling mud. He concluded that, because of natural borehole closure, an uncased hole presented no danger. In addition, cased dry wells would typically be filled with material equivalent to drilling mud because of the common practice of disposing of cuttings and debris in the hole. Only a cased production well that had not been properly plugged might potentially contain formation brine, which normally has a lower density than drilling mud, and would therefore begin flowing vertically at a lower pressure buildup. However, Pearce also noted that such a well would typically be situated in a production area where formation pressures are reduced. Furthermore, during the past several decades, laws have been in place requiring operators to follow well-defined plugging procedures for abandoning production wells. The likelihood of encountering such a "cased brine hole" within a reasonable distance (less than tens of miles) of the injection site

would be virtually nil. Numerous case studies provide powerful evidence of the protectiveness of existing AOR practices in the Gulf Coast, which are based on the presence of drilling mud rather than brine in abandoned boreholes.

The method Du Pont uses in determining the AOR is consistent generally with methods used by many others over the years: Price (1971), Texas Water Commission (1977), Johnston and Greene (1979), Barker (1981), Collins (1986), Davis (1986), Johnston and Knape (1986), Warner et al. (1986), Clark et al. (1987), Warner (1988), and Pearce (1989a). Many of these papers are presented as appendices to this section.

4.2.1.4 Case Studies

Agency Information Consultants (AIC) (1987a) and Clark et al. (1987, see Appendix 4-16) analyzed case histories from the Texas Railroad Commission files on leaking abandoned boreholes caused by Class II injection wells. The twenty-eight case histories identified by the EPA (1975) as significant examples of pollution incidents along with others, were investigated. These cases establish several important factors that may cause improperly plugged abandoned wells to leak. These factors include: 1) depth to the injection zone, 2) casing left in the borehole and open to the injection zone, 3) drilling method, and 4) boreholes in "hard" rock that tend to remain open indefinitely (as opposed to boreholes in "soft" rock where expandable clays or sloughing shales close the borehole). The 28 problem well incidents from the EPA study all occurred within 1.2 miles of an injection well. Clark et al. (1987) summarized that "the most likely pathway for leakage is a production well improperly abandoned with the production casing left open to the injection zone." Note that if a production well had been pumping from a deeper formation, it would have been cased through the injection zone. Therefore, there would be no conduit for fluid to enter. Corrosion of the production casing over the brief time after production ceased and at the depths of injection operations (absence of oxygen) would be a very unlikely occurrence. Class I wells are not allowed to inject into the same formation as, and in close proximity to, production wells. If an abandoned production well were present at a greater distance, the injection zone pressure would likely be drawn down by present-day production operations in the same locale.

Johnston and Greene (1979, see Appendix 4-9) also analyzed a number of case histories near Victoria. They reviewed 39 technical reports and identified 58 abandoned boreholes that could be considered potential problem wells. Plugging or monitoring was recommended for 25 of these boreholes, located at distances of 250 ft to 3.1 miles from an injection well. Calculations of pressure increase indicated that the other 33 wells would not pose a hazard. These wells were situated at distances ranging from 0.5 to 2.75 miles from the injection wells. This study demonstrates that a fixed radial distance should not be the sole criterion used in defining AOR; injection zone pressure buildup and borehole fluid properties are also important factors. Of the wells that had to be plugged or monitored, all were within a 2.5 mile radius except for one. This well was associated with another nearby injection facility, which demonstrates the importance of taking into account nearby operations that can influence pressures within the same injection interval. Johnson and Greene also noted that most reports of leaking abandoned wells or groundwater contamination have been reported for wells located in consolidated rock (where the phenomenon of natural borehole closure does not occur). Johnson and Greene concluded from their study that:

The data developed from the disposal zone models indicates that the current practice of investigating artificial penetrations within a 2.5 mile radius around proposed industrial waste disposal wells should be continued, unless justification based on reliable reservoir data indicates otherwise.

AIC (1987b,c) analyzed case studies based on records of "proper plugging hearings" conducted by the Texas Railroad Commission to investigate pollution problems in connection with the upward migration of fluids from improperly abandoned wells. They examined information from both unconsolidated plastic rock areas and consolidated hard rock areas. They determined that the potential for vertical fluid movement was much greater in hard rock areas than in plastic rock areas. This was attributed to the effects of the phenomenon of natural borehole closure, which occurs in plastic rocks but is not operative in hard rock country. Natural borehole closure allows uncased holes to creep closed rapidly, and enables plastic formations to seal shut around uncemented sections of cased borehole.

The AIC investigations of unconsolidated rock regions included thousands of fields and tens of thousands of abandoned wells. Only 16 of these wells were identified as "leakers" caused by Class II injection. All 16 wells were former production wells with casing still intact and open to the injection zone. The presence of casing prevented the natural borehole closure from occurring. This emphasizes the importance of natural borehole closure as a mechanism for eliminating upward fluid migration in plastic unconsolidated rock regions.

4.2.1.5 Area of Review Determination for Sabine River Works

Factors influencing the AOR include: 1) no vertically transmissive faults or fractures penetrating the injection zone or confining zone (see Sections 2.1 and 3.0), and the abandoned borehole(s) contain drilling fluid of density greater than or equal to 9 lb/gal, a conservative fluid density (Price, 1971; Collins, 1986; Davis, 1986; Johnston and Knape, 1986). In the event that a possible breach of the confining layer was unidentified, then USDWs would still be protected by the presence of a buffer aquifer located at approximately 2400 ft BLS.

The method Du Pont used to determine the AOR was to show that the COI/ZOE is less than the 2.0 mile fixed radius, and, thus, the 2.0-mile radius criterion prevails. The COI/ZOE was determined by: 1) distance from injection well(s) to an abandoned well, which determines the pressure increase at the abandoned well, 2) depth to the injection zone, and 3) density of fluid filling the abandoned borehole. Because draft regulations (August 27, 1987) proposed a 2.5-mile radius, and our original studies for the AOR were based on the 2.5 mile radius, Du Pont has retained the 2.5-mile radius. Data had already been gathered and were not a significant burden to incorporate. The no-migration demonstration satisfied 40 CFR 148.20 for the wells outside the AOR, and the results are presented in Sections 2 and 4.6.2.

A search was conducted for all wells in the AOR to determine whether they have been adequately completed or plugged. This search was completed by AIC, Austin, Texas. See Appendix 4-1 for documentation on the protocol used to locate the wells.

4.2.2 No-Migration Determination

Artificial penetrations within the 10,000 year extent of the waste plume were evaluated for the no-migration criteria. These artificial penetrations include six artificial penetrations within the 2.5-mile AOR and modeling of artificial penetrations outside the 2.5-mile radius but within the 10,000 year extent of the waste plume. Modeling indicated that upward diffusion for all artificial penetrations within the AOR and the additional area of the waste plume outside the AOR and at Orange dome were contained within the injection zone. Therefore, there would be no migration of hazardous waste out of the injection zone.

4.2.3 Uncertainties-Additional Safeguards

The goal of 40 CFR 146.62(d) is to deal with the uncertainties in characterizing geologic conditions in the subsurface or the consequence of failing to identify a breach in the confining zone, be it a man-made conduit (abandoned well) or a natural vertically transmissive fault or fracture. These additional safeguards are outlined in 40 CFR 146.62(d) and specify that owner or operator must demonstrate that the site meets one of the following minimum siting criteria:

1. the confining zone is separated from the base of the lowermost USDW by at least one sequence of permeable and less permeable strata (buffer aquifer) that will provide an added layer of protection for the USDW in the event of fluid movement in an unlocated borehole or transmissive fault, or

2. within the AOR, the piezometric surface of the fluid in the injection zone is less than the piezometric surface of the lowermost USDW, considering density effects, injection pressures and any significant pumping in the overlying USDW, or

3. no USDW is present, or

4. the Director may approve a site that does not meet one of the three requirements above if the owner or operator can demonstrate that because of the geology, nature of the waste, or other considerations, abandoned boreholes or other conduits would not cause endangerment of USDWs.

The Sabine River site meets the 40 CFR 146.62(d) requirement by satisfying the buffer aquifer condition. A number of buffer aquifers occur between the base of the USDW (approximately 1000 ft below land surface [BLS]) and the top of the confining zone (2900 ft BLS). The enhanced degree of protectiveness provided by buffer aquifers was discussed by Miller et al. (1986). Miller et al. (1986) indicated that if a breach of the confining layers existed, then fluid moving upward through the breach would be redirected horizontally into the buffer aquifer rather than continuing to move vertically toward the USDW. Thus, the buffer aquifer provides an additional safeguard to upward fluid movement. The pressure driving the upward movement decreases dramatically when the fluid reaches the buffer aquifer. Little pressure remains to continue the upward movement. The EPA adopted the buffer aquifer as one of the siting safeguard criteria protecting USDWs.

4.3 CHARACTERISTICS OF ABANDONED WELLS-GULF COAST

4.3.1 Natural Borehole Closure

Natural borehole closure can occur in the Gulf Coast where wells are abandoned without casing. Shallow Gulf Coast sediments are typically unconsolidated and possess plastic properties (Johnston and Green, 1979; Davis, 1986) resulting in natural closure (e.g., caving sands or swelling shales) of man-made boreholes.

Davis (1986, see Appendix 4-12) summarized the ability of shales to absorb water, a process that commonly results in borehole blockage. Wetting of shales by water causes instability, resulting primarily from overburden pressure, pore pressure, or tectonic stress. Borehole closure and shale sloughing are attributable to adsorption of water by shale. As shales are buried, more water is squeezed out by overburden, and the force is equal to the matrix stress. As the formation is drilled, compacting force is relieved on the borehole face by the drill bit. Consequently, a hydration force equal to the degree of relief develops. For example, in a normally pressured Gulf Coast shale at 10,000 ft, the shale hydration force in normal pore pressure is 5320 psi, which is much greater than the 250 psi exerted on the face of the wall (based on 9.5 lb/gal mud at 10,000 ft).

Clark et al. (1987, see Appendix 4-16), in a study of case histories from Texas Railroad Commission (TRC) files, found that abandoned boreholes in the Texas Gulf Coastal plain experienced natural borehole closure, which drastically reduced the potential for leakage from these abandoned wells. This data has been supported by the re-entry experiences of Klotzman (1986) and Meers (1987).

4.3.2 Mud Plugs

Introduction

For many years, mud plugs have been advocated for properly abandoning well bores because they provide an effective barrier to vertical fluid flow. Mud plugs have been shown to have low permeability and great resistance to movement. Additionally, mud plugs have been shown to

plug an artificial penetration through time and under the various conditions encountered within a well bore. A mud plug with low permeability, in combination with the hydrostatic head of an overbalanced mud column, is sufficient to counterbalance increased formation pressure due to injection, thereby creating an effective barrier to fluid flow. These characteristics of mud plugs, combined with borehole closure, minimize the chance of encountering a truly open conduit in an artificial penetration drilled into unconsolidated sediments.

Drilling mud is largely composed of clays and water. Commonly, bentonite (sodium montmorillonite) is added to the drilling mud to obtain viscosity in the slurry and to aid formation of wall cake (the low-permeability layer of clay coating and lining the borehole). Bentonite is hydrophyllic (it readily absorbs water), but its flat platy shape is the primary reason it is so desirable for use in drilling fluids.

Clay platelets aggregate (flocculate) in three ways: face-to-face, edge-to-edge, or edge-to-face because the platelets are electrically charged. This is the thixotropic or gelling property of a bentonite slurry that gives drilling mud its gel strength (discussed below). Gel structures build with time as the positive edge of one particle moves toward the negative surface of another, that is, when the platelets are layered (Gray et al., 1979). This orientation reduces the permeability of the mud column because tortuosity is increased.

The gel strength and wall cake of bentonite clay mud systems provide an effective barrier against both vertical migration of fluids within the well bore and fluid migration from the well bore into adjacent formations. In recent years the trend in plugging both deep and shallow wells has been to discontinue the use of a cement bentonite mixture in favor of pure bentonite (Riewe, 1989). The following sections examine various aspects of mud plugs and their ability to effectively prevent migration of fluids.

4.3.2.1 Permeability

The permeability of the drilling mud in abandoned wells is dependent upon the amount and size of the clay and other colloidals in the

slurry and the time that the mud has been left in the hole. Although the permeability of mud in deep boreholes has not been measured directly, the permeability of other similar clay mixtures such as those used in slurry wall construction and the bentonite grout slurry mixtures used to plug shallow borings has been measured. Alther (1982), while investigating the use of bentonite for clay caps and slurry wall containment, found that an admixture of bentonite and high permeability soils reduced the coefficient of permeability to 10^{-9} cm/sec. In his testing, Alther used a falling head permeameter to measure the permeability of a mixture of 8% bentonite and 92% Lake Michigan sand.

Polk and Gray (1984) investigated the adequacy of mud as a sealing agent in abandoned boreholes relating to mineral exploration. Their focus was on the ability of a bentonite mud to form a filter cake with a low enough permeability to ensure that there would not be migration between aquifers penetrated during drilling. Polk and Gray directly measured filter cake permeabilities using the cake formed in a standard API filter press filtration test run for 30 minutes at 100 psi. The cake formed on the filter paper was then tested with water to determine the cake's permeability. The cake had permeabilities ranging from 2×10^{-8} to 8×10^{-9} cm/sec, which was regarded as low enough to prevent water migration from one aquifer to another through the borehole.

Because the EPA defines low permeability for soil as 1×10^{-7} cm/sec, i.e., the minimum required permeability of the 3 ft of compacted clay beneath an MTR landfill or surface impoundment, then it is reasonable to believe than the permeability of a mud plug (~1×10^{-7} cm/sec or less) is more that sufficient to prevent movement of fluids within a well bore.

4.3.2.2 Longevity

Longevity of the mud plug has been demonstrated by actual attempts made to re-enter abandoned wells. Pearce (1989b) discussed a borehole re-entered by K. E. Davis Associates in Nueces County, Texas, during August, 1988. The Nora Schulze No. 2, a cased abandoned borehole (November 25, 1959, see Appendix 4-17) near Corpus Christi, Texas (Gulf Coast conditions) was re-entered. The well was originally

drilled with mud ranging in weight from 10.6 to 11.0 lb/gal for depths below 7300 ft. The mud that was originally used to plug the borehole was still in place when the re-entry was attempted. Mud was recovered during the re-entry to approximately 754 ft. Mud still filled the borehole up to the cement plug at the surface. Samples were taken at regular intervals, and the characteristics of the mud were measured after recovery. Mud weight averaged 11.1 lb/gal (this was for mud recovered in the top 800 ft of the well bore; in fact, the most dense mud was found at the top of the hole). Gel strengths measured on the recovered mud samples ranged from 217 to >320 lbs/100 ft^2. These values are ten times greater than the conservative 20 lbs/100 ft^2 commonly used in modeling. Additionally, shear strength was measured on the samples and was found to generally increase with depth. Values ranged from 170 to 7000 lbs/100 ft^2.

4.3.2.3 Depth to Top of Mud Plug

Many models assume that the top of the mud column is at or very near ground level for boreholes in the Gulf Coast area. This assumption is justified by the field examples cited below:

In the well bore re-entered by K. E. Davis Associates during 1988 (see Appendix 4-17), the top of the mud plug was found just below the 12 ft of cement at the top of the well bore.

Subsurface, Inc. (1976) re-entered and replugged the Brewster Bartle Drilling Company (British American Oil Production Company), University of Texas, No. 1B (Galveston, County, Texas) during 1976 at the request of Amoco and Monsanto. The 11,720-ft dry hole was abandoned with casing left in place to 11,100 ft. Cement plugs were placed from 11,000 to 11,200 ft, 130 to 180 ft, and on the surface. Mud-laden fluid filled the remainder, conforming to Railroad Commission requirements of 1961. During the re-entry, drilling mud was found immediately below the surface cement plug. A bit was run on tubing to 960 ft after the upper cement plug was broken through. The well was circulated out with 12-lb/gal mud.

AIC (1988, see Appendix 4-18), in a study of wells originally plugged 20-30 years ago, found that in the Gulf Coast (Texas) and West Texas, most operators reported finding the top of the mud just below the surface plug. In the Gulf Coast, mud was generally hard, whereas in West Texas, the mud was soft. These comments about the mud condition in the Gulf Coast were reported: mud sets up like cement, mud sets up firm after about five years, mud is hard and firm, the top of mud is located at about 100 to 200 ft, and the top of the mud is usually [just] below the top cement plug. (Even in West Texas, the top of the mud plug was found at approximately 100 ft or less below the surface!) Pearce (1989a) indicated that the maximum depth to the top of a mud plug would be the depth to the water table. As a reasonable worst-case condition, the top of the mud plug would be the depth to the water table.

Even if cement plugs are present in the borehole, it is still more conservative to model a full column of mud because the resistance of the cement plug is greater than the pressure exerted by the mud column. In addition, the system is closed because it is not possible to force significant quantities of mud into the permeable formation due to the presence of nearly impermeable wall cake formed on the formation wall. This mud wall cake prevents loss of fluid to the formation or any loss of fluid from the formation when the well is first drilled.

4.3.2.4 Dessication and Dehydration

A mud plug open to air cannot dessicate more than 10 ft into the ground, and the simple model described below illustrates why.

Under worst-case possible conditions, the mud plug of a well bore can be thought of as a water-saturated porous matrix. Water initially fills the matrix and evaporation occurs at the top surface (as if the mud plug were open to the air at the top). Evaporation would cause the top of the plug to dry out, and the drying out would continue downward (assuming no moisture was coming up from below, i.e., worst-case conditions). If the air at the surface has 0% humidity and the air at the dessication boundary is 100% humid, and assuming 100°F at the air-water interface, then the effective diffusion coefficient of water vapor through the air-filled pores can be assumed in the

worst case to be the same as that in free air (even neglecting the tortuosity of pore channels). After 100 years of evaporation, less than 10 ft of mud plug would dry out compared to thousands of ft for the total length of mud plug. Other conservative factors of the model include: 1) the hole is cased, so that formation water does not enter to keep the mud plug moist, 2) rainfall and ground water do not enter the hole, 3) water vapor near the surface has an average relative humidity of about 70% rather than 0%, and 4) surface tension reduces vapor pressure of water within the porous matrix. Thus, if exposed to "air", the top of a mud plug can begin to dry, but the drying, or dessication, will only extend to a depth of 10 ft (Miller, 1988a).

Mention has been made that drilling fluid might dehydrate upon being left in a borehole. This is an unlikely situation, especially below the water table (which is very near the surface in the Gulf Coast) in a saturated environment.

Davis (1986) referenced Garrison (1939), who noted that electrostatic force attracts planer water to the colloidal particles, forcing the clays to swell when wet and shrink when dry. The attraction of planer water to the faces of the plates is greater than the attraction of the sheets for each other; therefore, the structure tends to swell due to the absorbsion of the planer water from the drilling fluid. The clays would continue to attract water <u>from</u> the formation in a saturated environment such as the Gulf Coast.

4.3.2.5 Settling of Solids in Drilling Mud

Barite is commonly added to drilling mud to increase its bulk density. Particles below a critical size (diameter) can never settle out because of the gel strength of the drilling mud. This is comparable to fruit chunks suspended in jello. The higher the gel strength, the larger the particles that will remain in suspension. The problem can be solved as a solid mechanics problem where a sphere is suspended in an elastic solid. When the maximum shear stress on the surface of the sphere exceeds the gel strength of the mud, the particle will settle. For barite particles (density 4.2 gm/cc) the critical diameter (cm) for settling is equal to the gel strength of the drilling mud (20 lb/100 ft^2) divided by 100. For a worst-case gel strength of 20 lb/100 ft^2, all barite particles smaller than 0.2 cm will remain in

suspensionforever(Miller,1988b).NLBaroid(1988)showsabariteparticlesizedistributionwhereallpar 0.0188 cm). Thus, all barite particles remain in suspension at a minimal gel strength. Greater gel strength would support larger barite particles.

Gravitational settling has been overestimated; and, even though settling of larger particles may occur, it would not greatly diminish overall mud density (Pearce, 1989a).

4.3.2.6 Gel Strength

Mud gel strength increases the pressure necessary to initiate fluid migration. Although work remains to be done on mud gel strength, what is known has been covered in the literature (e.g., Barker, 1981; Collins, 1986 and 1989; Johnston and Knape, 1986). A summary of mud gel properties is given below. Currently no credit is given for mud gel strength by regulatory agencies.

Gel strength is the property of mud that suspends particles in a static mud column when circulation stops (e.g., drilling mud left in an abandoned borehole). Gel strength forms as a function of: 1) the amount and type of clays in suspension, 2) time, 3) temperature, 4) pressure, 5) pH, and 6) chemical agents in the mud.

There are two types of gels: progressive and fragile. Progressive gel has a fairly low initial gel strength that consistently increases with time. Progressive gels occur in mud that has high concentrations of solids. This type of mud is common in wells drilled early in the history of the petroleum industry before the introduction of sophisticated solid control equipment and inhibited mud systems. On the other hand, fragile gels might have a high initial gel that increases only slightly with time. This type of gel is found in treated muds, that is, muds that have an organic surfactant (lignites or lignosulfonates) added to peptize or deflocculate the clays. This type of inhibited mud is a fairly recent introduction to the drilling industry; the first thinning agent was introduced in about 1930 (Gray et al., 1980).

The pressure required to displace the gel can be large, and thus gel strength can be the main factor in preventing fluid migration within an abandoned well bore (Collins, 1986 and 1989; Johnston and Knape, 1986; Pearce, 1989b).

After studying the wide variety of factors contributing to mud gel strength, Barker (1981) determined that 20 lb/100 sq ft was a valid conservative (minimum) estimate of mud gel strength. Gray and Darley (in Collins, 1986) determined that approximately 20 lb/100 sq ft was the lowest possible gel strength that could occur.

Gel strength continues to increase with time, as supported by measured values and field data (Gray et al., 1980; Garrison, 1939, Pearce, 1989b) (see Figure 4-1).

Re-entries such the Nora Schulze No. 2 (described above) demonstrate that mud gel strength increases under static conditions through time and that this property of a drilling mud, along with the very small size of the collodial particles, allows the mud to maintain its density through time. For times approaching 10,000 years in an undisturbed borehole, there is no reason to believe that the mud plug would prove less than satisfactory.

4.3.2.7 Molecular Diffusion

If a contaminant plume in the injection formation encounters pre-existing abandoned boreholes, then any of these that are open to the injection formation could provide upward paths for molecular diffusion. The method used to determine the diffusion distance in borehole muds is the same as that described previously for diffusion in an aquitard layer (see Sections 2.1.2.2.1.2, 2.1.3.3.3.7, and Appendix 4 of Section 2.1). Namely, the diffusion coefficients of particular constituents in free water solution are multiplied by the Geometric Correction Factor appropriate to the mud in the borehole. This yields the effective diffusion coefficients for the constituents in the borehole mud from which diffusion distances over various time spans can be predicted.

It is standard practice to employ "muds" or drilling fluids in drilling oil and gas wells. Among the purposes of drilling mud are to remove cuttings from the borehole, to stabilize the borehole against collapse and against entry of formation fluids, and to suspend cuttings in the borehole when the drilling fluid is not being circulated. Properties of muds that serve these purposes are density (or weight), viscosity, and gel strength.

The physical characteristics that make drilling muds useful during drilling also make them moderately effective barriers against molecular diffusion (though not as effective as geologically deposited clays). This is particularly true of a commonly used base for mud, bentonite, which is predominantly sodium montmorillonite clay. The platy, electrically-charged clay particles comprising bentonite attract water, a polar molecule. This causes the clay to swell, thereby increasing the borehole fluid viscosity. Of the clays, montmorillonite has the greatest hydration potential and effects the greatest viscosity enhancement for a given amount of solids. This accounts for its long-standing popularity as an additive.

A second important property of clay-based drilling muds is the tendency of the plate-like clay particles to align so that positively charged edges are adjacent to negatively charged flat surfaces. If the mud is agitated, then the gel breaks down. If, on the other hand, the mud sits at rest, gel strength increases with time as the additional clay particles come into alignment. If the drilling fluid is at rest for some time, high pump pressures are sometimes necessary to restore circulation in the borehole that the fluid can be forced into weak or fractured formations (Driscoll, 1986).

Thus, in the case of a borehole abandoned for some time, the mud originally used during drilling has set to form a gel with a substantial gel strength. The gel is "a disheveled yet interconnected network of parallel clay particles separated by an average distance" (Jahnke, 1987). All boreholes intercepted by the 10,000 year plume will be investigated and plugged by the appropriate weight mud, at least 9 lb/gal.

Since gel strength results from a preferential alignment of clay particles, the borehole fluid possesses a low Geometric Correction Factor G for molecular diffusion. This is because G is equal to the reciprocal of the tortuosity factor, which is a measure of the extra path length that diffusing molecules must follow in the pores of the mud (see Section 2.1, Appendix IV), and the tortuosity in materials with platy structures is generally high.

Numerical values of quantities related to the Geometric Correction Factor have been measured for specific samples of clays by several researchers, and these results are adopted as indicative. Nye (1979) referred to the measurements of Cremers (1968) on four clays (a Wyoming bentonite, a montmorillonite, and two kaolinites). This work shows that the electrical formation factor, which is related to the Geometric Correction Factor G, is strongly dependent upon porosity; for Wyoming bentonite, G varies as porosity raised to the 12.6 power. This means that a 9 lb mud, which has a porosity of 0.95, has a Geometric Correction Factor of $(0.95)^{12.6} = 0.52$.

In another study, Jahnke (1987) diffused tritium in montmorillonite clay gels. Neutral tritium was used since it is not subject to sorption and thus gives a true measure of the geometrical effect of tortuosity (Jahnke and Radke, 1987). By fitting the effective diffusion coefficient to the experimental data, he determined tortuosity factors from 2.7 to 3.2. The former value was associated with a mud of 13.6 weight percent of solids, which corresponds to 9-lb mud (Driscoll, 1986). Since G is the reciprocal of the tortuosity factor, this mud had a G of 0.37. For free aqueous solution (brine), the geometric correction factor G was set to unity.

4.4 DETERMINATION OF THE AREA OF REVIEW

As shown below, the calculated cone of influence was determined to be less than the fixed 2.5-mile radius around the injection wells. Thus, the 2.5-mile radius around the well bore(s) criterion prevails for the AOR. Factors influencing the AOR include:

1. the absence of transmissive faults or fractures penetrating the Sabine River Works injection zone or confining zone, and

2. a theoretical unidentified borehole would contain 9 lb/gal or greater drilling fluid, a conservative mud density (Price, 1971; Collins, 1986; Davis, 1986; Johnston and Knape, 1986).

All records for all abandoned wells were evaluated in the 2.5 mile AOR.

The COI at the Sabine River site was calculated for eight sands. See Figures 4-4, 4-7, 4-10, 4-13, 4-16, 4-19, 4-22, and 4-25. The M sand has the highest pressure buildup and the J sand is the shallowest. Therefore, because the shortest mud column to creates the least pressure resistance, modeling of these two sands present the most conservative case. Both these sands were modeled (Tables 4-2 and 4-3) and even though the 5400' M sand yields more pressure resistance, due to depth of mud column, this zone exhibits the most potential for upper fluid movement due to higher injection pressures. Plots of pressure in the injection interval versus distance in the year 2000 (at average and maximum injection rates) are presented in Figures 4-2, 4-3, 4-5, 4-6, 4-8, 4-9, 4-11, 4-12, 4-14, 4-15, 4-17, 4-18, 4-20, 4-21, 4-23, and 4-24. The COIs were calculated as follows:

	9.0 lb mud gradient (psi/ft)	-form.pres gradient (psi/ft)	=gradient (psi/ft)	minimum depth[1] (ft)	=pressure buildup calculated[2] (psi)		COI radius[3] (ft)
4600' J sand	0.468	0.452	0.016	4382	70	<500	158
5400' M sand	0.468	0.452	0.016	5112	82	4100	1050

See 4-20-90 Performance # 8

[1] Minimum depth to sand within the AOR.
[2] Conservative pressure required to initiate movement of 9 lb/mud at minimum depth.
[3] Distance needed for pressure to fall below that required to initiate movement of 9 lb/mud in an abandoned borehole.

As shown above, the COI (the area within which increased injection zone pressures would be sufficient to drive fluids into USDW) lies well within the 2.5-mile radius of the injection wells; and, therefore, the 2.5-mile radius criterion for the AOR previals.

Within this 2.5 mile radius, 69 aritificial penetrations were identified. Forty-eight of these artificial penetrations (Table 4-1) were plugged properly to satisfy the criteria for non-endangerment to USDWs. Complete review of the AOR determines that there are no known artificial penetrations within the COI. Five wells within the AOR are active oil and gas wells and another five wells do not penetrate the uppermost injection interval. The remaining eleven wells were modeled for non-endangerment evaluation and determined not to be a threat to USDWs (Tables 4-2 and 4-3).

It is important to note that this calculation of AOR is conservative, and contains a significant margin of safety. This additional safety factor is the gel strength of the drilling mud, which has been intentionally omitted in the present assessment. Gel strength contributes greatly to the ability of the mud to resist flow, and helps prevent fluid displacement in the borehole.

4.5 ARTIFICIAL PENETRATIONS IN THE AREA OF REVIEW

4.5.1 Records Search

A thorough and diligent search was conducted to locate records on artificial penetrations in the AOR for the Sabine River Works. AIC researched the Texas Railroad Commission (TRC) in Austin as well as other data sources for county/field maps and state forms to determine the locations of all artificial penetrations present within the 2.5-mile radius AOR. Du Pont obtained electric well logs and scout tickets by searching the Texas Bureau of Economic Geology Sample Library and commercial log library companies such as Cambe Geological Services, Inc. and Petroleum Information. Du Pont internal documents, such as old abandoned well studies, replug documents, maps, reservoir pressure studies, and well schematics were obtained through the Du Pont Information Center at the Gulf Coast Regional Consulting (IC-GCRC) office in Beaumont, Texas (Price, 1975; Klotzman, 1972; URM, 1983).

Well Type

As a result of the record search, 69 wells were identified in the 2.5-mile radius AOR at the Sabine River site. Five active oil/gas production wells are located in the AOR. These five wells are presently producing out of sands which are structurally and stratigraphically deeper than the lowermost injection sand, the 6400', T sand. Although there are 78 artificial penetration numbers, only 69 are actual artificial penetrations. Artificial Penetrations 6 and 8 are actually one surface location, which was drilled and later side-tracked. See tables 4-1 and 4-2 for a tabulation of all artificial penetrations addressed in this demonstration. Also note that the artificial penetration numbers are not all consecutive. The numbers 5, 12, 13, 14, 15, 18 and 26 were deleted during the artificial penetration search and evaluation process.

4.5.1.1 File Search and Retrieval Procedures for the Texas Railroad Commission

The well record filing system of the TRC is cumbersome due to changes in filing procedures implemented through the years. In order to retrieve oil and gas well records, the following general outlined procedure was used for researching each well within a given area.

Maps

Before the retrieval process began, it was necessary to know the operator, lease, county, and survey for each well. This information is normally found on commercially prepared oil and gas base maps. The TRC maintains two types of maps, which the researcher used to determine operator, well name, approximate drilling date, and field name. The two types of maps on file at the TRC are county maps and field maps.

County Maps

These maps are produced by commercial firms, who obtained the data to build the oil and gas bases from "scout" tickets, completion data obtained from individual oil companies in the early years, and then, in later years, from the TRC itself. The TRC purchases these maps and utilizes them as base maps, plotting incoming information filed by oil and gas operators. Changes in the status of existing wells are noted, as well as factual material on new wells. When the TRC purchases the commercial base, the information found on the maps is accepted as correct, and no attempt is made to verify the data unless a discrepancy is noted when a well's status is updated. Errors can also occur during the updating process by TRC personnel.

Field Maps

These maps are prepared by TRC personnel from the commercial base maps. "Field Maps" are prepared when there is an extremely high well concentration in an area such as Orange-Hackberry, and it is necessary to expand the scale of the area so that wells can be properly identified. All data, including survey name, fee name, acreage and configuration of tracts of land, operator name, and location are taken from the county map and transposed onto the "field map". Once the

"field map" is prepared, any wells drilled, deepened, plugged back, or plugged in the area encompassed are spotted on this map, but not on the county map. It is therefore quite common for information on county maps and "field maps" to disagree. These discrepancies range from differences in operator name or well location to completion dates of wells.

AIC utilizes both types of maps on file with the TRC as well as other available commercial oil and gas base maps. The information found on these various base maps is used in the next step of the research process.

Microfilm Records

All records filed with the TRC prior to 1973 are found on microfiche and microfilm. Records in some TRC districts are filmed through 1980. These microfiche and microfilm records are organized in several different systems, such as operator and lease name, or district, field, and operator name, or district, field, and lease number. Within the aforementioned filing systems, there are a large number of exceptions to the filing procedures that create additional filing systems within these categories. Besides the filing exceptions, there is also the additional problem of misfiled records. These misfiled records range from having the records of one operator filed under another operator's number, to having records filed in one time period being filed in another time period set. Hence, the filing system is filled with pitfalls, which in combination with the multiple changes in filing procedures, cause excessive time to be spent trying to track down specific records.

The various types of standard film sets are: 1) unit cards, 2) well records-folders rolls, 3) well records-runs 20-30 and A to I, 4) well records-major runs, 5) well records-old warehouse film, 6) well records-K, L, and M film, 7) potential film, and 8) wildcat and suspense film. In addition to film sets, there are well record files and suspense files.

Unit Cards

These are microfiche records for wells which had records filed with the TRC prior to 1962. These "units" are filed sequentially by an operator number assigned by the TRC when the operator filed the required organization report with the agency. The operator number can be referenced in either the "county book" or the "county microfiche". There is a "county book" maintained for each county within the state. Within the "county book", the information is organized alphabetically by lease name, which cross references to the operator name and corresponding operator number. The "county microfiche" are a recent addition to the TRC filing system. The agency took the "county books" and reorganized the leases into alphabetic order and microfilmed the information. Although the "county books" are not organized as neatly as the "county microfiche", they are the original system and are more accurate due to unintentional omissions made during reorganization of the listings.

Operator numbers can also be obtained from old copies of organization ledgers maintained by the TRC. These ledgers are in five separate sets, which correspond to various time periods from the 1920s to the 1960s. These ledgers list only operator names, addresses, and numbers assigned by the agency, and are used as a last resort, since they do not indicate lease names and often list multiple operators with the same name.

Once the operator name is matched to a lease name and an operator number is given, the unit card, if available, is pulled. The lease names are filed alphabetically within each operator number. Because there are exceptions to the filing system, if the desired information is not available or only partially available on the unit card, then the researcher must proceed to the next set of microfilm.

Well Records-Folders Rolls

Duplicate copies of unit cards, which sometimes contain information that was not included in the initial filming of the unit cards, is referenced on the folder rolls. The folder rolls are organized by the operator number and folder number that appear on the unit card jacket. Some folder rolls have only an operator number. These rolls are called "add-on rolls" and also contain records not included in the initial filming of the unit cards.

Well Records-Runs 20 to 30 and A to I

These rolls are organized by operator number and by specific periods of years. They cover the period from 1945 to 1960, and there are commonly three to five rolls for a specific year and operator number. When information is not available on the unit cards, then these are the next sets of film records to be researched.

Well Records-Major Runs

This is a special set of film that contains information only on records filed by major operators. These rolls are organized by operator and then alphabetically by lease name. It should be noted that there are very few unit cards for major companies; and that, if any information has been filed on a lease or well, it will be found on this set of film. It should also be noted that major operators, even in the early years of the oil business, were very prudent about filing completions and plugs for the wells they operated.

Well Records-Old Warehouse Film

This set of film contains some of the earliest information filed with the TRC and includes oil and gas well records filed from 1919 to 1939. There are only five rolls of this film, with three rolls organized numerically by operator number and two rolls organized alphabetically by operator name.

Well Records - K, L, and M Film

In March, 1966, the TRC instituted a new filing system. However, before the system could be fully implemented, many well records that had been filed during the period of transition were placed onto the K, L, and M film. The K Run covers portions of records filed from 1963 to 1964, the L Run covers portions of records filed from 1964 to 1965, and the M Run covers portions of records filed from 1965 to March 1966. The K, L, and M film is organized by operator number, with leases listed alphabetically within operator number.

Potential Film

During March, 1966, the TRC filing system was converted to the "potential" filing system which is currently used today. This film contains records of all wells that produced oil and/or gas and were placed in a designated oil or gas field. This film is organized by TRC District, field name, and oil lease number or gas well identification number.

Wildcat and Suspense Film

This film contains records of all wells that were applied for in wildcat fields or new leases in designated fields that did not have a lease identification number previously assigned, because there were no producing wells on the lease in the field. This film is organized by district, county, and/or American Petroleum Institute (API) number. The API number system has been in effect since April, 1966. The numbers have been stored within the TRC computer system, as well as being noted on all forms filed for the well. The system allows retrieval of information showing drilling status, operator, lease name, oil lease number or gas identification number, and field name. This is a very efficient system and allows quick and accurate retrieval of data filed since 1978.

Well Record Files

These are the hard copy files of data not yet placed on microfilm. These files are organized by district, field name, and oil lease number or gas identification number. These files contain the most recent data processed by the Central Records staff of the TRC. Inside these folders are references to data that potentially can be placed onto film.

Suspense Files

These files contain the most recent information filed with the Central Records Department. This is the holding area for information placed into existing well record files or that requires new oil lease or gas identification files. The information is filed by district and API number. To obtain API numbers, it is necessary to search "suspense cards" that are filed by district, county, and alphabetically by lease name. Records that have not been placed in suspense files are usually found within the Map Department, where they are held until data is placed onto the county oil and gas base maps or on field maps.

Summary

In retrieving information from the TRC, AIC commonly has to examine every file system available to locate a particular piece of information. Unfortunately, after all avenues have been searched, the desired records may not be available in the filing system. This is normally due to operator omission or records lost and/or misfiled by the TRC. In cases such as this, other sources (beyond public records) outside of the TRC, such as log libraries or direct contact the individual operators, must be utilized.

4.5.2 Confining Zone and Injection Zone Penetration

Within the 2.5-mile AOR, all artificial penetrations investigated were drilled to sufficient depth to penetrate the permitted confining zone and/or injection zone at the Sabine River Works site. Therefore, all artificial penetrations were evaluated as to the adequacy of

construction and/or plugging in accordance with the criteria outlined in Section 4, Appendix 4-1, Artificial Penetration Protocol. Proper plugging for non-endangerment to USDWs consists primarily of a cement plug between the top of the injection zone and the base of the USDW.

4.5.3 Satisfactorily Plugged by Cement for Non-endangerment to USDWs

Forty-eight of the 69 total artificial penetrations in the AOR are satisfactorily abandoned with a cement plug between the top of the injection zone and the base of the USDW (see Table 4-1, Figures 4-28 through 4-96, and Appendices 4-3, 4-5 and 4-6). Five wells are currenty producing and during abandonment will have a cement plug pumped into the wellbore as per TRC plugging requirements. In the vacinity of the Sabine River Works most surface casing is set to 1500-1600 ft insuring that when the wells are plugged, the cement placed at the base of this surface casing will be between the base of the USDW (1000 ft) and the top of the injection zone. The top of the injection zone is ~3600 ft and the top of the injection intervals is 4300 ft. Eleven artificial penetrations with records are plugged with heavy mud or weighted brine, and modeling results showed that there is sufficient density to prevent fluid movement in any abandoned well (see Section 4.6, and Tables 4-2 and 4-3). Five remaining wells do not penetrate the injection intervals (see Table 4-1). These wells have not been modeled since they do not penetrate the injection intervals.

4.5.4 Satisfactorily Plugged by Cement for No-migration Criteria

Six artificial penetrations within the non-endangerment AOR were found to fall within the extent of the 10,000 year plume. These wells, APs 63, 64, 65, 66, 68 and 69 were individually investigated. Records indicate (Appendices 4-3, 4-4, 4-5, 4-6), that APs 63, 65, 66, and 69 do not intersect the uppermost, J, sand. Therefore these could not be a conduit for upward movement. The remaining wells, 64 and 68, were determined to contain drilling mud with no cement plug across the top of the injection zone. These two wells were modeled for molecular diffusion (Section 4.6.2). Modeling showed that if injected material

were allowed to enter these artificial penetrations at the present day, the maximum extent of the material above health based limits would be 310 feet. Diffusing up from the uppermost (worst case) injection sand, the J sand, the waste front will still be 500+ ft beneath the top of the injection zone.

All wells outside the non-endangerment AOR within the extent of the 10,000 year plume were conservatively assumed to have no cement plug across the top of the injection zone. Molecular diffusion studies show that these wells would not allow migration diffusion out of the injection zone (see Section 4.6.2). No corrective is proposed on any artificial penetration within the extent of the 10,000 year waste plumes.

4.6 NON-ENDANGERMENT AND NO-MIGRATION DEMONSTRATION

Based on flow and containment modeling, there is no endangerment to USDWs and no migration from the injection zone at Sabine River Works within a 2.5-mile radius due to pressure increase over background caused by injection. Additionally, 10,000-year plume drift and molecular diffusion modeling shows that there will be no migration of any injected materials out of the injection zone through the shale aquitards or up a mud-filled borehole for a minimum of 10,000 years.

4.6.1 Cone of Influence Summary

The COI as previously calculated is a 1050 ft radius around the injection wells. This was based on a conservative 9-lb/gal mud allowance in an abandoned borehole and maximum permitted injection rates. Within the COI, artificial penetrations open to the injection interval with less than a 9-lb/gal mud could possibly allow fluid movement within the borehole.

Outside the COI and within 2.5 miles, pressures are not sufficient to initiate fluid movement of a mud column. Thus, because all artificial penetrations outside the COI and within 2.5 miles were abandoned with weighted brine, mud and/or cement, then increased pressure due to injection operations is not sufficient to initiate fluid movement in a borehole.

Review of the records indicates that all boreholes of abandoned wells were filled with weighted brine, heavy mud and/or cement plugs. All artificial penetrations were drilled using rotary rig methods. Driller's logs did not indicate lost circulation zones; thus, mud and cement losses into the formations were minimal. Standard drilling and completion practices necessitated the use of mud and/or cement in the annulus of producing oil/gas wells. Thus, increased pressures due to injection operations are insufficient to initiate fluid movement in the active wells. Therefore, all artificial penetrations within the 2.5 mile AOR are sufficiently plugged or constructed to prevent movement of fluids in the well bore.

4.6.2 No-Migration Demonstration Molecular Diffusion

Based upon the discussion in Section 2.1.3.5 a value of 0.576 is adopted for the Geometric Correction Factor for diffusion in mud-filled boreholes. Accordingly, the respective effective diffusion coefficients for constituents at the Sabine River Works are:

	Concentration Reduction Factor	Diffusion Coefficient, Aqueous Solution
Waste Wells 5 and 6 (ADN alkaline waste)		
benzene	8.3×10^{-5}	1.8×10^{-5} cm^2/s
phenol	1.2×10^{-2}	1.8×10^{-5}
Waste Well 10 and 11 (adipic acid waste)		
benzene	1.3×10^{-2}	1.8×10^{-5}
HCN	3.3×10^{-2}	3.7×10^{-5}
Waste Wells 3 and 9 (ADN acidic waste)		
benzene	5.3×10^{-5}	1.8×10^{-5}
nickel	6.9×10^{-4}	1.2×10^{-5}

II. Predicted diffusion distances after 10,000 years:

	SHALE	BOREHOLE
Waste Well 5 and 6		
benzene	100 feet	310
phenol	67	200
Waste Well 10 and 11		
benzene	66	200
HCN	81	240
Waste Wells 3 and 9		
benzene	110	310
nickel	74	220

These distances are the vertical thicknesses of shale or mud required to reduce the concentrations of the constituents to less than published health-based standard levels. (The Concentration Reduction Factors were given previously in Section 2.1.3.3.7.) These distances are over-estimates because the constituents cannot begin diffusing into the borehole until the time the plume actually reaches the borehole.

Since the distance from the top of the petition injection sand at Sabine River Works is approximately 4500 ft, molecular diffusion will be contained within the injection zone for a period of 10,000 yrs. Due to the low density waste plume overwhelming the regional ground-water flow gradient, movement of the plume will be toward the Orange Dome, west of the plant site. The time frame for the plume to reach the dome would be 3000 yrs. According to Figure 4-26, molecular diffusion in a mud-filled borehole with a residency time of 7000 yrs at the dome will have an upward molecular diffusion distance of 260 ft. Molecular diffusion in a brine filled borehole with a residency time of 7000 yrs at the dome (see Figure 4-27) will have an upward diffusion distance of 375 ft. These distances are contained within the injection zone.

4.7 CORRECTIVE ACTION

Evaluations of artificial penetrations for non-endangerment to USDWs indicate no corrective action is necessary because of pressure buildup in the injection zone.

For the no-migration criteria, artificial penetrations were modeled to satisfactorily demonstrate no migration of hazardous constituents out of the injection zone. This modeling indicates no corrective action is necessary.

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