2-17-83 (1)
SANDIA REPORT

SAND82-1616 • Unlimited Release

Printed November 1982

I-8177

27
3-7-83
**Effects of Oxygen, Salt, and pH
Level on Corrosion Rate of Drill-
Stem Steel**

SAND--82-1616

DE83 007580

Lawrence J. Weirick

MASTER

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550
for the United States Department of Energy
under Contract DE-AC04-76DP00789

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Issued by Sandia National Laboratories, operated for the United States Department of Energy by Sandia Corporation.

NOTICE: This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government, any agency thereof or any of their contractors or subcontractors. The views and opinions expressed herein do not necessarily state or reflect those of the United States Government, any agency thereof or any of their contractors or subcontractors.

Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

NTIS price codes
Printed copy: A03
Microfiche copy: A01

EFFECTS OF OXYGEN, SALT and pH LEVEL ON CORROSION
RATE OF DRILL-STEM STEEL

L. J. Weirick
Sandia National Laboratories
Albuquerque, New Mexico 87185

ABSTRACT

A major contributor to the high cost of drilling and completing geothermal wells is extensive corrosion of drill pipe. A technique proposed to control corrosion of the drill pipe is removal of oxygen from the drilling fluid. One approach to oxygen reduction is to substitute an anaerobic gas for air in the drilling fluid. A critical question to be answered when designing the anaerobic gas generator is what level of oxygen concentration is acceptable within the inert gas such that a low corrosion rate will be maintained. A laboratory program was done to answer this question. The program was designed to determine the effect of oxygen content, salt concentration and pH level on the corrosion rate of plain carbon steel.

The corrosion rate of steel was found to decrease with increasing salt concentration at fixed pH levels and with oxygen contents in solution at equilibrium with air at 90°C. The corrosion rate was found to decrease with increasing pH at fixed concentrations of salt and oxygen at 90°C. The corrosion rate was also found to be proportional to the dissolved oxygen concentration at fixed pH levels and salt concentration. It is recommended that the anaerobic gas generator be designed to lower the oxygen concentration one order of magnitude below that in solution in equilibrium with air, that is, to approximately 500 ppb at 90°C.

NOTICE

PORTIONS OF THIS REPORT ARE ILLEGIBLE. It has been reproduced from the best available copy to permit the broadest possible availability. DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED *leg 3*

INTRODUCTION

The present report documents work done in support of a Sandia managed Geothermal Drilling and Completion Technology Development Program. The near-term goal of the program was to develop the technology required to reduce the cost of drilling and completing geothermal wells by 25% by 1983. A major contributor to the high cost of drilling and completing geothermal wells is extensive corrosion of drill pipe. Since a low density drilling fluid must be used when drilling in the typically under-pressured geothermal reservoirs, air drilling techniques are commonly used. In addition, water is usually injected into the air stream to aid cuttings removal. The combination of aerated water, high temperatures, and high velocities results in rapid drill pipe corrosion leading to pipe downgrading or premature failure.

The potential-pH equilibrium diagram (Pourbaix diagram) for the element iron at 25°C is shown in Figure 1 (Ref. 1). This diagram is an electrochemical phase diagram for iron showing the regions of phase stability for iron, iron compounds and iron ions in solution as a function of electrode potential (E) and hydrogen ion concentration (pH). The Pourbaix diagram for water at 25°C is shown in Figure 2 (Ref. 1), and indicates the regions of stability for water, oxygen and hydrogen as a function of potential (E) and pH. Combining the phase diagrams for iron

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

and water onto one diagram gives the potential-pH equilibrium diagram for the system iron-water shown in Figure 3 (Ref. 1). From Figure 3 iron appears to be a base metal, as its domain of thermodynamic stability, at 25°C and atmospheric pressure, has no portion in common with that of water. Thus iron in the presence of water may corrode with the evolution of hydrogen. This reaction will be very vigorous in acid solutions, will become progressively less vigorous as the pH of the solution increases, and will almost cease at pH's around 10-13 when the iron will become covered with a film of hydroxide. At very high pH's, above about 13, iron will again corrode in solutions free from oxidizing agents.

The open circuit potential of iron immersed in a solution is increased by the presence of oxidizing agents. The addition of oxidizing agents will therefore have the effect either of passivating the metal or of increasing its corrosion rate, depending on whether or not the increase in potential is sufficient to bring the metal into the passivation domain. Iron will be passivated by oxidizing agents more easily if the range of electrode potentials at which corrosion is possible is small. These arguments are summarized graphically in Figure 4 (Ref. 1). From Figure 4, passivation will be relatively difficult, or even impossible, at pH's below about 8; it will be relatively easy at pH's above about 8, and very easy at pH's between about 10 and

12. This knowledge has been applied in the presently used approach in geothermal wells to reduce corrosion of the drill pipe. Caustic soda (NaOH) is added to the drilling fluid to raise the pH of the water to about 11. This technique is successful in reducing the corrosion to an acceptable rate economically. However, this approach is still very costly, and alternate means are being examined and tried.

Another technique proposed to control corrosion is removal of oxygen from the drilling fluid. Oxygen scavengers such as ammonium bisulfite have been used for mud drilling but are not practical when large quantities of air are needed. Another approach to oxygen reduction is to substitute an anaerobic gas for air in the drilling fluid. Such a test was conceived by Caskey and Copass (Ref. 2) at Sandia. With the cooperation of Union Geothermal Co. of New Mexico, a subsidiary of Union Oil Company of California, a field test was done on Baca Well 22* in Nov. 1980. The results of this field test are given in Ref. 3 by Caskey and Copass. To summarize here: Two drilling fluids were alternately used to compare drill pipe corrosion rates. The first fluid was an air-water mist with corrosion control chemicals (primarily NaOH additive to raise the pH to 11).

*Baca Well 22 in the Redondo Creek Field at the Baca location in Sandoval County of northern New Mexico.

The other fluid was a nitrogen-water mist without added chemicals. Data from corrosion rings, corrosion probes, fluid samples and flow line instrumentation show that the inert drilling fluid (nitrogen) reduced corrosion rates by more than an order of magnitude relative to that measured in an air-water mixture. This reduction of corrosion rate is greater than that obtained by adding chemicals to the air-water mixture, which reduced the corrosion rate by many orders of magnitude below the baseline corrosion rate of air-water without additions. Because of the success of this test, Sandia is pursuing the development of an on-site anaerobic gas generator.

A critical question to be answered when designing the anaerobic gas generator is what level of oxygen concentration is acceptable within the inert gas such that a low corrosion rate can be maintained. An investigation of this question using field tests is prohibitively expensive. A laboratory program was thus begun to study this question. The program was designed to determine the effects of oxygen content, salt concentration and pH level on the corrosion rate of plain carbon steel.

EXPERIMENTAL PROCEDURES

Coupons were made from drill stem carbon steel Schedule E# to the dimensions of 50 mm x 18 mm x 1.5 mm (2 inches x 0.688

0.31C, 1.49 Mn, 0.12 Mo, 0.14 Si, 0.004 P, 0.016 S-balance Fe

inch x 0.06 inch). The coupons were machined and ground to a 32 microinch finish. A 3 mm (1/8 inch) diameter hole was drilled near one end for support purposes.

Solutions were made using deionized water, NaCl, NaOH and HCl. The amount of each ingredient in a particular solution was determined by the salt concentration and pH level desired. The procedure used was to first set the salt concentration and then adjust the pH to the desired level.

The oxygen content within the solution was obtained by controlling the oxygen content within the cover gas above the solution. Three oxygen levels within the solution were initially chosen for screening tests. These oxygen levels were 1) deaerated solutions (using nitrogen as the cover gas), 2) 50 ppb O₂ in solution, and 3) air saturated solutions (~5000 ppb O₂). T. Hinkebein, 4755, calculated the oxygen content required in the cover gas at the respective salt concentrations at 90°C to obtain 50 ppb O₂ in solution. These data are given in Table I. Upon completion of the screening tests, it was decided that additional tests were needed at higher oxygen contents. The oxygen content in solution as a function of concentration in the cover gas at 90°C is given in Table I. The cover gas was introduced into the solution by means of a glass frit at the end of a tube submerged in the solution which also served to stir the solution to maintain equilibrium between cover gas and solution.

At the completion of the above detailed series of tests, two additional tests were run in water obtained from the Baca

geothermal area. The first had an oxygen content set at 500 ppb, the second was run in a solution equilibrated with air.

A schematic of the corrosion apparatus is shown in Figure 5. The heating mantle and controller maintained the solution temperature at 90°C. The condenser above the flask kept the water loss to a minimum, thus maintaining the salt concentration and pH level close to the desired values. Inserted into the side of the flask was a glass tube which contained the controller thermocouple and had a hook on the end from which the specimen coupon was hung.

The testing sequence was as follows: A solution of desired salt concentration and pH was prepared, placed into the flask and heated to 90°C. The desired gas was then bubbled through. After the solution reached temperature and oxygen equilibrium (which typically took approximately 2 hours), the sample was suspended in the solution. The sample had been cleaned (acetone, alcohol rinse) and weighed before insertion. The sample was exposed to the solution for 120 hours, then removed and photographed. The sample was then cleaned of corrosion product by dipping in Clark's solution* and weighed. The difference between initial and final weight was used to calculate the weight loss and corrosion rate .

*Clark's solution: 1 litre hydrochloric acid, 20g antimony trioxide, 50g stannous chloride

RESULTS

Effect of Salt Concentration

The effect of salt concentration on the corrosion rate of drill stem material in air-saturated solutions at 90°C as a function of pH level is shown in Figure 6. It is seen that at a pH of 6, the corrosion rate is reduced by only a small extent with increasing salt concentration. At a pH of 8, the reduction in corrosion rate with increasing salt concentration is appreciable. At a pH of 11, the reduction in corrosion rate is decreased dramatically from near 20 mils per year (mpy) in 0.1% NaCl solution to near 0.1 mpy in a 22% NaCl solution.

Selected examples of this nine-specimen set are shown in Figure 7. Figure 7a is the specimen which was tested in 0.1% NaCl at a pH of 6. Very heavy, uniform corrosion is seen. The specimen tested at a pH of 8 in 0.1% NaCl had a similar appearance. The specimen tested at a pH of 6 in 3.5% NaCl is shown in Figure 7b. It is seen that the corrosion was severe on the bottom half and moderate on the top half. The specimen tested at a pH of 8 in 3.5% NaCl had a similar appearance. Figure 7c is the specimen which was tested in 22% NaCl at a pH of 6. It can be seen that the corrosion was moderate and very localized. Areas of corrosion product "growth" emanate from the sample edges, i.e., bottom, top or sides. Specimens tested at a pH of 11 in 0.1% and 3.5% NaCl and the specimen tested at a pH of 8 in 22% NaCl had similar appearances. Differences in the appearance of these specimens were mainly due to the varying location of the corrosion attack.

The calculation of a corrosion rate in mils per year (mpy) for these specimens is tenuous at best and was done only for the purpose of making relative comparisons. These results will be explained in the Discussions Section of this paper.

Corrosion tests done in salt solutions at 90°C as a function of pH level where the oxygen content in solution was low (at 50 ppb and below) resulted in such low corrosion rates (below 1 mpy) that no discernible salt concentration effects were observed, data given in Table II. Figure 8 is an example of a specimen from this 18 specimen set, i.e., oxygen contents of 50 ppb and near zero, pH levels of 6, 8 and 11 and salt concentrations of 0.1%, 3.5% and 22% NaCl. It can be seen that corrosion was negligible or at most very light and was exhibited primarily as a few isolated pits. The specimen tested in the previous set at a pH of 11 in 22% NaCl saturated with air had a similar appearance. Again, the corrosion rates calculated for these specimens were all below 1 mpy.

Effect of pH Level

The effect of pH level on the corrosion rate of drill stem material in air-saturated solutions at 90°C as a function of salt concentration is shown in Figure 9. It is seen that at a salt concentration of 0.1%, the corrosion rate is reduced only by a small extent with increasing pH level (6-11). At a salt concentration of 3.5%, the reduction in corrosion rate with increasing pH level is appreciable. At a salt concentration of 22%, the

reduction in corrosion rate is dramatic, dropping from over 22 mpy at pH 6 to near 0.1 mpy at pH 11. The same set of nine specimens discussed in the previous section are pertinent in this section, and the same specimens selected in Figure 7 as examples can be used here. Looking again at Figures 7a, 7b and 7c it can be seen that the corresponding corrosion rates calculated for these respective specimens are progressively lower due more to reduction in the amount of specimen area affected than in the severity of corrosion itself at an affected area. Therefore, in air-saturated solutions, either increasing the pH level at fixed concentrations of salt or increasing the salt concentration at a fixed pH level will result in a lower calculated corrosion rate because the area attacked becomes smaller. An explanation of these results will be presented later in the Discussions Section of this paper.

Corrosion tests in solutions of low oxygen content (at 50 ppb or below) resulted in such low corrosion rates (below 1 mpy) that no discernible pH effects were observed, particularly at higher salt concentrations.

Effect of Oxygen Content

The effect of dissolved oxygen content on the corrosion rate of drill stem material in 0.1% salt solutions at 90°C for three pH levels (6, 8, 11) is shown in Figure 10. Consistently for all three pH levels, a decrease in oxygen content caused a

respective decrease in corrosion rate. Also, it should be noted in Figure 10, that the relationship shows linear behavior, i.e. for the range of oxygen contents investigated, a decrease in oxygen content caused a proportional decrease in corrosion rate. This relationship can also be observed visually by use of the following examples from these sets of specimens. Figure 11 shows three examples from the set of specimens run in 0.1% NaCl at a pH of 6 as a function of oxygen content. The specimens shown in Figures 11a, b and c, were tested in oxygen contents of 250, 1000 and 1500 ppb, respectively. It can be seen that for these conditions the corrosion was fairly uniform and increasingly severe with increasing oxygen content.

An analogous and consistent example of this relationship is shown by the appearance of specimens in Figure 12. These three specimens are from a set which had been tested in 0.1% NaCl at a pH of 8 as a function of oxygen content. The specimens shown in Figures 12a, b and c, were tested in oxygen contents of 250, 500 and 1500 ppb, respectively. Again, it can be seen that for these conditions the corrosion becomes increasingly severe with increasing oxygen content. However, in this case for a pH of 8, the corrosion was more localized than on the specimens tested at pH 6, as had been discussed previously in the section on "Effect of pH Level" for air-saturated solutions.

Figure 13 shows the data presented in Figure 10 plotted in a different manner. Figure 13 is a plot of corrosion rate versus pH level for various oxygen contents. The relatively small

change in corrosion rate observed by increasing the pH from 6 to 11 for a given oxygen content is apparent. Therefore, for the conditions tested in this program (i.e., 0.1% NaCl, pH 6-11, O₂ 0-5000 ppb) the reduction in oxygen content has a proportionately greater effect upon reducing the corrosion rate than does increasing the pH from 6 to 11. Although the corrosion rate calculations indicate that the effect of pH on corrosion response was minimal, observation of the corrosion specimens suggests otherwise. A specimen set which serves as an example of the profound pH effect is shown in Figure 14. Specimens shown in Figures 14a, b and c, were tested in 0.1% NaCl with an oxygen content of 1500 ppb at pH levels of 6, 8 and 11, respectively. A reduction in the area of the specimen attacked by increasing the pH is readily seen. A second major effect was noticed with this specimen set. The color of the corrosion products for specimens tested at pH levels of 6 and 8 in 0.1% NaCl for all of the oxygen conditions from deaerated to air-saturated is reddish-brown or "rust" colored. This color suggests that the corrosion product is hematite, Fe₂O₃, or a hydrated hematite, Fe₂O₃·xH₂O, compound. This result agrees with that predicted from the equilibrium phase diagram shown in Figure 1 and discussed in the Introduction.

In contrast, the color of the corrosion products for specimens tested at the pH level of 11 in 0.1% NaCl solutions at all levels of oxygen is a pale green. This color suggests that the

corrosion product is iron hydroxide, $\text{Fe}(\text{OH})_2$. Again, this result agrees with that predicted by the Pourbaix Diagram.

The mechanistic reason for the sensitivity of corrosion rate to oxygen content is further explored in the Discussion section of this paper.

Baca Water

At the completion of the above detailed series of tests, two additional tests were run in water obtained from the Baca geothermal area. The first had an oxygen content set at 500 ppb, the second was run in a solution equilibrated with air (oxygen content ~5200 ppb). In the first test, the corrosion rates observed were low and compared well to previous analogous tests run in laboratory solutions with 0.1% NaCl at pH's of 6, 8 and 11. However, in the second, the corrosion rate at the pH 11 level was considerably smaller than for previous tests (Figure 15). The reason for this difference is not known. A number of factors could influence this change. Among the factors are additives such as inhibitors in the Baca water, but not present in the laboratory solutions. Also, the Baca water contains an appreciable amount of sulfate and bicarbonate, which may have an influence. Increasing the pH to 11 would increase the tendency for CaCO_3 to precipitate out as scale and reduce the corrosion rate. The tendency for CaSO_4 scale formation as a function of pH is not as well understood. Additional tests proposed to understand these differences are discussed in a later section of this paper on Future Work.

DISCUSSIONS

Effect of Salt Concentration

It had been found, as shown in Figure 6, that the corrosion rate of steel at a given pH level decreased with increased concentration of salt. Since oxygen solubility in water decreases continuously with NaCl concentration and since oxygen depolarization controls the corrosion rate throughout the NaCl concentration range, the decrease in corrosion rate with increasing NaCl concentration is an expected result.

Effect of pH Level

It had also been found, as shown in Figure 9, that the corrosion rate of steel at a given salt concentration decreased with increased pH level. Since an increase in alkalinity of the environment raises the pH of the iron surface, the corrosion rate correspondingly decreases because iron becomes increasingly passive in the presence of alkalies and dissolved oxygen, as explained in the Introduction section of this report. Again, the higher the pH, the higher the concentration of OH^- which reacts with the iron and forms a passivating film of $\text{Fe}(\text{OH})_2$ on the surface.

Combined Effects of Salt Concentration and pH Level

In distilled water having low conductivity, anodes and cathodes must be located relatively near each other. Consequently, OH^- ions forming at cathodes are always in the proximity of Fe^{++}

ions forming at nearby anodes, resulting in a film of $\text{Fe}(\text{OH})_2$ adjacent to and adherent to the metal surface. This provides an effective diffusion barrier film.

In NaCl solutions, on the other hand, the conductivity is greater, hence anodes and cathodes can operate much further removed one from the other. At such cathodes, NaOH does not react immediately with FeCl_2 formed at anodes; instead, these substances diffuse into the solution and react to form $\text{Fe}(\text{OH})_2$ away from the metal surface. Any $\text{Fe}(\text{OH})_2$ so formed does not provide a protective barrier layer on the metal surface. Hence iron corrodes more rapidly in dilute NaCl because more dissolved oxygen can reach cathodic areas due to the absence of the protective barrier layer. Another cause adding to the increase in the corrosion rate with the addition of salt is the breakdown in the protective oxide film on the iron by the chloride ion.

At increasing NaCl concentrations, the continuing decreased solubility of oxygen becomes more important than changes in the diffusive barrier layer, and corrosion decreases (Ref. 4). Thus, as seen in Figure 9, in spite of the high pH, the solutions containing dilute NaCl produce substantial corrosion of the steel because of the interference with the $\text{Fe}(\text{OH})_2$ barrier layer. The solution containing the most OH (pH 11) and the least amount of oxygen (22% NaCl) has the lowest corrosion rate of all conditions surveyed.

In distilled water, the surface of iron is always in contact with a saturated solution of hydrated ferrous oxide, the

observed pH of which is about 9.5. Above pH 10, this increase in alkalinity of the environment raises the pH of the iron surface. The corrosion rate correspondingly decreases because iron becomes increasingly passive (i.e., more easily forms $\text{Fe}(\text{OH})_2$) in the presence of alkalies and dissolved oxygen.

In solutions where the pH is controlled below the equilibrium value of 9.5 (e.g., pH 8 or 6), it is more difficult for the $\text{Fe}(\text{OH})_2$ barrier film to form and the corrosion rate correspondingly increases. Thus, as seen in Figure 6, in spite of the low oxygen concentrations of the solutions containing 22% NaCl, the solutions at pH levels of 6 and 8 cause substantial corrosion of the steel because of the increased difficulty with which the $\text{Fe}(\text{OH})_2$ barrier layer forms. The solution containing the least OH^- (pH 6) and the most amount of oxygen (0.1% NaCl) has the highest corrosion rate of all conditions surveyed.

Effect of Dissolved Oxygen

When iron corrodes, the rate is usually controlled by the cathodic reaction, which in general is much slower than the anodic reaction. In deaerated acidic and alkaline solutions, the respective cathodic reactions are the following:

In the absence of dissolved oxygen, the corrosion rate of steel in near-neutral solutions at room temperature is negligible.

The cathodic reaction can be accelerated by dissolved oxygen in accord with the following reaction, a process called "depolarization":

Dissolved oxygen reacts with hydrogen atoms adsorbed at random on the iron surface. The oxidation reaction proceeds as rapidly as oxygen reaches the metal surface. Since the diffusion rate at steady state is proportional to oxygen concentration, it follows from equation (3) that the corrosion rate of iron is also proportional to oxygen concentration (Ref. 4). Deviations from the linear relation between corrosion rate and oxygen concentration occur sooner in distilled water than when Cl^- ions are present. This value for deviation increases with increasing dissolved salts and with temperature, and decreases with an increase in water velocity and pH. The data of Figure 11, plotted on linear graph paper, show that this linear relationship has held, within experimental error, for the range of conditions investigated within this study.

CONCLUSIONS

1. The corrosion rate of steel was found to decrease with increasing salt concentration at fixed pH levels and oxygen contents of the gas in equilibrium with the solution at 90°C.
2. The corrosion rate was found to decrease with increasing pH at fixed concentrations of salt and oxygen at 90°C.

3. The lowest corrosion rate was observed at the highest salt concentration and pH level.
4. The highest corrosion rate was observed at the lowest salt concentration and pH level.
5. The corrosion rate was found to be directly proportional to the dissolved oxygen concentration at fixed pH levels and salt concentration.
6. The Baca water produced lower corrosion rates than the laboratory solutions, most likely due to the additives.

FUTURE WORK

Three areas of research are proposed for continuing work. The first is to expand on the effect of oxygen on corrosion rate in Baca water and compare these results to those previously obtained with laboratory solutions.

The second area is to determine the effect of sulfate and carbonate additives on corrosion rate in laboratory solutions of specific salt, pH and oxygen levels. The intent of this work is to determine which specie in Baca water is affecting its change in corrosion rate compared to laboratory solutions.

The third area proposed for study is an investigation of the effect on corrosion rate in Baca water of simultaneously reducing the oxygen content from air equilibrium values and adding NaOH to increase the pH to more basic values. The intent of this work is to determine if the most cost effective manner

of reducing corrosion rate is a combination of techniques rather than either increasing pH or reducing the oxygen content.

ACKNOWLEDGMENTS

The author wishes to acknowledge the support of the following people: C. J. Greenholt, 1841, for preparing specimens and solutions, running the tests, taking the weight data and the photographs, and assisting with this manuscript; and T. E. Hinkebein, 4755, for calculating the oxygen contents required in the cover gas to obtain desired oxygen levels in solutions.

REFERENCES

1. Pourbaix, Marcel, Atlas of Electrochemical Equilibria in Aqueous Solutions, National Association of Corrosion Engineers, Houston, TX, 1974.
2. Caskey, B. C. and Copass, K. S., Geothermal Drill Pipe Corrosion Test Plan, Sandia National Laboratories, SAND80-1090, Albuquerque, New Mexico, Dec. 1980.
3. Caskey B. C. and Copass, K. S., Drill Pipe Corrosion Control Using an Inert Drilling Fluid, Sandia National Laboratories, SAND80-2810, Albuquerque, New Mexico, 1981.
4. Uhlig, H. H., Corrosion and Corrosion Control, John Wiley and Sons, Inc., New York, 1963.

TABLE I

Oxygen Contents in Cover Gas to Obtain
Dissolved Oxygen in Solution at 90°C

0.1% NaCl

<u>ppm O₂ in gas</u>	<u>ppb O₂ in solution</u>
2250	50
4500	100
6750	150
11250 (1.13%)	250
22500 (2.25%)	500
45000 (4.5%)	1000 (1ppm)
67500 (6.75%)	1500 (1.5ppm)

3.5% NaCl

2600	50
------	----

22.0% NaCl

7090	50
------	----

TABLE II

Corrosion Rate, MPY Loss at 90°C

pH6

<u>NaCl, %</u>	<u>0.1</u>	<u>3.5</u>	<u>22</u>
N ₂	0.6	0.3	0.02
50 ppb O ₂	0.9	0.5	0.14
Air	25.3	23.1	22.5

pH8

<u>NaCl, %</u>	<u>0.1</u>	<u>3.5</u>	<u>22</u>
N ₂	0.3	0.0	0.07
50 ppb O ₂	0.3	0.6	0.8
Air	23.5	16.9	13.4

pH11

<u>NaCl, %</u>	<u>0.1</u>	<u>3.5</u>	<u>22</u>
N ₂	-0.1 (gain)	0.2	0.0
50 ppb O ₂	0.1	0.2	0.0
Air	19.4	11.2	0.1

FIGURE 1. Potential-pH equilibrium diagram for the element iron at 25°C

FIGURE 2. Potential-pH equilibrium diagram for water at 25°C

FIGURE 3. Potential-pH equilibrium diagram for the iron-water system at 25°C

FIGURE 4. Conditions for corrosion, immunity and passivation of iron

FIGURE 5. Schematic of corrosion apparatus

FIGURE 6. Corrosion rate versus salt concentration as a function of pH level in air-saturated solutions at 90°C

Fig. 7a

Fig. 7b

FIGURES 7a, 7b, 7c. Selected examples of corrosion specimens tested in air-saturated solutions

Fig. 7c

FIGURE 8. Example of corrosion specimen tested in solution where oxygen content was low

FIGURE 9. Corrosion rate versus pH level as a function of salt concentrations in air-saturated solutions at 90°C

FIGURE 10. Linear plot of corrosion rate versus dissolved oxygen content

Fig. 11a

Fig. 11b

FIGURES 11a, 11b, 11c. Corrosion specimens tested in 0.1% NaCl at a pH of 6 as a function of oxygen content

Fig. 11c

Fig. 12a

Fig. 12b

FIGURES 12a, 12b, 12c. Corrosion specimens tested in 0.1% NaCl at a pH of 8 as a function of oxygen content

Fig. 12c

FIGURE 13. Corrosion rate versus pH as a function of oxygen content in 0.1% NaCl

Fig. 14a

Fig. 14b

FIGURES 14a, 14b, 14c. Corrosion specimen set showing pH effect on corrosion response

Fig. 14c

FIGURE 15. Corrosion rate versus pH level as a function of oxygen content in Baca water

Distribution:

1830 M. J. Davis
1832 R. J. Salzbrenner
1832 J. A. Ruppen
1840 N. J. Magnani
1841 R. B. Diegle
1841 C. J. Greenholt
1841 L. J. Weirick (10)
3141 L. J. Erickson (5)
3151 W. L. Garner (3)
3154-3 C. Dalin (25)
for DOE/TIC
8310 R. W. Rohde
8315 L. A. West
9740 R. K. Traeger
9741 J. R. Kelsey
9741 C. C. Carson
9741 B. C. Coskey
9755 T. E. Hinkebein