# Corrosion performance of Ni-Cr-Fe alloys in geothermal hypersaline brines

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The early development of the Salton Sea geothermal resource proved that carbon steel tubulars do not provide satisfactory service life in the high-temperature, hypersaline brines. A large-scale corrosion test was designed to find the most cost-effective alloys for completing these wells. A series of Ni-Cr-Mo alloys were tested over several years in three production wells and two injection wells. The various alloys were made into 8⅝ in. (22 cm) outside diameter by 0.400 in. (1.0 cm) wall production casing strings about 1500 ft. (457 m) long. The well bore was divided into three temperature regimes and several joints of each alloy were tested in each regime. This paper discusses the corrosion effects of the brine on the various alloys for lengthy periods under actual flowing conditions. Long-term corrosion tests were also conducted on alloys considered for injection tubing.

## Introduction

Geothermal energy from the Salton Sea field is used to drive eleven turbines which generate 300 megawatts of power. Located in the Imperial Valley of California, the Salton Sea is one of the largest geothermal fields in the world. This energy exists in the form of steam or a combination of steam and water. The Salton Sea fluids are characterized by their high salinity, having total dissolved solids ranging from 13% to 30% with a pH of 5.1 to 4.6.

The corrosion test that is reported in this paper was conducted in an effort to find some alloys that were capable of withstanding the corrosiveness of the hot brines being produced from the Salton Sea field. Until the time of this test Unocal Corp. had been using carbon steel and some other relatively low alloy steels as production casing and the lifetimes were unacceptably low.

The decision to put together such an elaborate full scale test was not made without sufficient evidence that lower alloys would not work. The final incident that was the impetus for Unocal to initiate this study was a string of 9Cr-1Mo steel production casing that developed holes in the casing walls after just 5 months of service. The 9Cr-1Mo alloy had been tested in another geothermal well for 3 months and its performance indicated that it would provide a reasonable service life. This experience showed that individual wells can perform much differently from other wells in the same area from a corrosion standpoint. So in the full-scale test three production wells and two injection wells were chosen as test wells.

The objectives of this test program were:

1. To rank the alloys by corrosion resistance in the environment
2. Determine the susceptibility of the alloys to stress corrosion cracking
3. Determine how brine chemistry, temperature, and pressure affects the corrosion rate of the alloys

# Production Casing

## Test Procedure

All tubulars were cold worked to 110 ksi yield strength to prevent yielding in compression in the event they were cemented in the well. C-ring stress corrosion cracking tests were conducted on all the candidate alloys prior to starting the full-scale test; those alloys that cracked were eliminated.

The high nickel superalloys listed in *Table I* were tested as coupons and as casing in the hottest 500 ft. (152 m) of the test string. They were found to be almost immune to any general corrosion or pitting. The coupons still showed the machining marks after testing. Therefore, further testing was conducted on alloys having a lower nickel+chromium+molybdenum content. These alloys and their nominal compositions are listed in *Table II.* Previous coupon tests and ultrasonic thickness gauging had shown that general corrosion is not a problem in these alloys; pitting corrosion is the main concern.

The tests were conducted in three production wells and two injection wells. The wells and the flowing well conditions are listed in *Table III.* The typical composition of a Salton Sea brine is shown in *Table IV.*

The pitting corrosion rates were calculated by linear extrapolation and extreme value statistics.

1) The deepest measured pit, divided by the production time, described as the optimistic pitting rate, gives the lowest rate when compared to the extreme-value calculation.
2) In the extreme-value statistical theory a known extreme in each of several small adjacent increments of space (or time) can be used to predict the extreme value of a much larger increment. For example, the deepest pit in each of twenty-two inch "lengths" of pipe can be used to predict the deepest pit that will be found in a 1000 ft. (305 m) length of pipe. The predicted corrosion rate is a function of the size of the measured area used to generate the prediction. The larger the area that is measured, the more accurate the predicted corrosion rates. This method gives the probable pitting corrosion rate which is always greater than the optimistic pitting rate.

All corrosion rates are calculated using production time rather than installed time because it provides the highest rate or most conservative rating of service performance.

A detailed discussion of the techniques used in producing the predicted corrosion rates is given in *Reference 1.*

The entire production casing was pulled from the well and selected joints were cleaned prior to measuring the pit depths. The joints were hydro-blasted to remove scale that was deposited on the casing walls. The final cleaning was accomplished by a silica sandblast. The inside diameter on each (1.6 ft., 0.5 m) end of the tube was marked into four quadrants. The two deepest pits in each 0.2 ft. (0.06 cm) of each quadrant were measured and recorded. Both ends (a total of 3.2 ft., 1.0 m) of each joint were inspected.

**Table I** High-nickel superalloys Nominal composition

| UNS Number | Alloy Composition (wt %) | | | | |
|---|---|---|---|---|---|
| | Fe | Cr | Ni | Mo | Other Elements |
| N10276 | 5.5 | 15 | 55.5 | 16 | 4.0 (W) 2.5 Max.(Co) 0.35 Max.(V) |
| N06625 | 5.0 Max. | 22 | 58.0 Min. | 9 | 0.40 Max.(Ti, Al), 1.0 Max. (Co), 3.15 (Cb+Ta) |
| N06022 | 3.0 | 21.5 | 56.0 | 13.5 | 3(W),.35(V) |
| MP35N* | 1.0 | 20.0 | 33.0 | 10.0 | 1.0 (Ti). 35.0, (Co) |
| N06110 | – | 31.0 | 56.0 | 10.0 | 0.25 (Ti), 2.0 (W) |

* Common Name - no UNS Number assigned

**Table II** Alloys tested as production casing

| UNS Number | Alloy Composition (wt %) | | | | | |
|---|---|---|---|---|---|---|
| | Fe | Cr | Ni | Mo | Si | Other Elements |
| Ni-Cr-Mo: | | | | | | |
| 2025* | 43.5 | 21 | 29 | 4.0 | – | 0.5 Max Ti |
| N08135 | 35 | 22 | 36 | 5.0 | – | 0.35 Max Ti |
| N08535 | 31 | 25.5 | 38 | 3.5 | – | 0.5 Max Ti |
| N06255 | 16 | 24.5 | 50 | 6 | – | 1.5 Max Ti |
| N08028 | 36.5 | 27.0 | 31.0 | 3.5 | – | – |
| N08825 | 22.0 Min | 21.5 | 42 | 3 | 0.05 Max | 0.6 - 1.2 Ti 0.2 Max Al |
| S31803 | Bal. | 22 | 5.5 | 3.0 | 0.8 | 0.14 N |
| S31260 | Bal. | 25 | 7.0 | 3.0 | 0.8 | 0.20 N 0.3 W |

*Common Name - no UNS Number assigned

**Table III** Well conditions for alloy tests

| Well | Avg WHT °F-°C | WHP Range (PSIG) | Avg. Rate (K#/Hr) | TDS (wt%) | pH | Inst Time (days) | Prod/Inj Time (days) |
|---|---|---|---|---|---|---|---|
| IID 12 | 455-235 | 420-350 | 672 | 23.47 | – | 637 | 517 |
| Sinc. 20 | 465-240 | 460-348 | 540 | 23.90 | – | 2529 | 2220 |
| Sinc.15 | 220-104 | 0 | 455 | 31.65 | 5.1-4.6 | 368 | 234 |
| IID 6 | 217-103 | 0 | 543 | 31.65 | 5.1-4.6 | 213 | 170 |
| Veysey 12 | 433-223 | 580-345 | 470 | 12.56 | – | 368 | 234 |

WHT Well Head Temperature; WHP Well Head Pressure; K#/Hr Thousand Pounds per Hour; TDS Total Dissolved Solids; Inst Installed Time; Prod/Inj Production or Injection Time

**Table IV** Typical brine composition of a Salton Sea Well (pH=5.8)

| Element | ppm | Element | ppm | Element | ppm | Element | ppm |
|---|---|---|---|---|---|---|---|
| As | 8 | Pb | 66 | $SiO_2$ | 658 | Br | 68 |
| Ba | 100 | Li | 177 | Na | 59,800 | Cl | 126,700 |
| B | 301 | Mg | 80 | $CO_2$ | 125 | I | 5 |
| Ca | 24,000 | Mn | 785 | Sn | 402 | $SO_4$ | 22 |
| Cu | 7 | K | 12,840 | Zn | 287 | TDS | 261,800 |
| Fe | 708 | Rb | 62 | $NH_3$ | 339 | $H_2S$ | 90 |

# Results

## Sinclair 20

The six alloys listed in *Table II* were installed in the Sinclair 20 well in March of 1984. The entire string was pulled for intermediate inspection three times and was removed from testing in February of 1991. The total testing time was 2220 days. *Table V* shows the production exposure time for each joint and the corrosion rates as of February, 1987.

**Table V** Salton Sea Field, Sinclair 20 Geothermal Producer, 8⅝ x 0.400 in. (22 x 1.0 cm) wall hangdown string from surface to 1800 ft. (1189 m) casing retrieved in February, 1987.

| UNS Number | Approx Depth ft.(m) | Prod Time Days | Corrosion Rate* Opt Corr Rate mpy | Prob Corr Rate mpy |
|---|---|---|---|---|
| N08028 | 1765(538) | 934 | 7 | 17 |
| N08028 | 1761(537) | 934 | | |
| N08028 | 1757(536) | 934 | 4 | 15 |
| N08028 | 1741(531) | 934 | 5 | 16 |
| N08028 | 1723(525) | 934 | 15 | 56 |
| N08028 | 1694(516) | 714 | 20 | 54 |
| 3040** | 1639(500) | 714 | 18 | 42 |
| N06255 | 1615(492) | 714 | 9 | 25 |
| N08825 | 1591(485) | 714 | 22 | 49 |
| N08535 | 1567(478) | 714 | 14 | 30 |
| N08135 | 1544(471) | 714 | 14 | 30 |
| N08135 | 1521(464) | 934 | 15 | 36 |
| N08535 | 1451(442) | 934 | 10 | 22 |
| N08825 | 1428(435) | 934 | 11 | 26 |
| N06255 | 1361(415) | 934 | 12 | 32 |
| N08135 | 1338(408) | 714 | 14 | 30 |
| N08028 | 1243(379) | 714 | 18 | 37 |
| N08535 | 1205(367) | 714 | 15 | 43 |
| N08825 | 1113(339) | 714 | 16 | 33 |
| N06255 | 1043(318) | 714 | 11 | 31 |
| N06255 | 881(269) | 714 | 10 | 22 |
| N06255 | 857(261) | 714 | 9 | 24 |
| N08825 | 766(234) | 714 | 14 | 24 |
| N08535 | 718(219) | 714 | 15 | 43 |
| N08028 | 680(207) | 714 | 13 | 39 |
| N08135 | 663(202) | 934 | 14 | 38 |
| N08028 | 474(145) | 934 | 12 | 33 |
| N08535 | 361(110) | 934 | 8 | 23 |
| N08825 | 251(77) | 934 | 2 | 8 |
| N06255 | 137(42) | 934 | 11 | 30 |
| N06255 | 112(34) | 934 | 2 | 6 |

* As determined at tube ends. See "Test Procedure"
**Common name - no UNS Number assigned

Several joints were analyzed for corrosion at each inspection. The remaining joints, along with several new joints, were reinstalled. *Table VI* shows the optimistic and probable corrosion rates during the three exposure periods. The optimistic (opt.) corrosion rate is the deepest measured pit divided by production time in years. Probable (prob.) corrosion rate was determined by the extreme-value method and is the statistical extrapolation of pitting data at the *50%* probability level of a 2000 ft. (610 m) string of 8⅝ in. (22 cm) casing.

The probable corrosion rate is plotted in *Figure 1* for the depth of 1000 to 1500 ft. (305 to 457 m). Based on these rates the life for a 0.400 in. (1.0 cm) wall tube was predicted and is shown as *Figure 2.* These figures show that based on

**Table VI** Salton Sea Field, Sinclair 20
8⅝ x 0.400 in. (22 x 1.0 cm) wall hangdown string from surface to 1800 ft. (549 m)

| UNS Number | Approximate Depth (ft) | Opt. Corr. Rate mpy, during periods* A | B | C | D | Prob. Corr. Rate mpy, during periods* A | B | C | D |
|---|---|---|---|---|---|---|---|---|---|
| N08135 | 0 - 500 | NA | NA | NA | | NA | NA | NA | |
| | 500-1000 | 50 | NA | 14 | 7 | 104 | NA | 38 | 16 |
| | 1000+ | 56 | 14 | 15 | | 147 | 30 | 36 | |
| N08535 | 0 - 500 | NA | NA | 8 | 5 | NA | NA | 23 | |
| | 500-1000 | 50 | 15 | NA | | 97 | 43 | NA | 13 |
| | 1000+ | 63 | 15 | 10 | | 115 | 43 | 22 | |
| N06255 | 0 -500 | 47 | NA | 11 | 3 | 86 | NA | 30 | |
| | 500 -1000 | 33 | 10 | NA | | 81 | 24 | NA | 8 |
| | 1000+ | 58 | 11 | 12 | | 95 | 31 | 32 | |
| N08028 | 0-500 | 50 | 12 | NA | 6 | 76 | 33 | NA | |
| | 500-1000 | 66 | 13 | NA | | 142 | 39 | NA | 15 |
| | 1000+ | 83 | 20 | 15 | | 157 | 54 | 56 | |
| N08825 | 0-500 | 15 | NA | 2 | 5 | 51 | NA | 8 | |
| | 500-1000 | NA | 14 | NA | | NA | 24 | NA | 14 |
| | 1000+ | 43 | 22 | 11 | | 116 | 49 | 26 | |

*Exposure Period

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| A. | Installed | 03/06/84 | to | 11/17/84 | 256 days | C. | Installed | 03/06/84 | to | 03/04/87 | 1093 days |
| | Produced | 04/06/84 | to | 11/12/84 | 220 days | | Produced | 04/06/84 | to | 02/08/87 | 934 days |
| B. | Installed | 11/21/84 | to | 03/04/87 | 833 days | D. | Installed | 03/06/84 | to | 02/02/91 | 2529 days |
| | Produced | 12/19/84 | to | 02/08/87 | 714 days | | Produced | 04/06/84 | to | 02/02/91 | 2220 days |

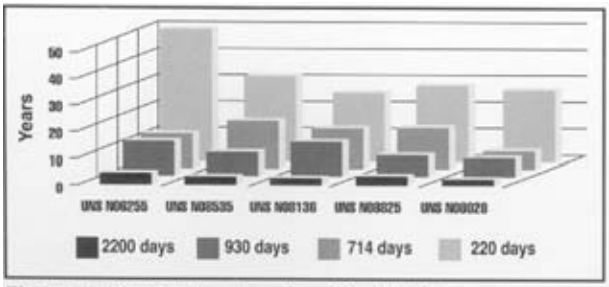


**Figure 1** Predicted casing life – Sinclair 20.

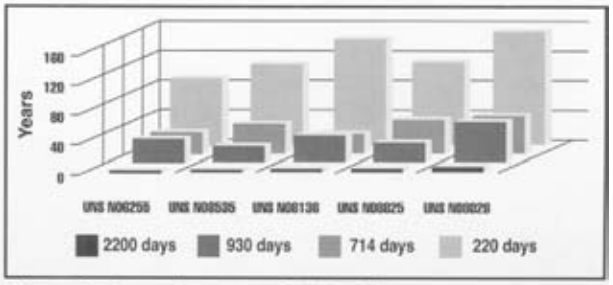


**Figure 2** Corrosion rate – Sinclair 20.

a 220-day test the predicted corrosion rate would have been so high, and the life would have been so short, that none of the alloys would have been used. However, based on 2220 days of testing all the alloys would be acceptable.

*NOTE: All time periods are days of exposure to actual production conditions. The actual installed times are longer as listed in the individual tables.*

### IID 12

The IID 12 well tests began in March of 1984. The string was pulled for intermediate inspection after an exposure of 218 and 320 days and finally retrieved in December of 1985. Total exposure time was 633 days. *Table VII* shows the optimistic and probable corrosion rates after the three exposure periods. This well, unlike the Sinclair 20 well, shows a significant effect of well depth with the 1000+ ft. (305 m) depth having a corrosion rate in some cases of several times higher than tubing at the 500 ft. (152 m) level. The only obvious difference in the wells is that the IID 12 well has a production rate about 25% higher than the rate for Sinclair 20.

**Table VII** Salton Sea Field, IID 12
8⅝ x 0.400 in. (22 x 1.0 cm) wall hangdown string from surface to 1600 ft. (488 m)

| UNS Number | Aproximate Depth (ft) | Opt. Corr. Rate mpy, during periods* | | | Prob. Corr. Rate mpy, during periods* | | |
|---|---|---|---|---|---|---|---|
| | | A | B | C | A | B | C |
| N08135 | 0-500 | 30 | 7 | 7 | 126 | 18 | 17 |
| | 500-1000 | 72 | NA | NA | 363 | NA | NA |
| | 1000+ | 78 | 23 | 23 | 143 | 47 | 59 |
| N08535 | 0-500 | 7 | 9 | 17 | NA | 19 | 33 |
| | 500-1000 | 37 | 17 | 16 | 111 | 33 | 57 |
| | 1000+ | 85 | 22 | 16 | 166 | 71 | 56 |
| N06255 | 0-500 | 18 | 7 | 13 | 111 | 23 | 22 |
| | 500-1000 | NA | 14 | NA | NA | 28 | NA |
| | 1000+ | 41 | 22 | NA | 56 | 81 | NA |
| N08028 | 0-500 | NA | 10 | NA | NA | 20 | NA |
| | 500-1000 | 44 | 22 | NA | 112 | 37 | NA |
| | 1000+ | 68 | 22 | 23 | 135 | 52 | 59 |
| N08825 | 0-500 | 7 | 15 | 8 | NA | 29 | 19 |
| | 500-1000 | 37 | 15 | NA | 65 | 24 | NA |
| | 1000+ | 37 | 15 | NA | 65 | 24 | NA |

*Exposure Period

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| A. | Installed | 03/16/84 | to | 10/20/84 | 218 days | C. | Installed | 03/16/84 | to | 12/14/85 | 637 days |
| | Produced | 03/26/84 | to | 10/08/84 | 197 days | | Produced | 03/26/84 | to | 10/01/85 | 517 days |
| B. | Installed | 10/25/84 | to | 12/14/85 | 415 days | | | | | | |
| | Produced | 11/02/84 | to | 10/01/85 | 320 days | | | | | | |

**Table VIII** Brawley Field, Veysey 12
8⅝ x 0.400 in. (22 x 1.0 cm) wall hangdow n string from surface to 3900 ft. (1189 m)

| UNS Number | | Opt. Corr. Rate mpy, during periods* | | | Prob. Corr. Rate mpy, during periods* | | |
|---|---|---|---|---|---|---|---|
| | | A | B | C | A | B | C |
| 3040** | See Note 1 | | 178 | | | 406 | |
| UNS N06255 | | 91 | 168 | 44 | 182 | 420 | 115 |
| UNS N08825 | | 121 | 145 | 97 | 211 | 402 | 232 |
| UNS N08535 | | 136 | 178 | 70 | 173 | 463 | 145 |
| UNS N08135 | | 139 | 181 | 70 | 259 | 556 | 49 |
| UNS S31260 | | 151 | | | | | |

*Exposure Period

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| A. | Installed | 06/08/84 | to | 11/02/84 | 148 days | C. | Installed | 06/08/84 | to | 06/19/85 | 368 days |
| | Produced | 06/21/84 | to | 10/19/84 | 121 days | | Produced | 06/21/84 | to | 05/30/85 | 234 days |
| B. | Installed | 11/11/84 | to | 06/19/85 | 220 days | | | | | | |
| | Produced | 02/07/85 | to | 05/30/85 | 113 days | | | | | | |

**Common name - no UNS Number assigned

NOTE 1: All joints were installed between 3400 ft. and 3900 ft. (1036 and 1189 m) depth.

### Veysey 12

The Veysey 12 well located in the Brawley field was also used for these tests. Installation was in June of 1984, and inspections were made after 148 days and 220 days. The test ended in June of 1985 after an exposure of 368 days. All the joints in this well were installed between 3,400 and 3,900 ft. (1036 and 1189 m), more than twice the depth of those in the Salton Sea field. *Table VIII* shows the optimistic and probable corrosion rates after the three exposure periods. The total exposure time was close to the shortest time (A) for Sinclair 20 and IID 12 and corrosion rates were similar. Here again the short testing time would probably cause a wrong prediction of the actual long-term corrosion rate.

## Injector Tubing

Strings of 3½ in. (9 cm) tubing were tested in three injection wells. Two wells had about 760 ft. (232 m) of injection tubing while the other had about 1800 ft (548 m). These 3½ in. (9 cm) tubes were suspended inside of 8⅝ in. (22 cm) tubes. Both sizes of tubing were cold worked to achieve a yield strength of 110 ksi at 500°F (260°C).

## Sinclair 15

In April of 1984 an 8⅝ x 0.400 in. (22 x 1.0 cm) wall hangdown string was installed in the Sinclair 15 geothermal injection well from the surface to 3100 ft. (945 m). A 3½ x 0.254 in. (9 x 0.6 cm) wall tubing string was hung inside of the 8⅝ in. (22 cm) string from the surface to a depth of 800 ft. (244 m).

The initial 8⅝ in. (22 cm) string consisting of four Ni-Cr-Mo alloys was pulled for inspection after 486 days. A replacement string made up of UNS S31260, UNS S31803 and Cr 1Mo was installed and pulled in February of 1987 after 170 days. The alloys tested and the optimistic and probable pitting corrosion rates are shown in *Table IX.*

Threaded connections of the 8⅝ in. (22 cm) casing were visually inspected for cracking. Cracking was found on a duplex stainless steel connection manufactured by a centrifugal casting method. End inspections were performed as previously described for production tubing. The probable corrosion rates calculated for Period A are similar to rates seen in other injectors and to the corrosion rates seen on the alloy tubing tested in this well. The pitting rates seen on both the UNS J92205 and the UNS 531260 installed near the surface during period B are several times higher than pitting rates seen previously.

*NOTE: All time periods are days of exposure to actual injection conditions. The actual installed times are longer as listed in the individual tables.*

At these pitting rates a 0.4 in. (1 cm) wall tubular would be perforated in 1.1 to 3.5 years. Samples of the duplex SS alloys from Period B were analyzed. The high pitting rates found in the upper portion of the wellbore may be related to the silica scale which could create under-deposit conditions that promote pitting. The long shut-in period and the possible existence of oxygen in the vapour space above the liquid level in the well may be another explanation for the high pitting rate observed. The existence of oxygen would definitely exacerbate pitting corrosion under the silica scale.

The 3½ in. (22 cm) string was pulled for inspection in 171 days, and again after a total of 383 days. Since the majority of injection flow was directed down the 8⅝ x 3½ in. (22 x 9 cm) annulus, the outside of the smaller tubing string was inspected for corrosion. The pitting rates were based on the injection time and were calculated by dividing the pit depth by the time. Statistical analyses were performed on the injection tubing corrosion results. *Table X* shows the alloys tested and the resulting corrosion rates. Only alloy UNS N06255 showed improved corrosion resistance when compared to the duplex stainless steels. Alloys exposed during the Period B only show consistently higher pitting rates than those seen in either Period A or C. Assuming a 0.254 in. wall tubing and using the highest probable pitting rate after Period C, the UNS N06255 would last approximately 14 years before perforation, while the UNS S31260 would last approximately 11 years before perforation.

**Table IX** Salton Sea Field, Sinclair 15 8⅝ x 0.400 in. (22 x 1.0 cm) wall hangdown string from surface to 3100 ft. (945 m)

| | | Opt. Corr. Rate mpy, for periods* | | Prob. Corr. Rate mpy, for periods* | |
|---|---|---|---|---|---|
| | | A | B | A | B |
| UNS N0813 | 2905 | 4 | – | 12 | – |
| UNS N08535 | 2859 | 5 | – | 17 | – |
| UNS N08825 | 2909 | 6 | – | 16 | – |
| UNS N06255 | 2760 | 4 | – | 10 | – |
| UNS S31260 | 292 | – | 140 | – | 348 |
| | 1108 | – | 0 | – | – |
| | 1839 | – | 0 | – | – |
| | 2571 | – | 31 | – | – |
| | 2949 | 17 | – | 46 | – |
| UNS S31803 | 29 | – | 120 | – | – |
| | 67 | – | 118 | – | 256 |
| | 1339 | – | 6 | – | – |
| 9 Cr 1 Mo | 65 | 45 | – | 60 | – |
| | 805 | 11 | – | 18 | – |
| | 1894 | 14 | – | 25 | – |
| | 2579 | 53 | – | 83 | – |

*Exposure Period

| | | | | | |
|---|---|---|---|---|---|
| A. | Installed: | 04/12/84 | to | 11/27/85 | 594 days |
| | Injected | 04/20/84 | to | 10/01/85 | 486 days |
| B. | Installed | 12/07/85 | to | 02/09/87 | 429 days |
| | Injected | 01/10/86 | to | 09/30/86 | 170 days |

## IID 6

Various Ni-Cr-Mo and duplex stainless steel alloys were installed in March of 1984 as an 800 ft. (244 m) tubing string in IID 6. The entire string was retrieved after 175 days, and again after 464 days. Most of the string was also examined after an intermediate period of 289 days. *Table XI* shows the alloys tested, and the resulting corrosion rates. Here again only alloys UNS N06255 and UNS N08825 showed a significant improvement over the duplex alloys. No consistent change in corrosion is seen between exposure Periods A and B. In both Sinclair 15 and IID 6 the pitting rate decreases as the exposure time increases.

However, exposure Period C does show consistently lower optimistic and probable corrosion rates for all alloys. A 0.400 in. (1 cm) wall UNS N06255 or UNS N08825 tubular would have an expected life of 20+ years, while a duplex stainless steel would have an expected life of 13 to 17 years. The .254 in. (0.6 cm) wall of the 3½ in. (9 cm) tubing would cor-

**Table X** Salton Sea Field, Sinclair 15 Geothermal injector 3½ in. (9 cm) tubing string 0.254 in. (0.6 cm) wall, from surface to 800 ft. (244 m)

| UNS Number | Approx Depth ft.(m) | Opt. Corr. Rate, mpy | | | Prob. Corr. Rate, mpy | | |
|---|---|---|---|---|---|---|---|
| | | Exposure Period* | | | | | |
| | | A | B | C | A | B | C |
| S31803 | 0 to 800(244) | 23 | 57 | 25 | 58 | 71 | 33 |
| S31260 | 0 to 800(244) | 26 | 57 | 17 | 48 | 81 | 23 |
| 2025** | 0 to 800(244) | 21 | | 13 | 41 | | 21 |
| N08135 | 0 to 800(244) | 26 | 34 | 12 | 66 | 65 | 25 |
| N08535 | 0 to 800(244) | 15 | 28 | 17 | 40 | 56 | 32 |
| N08825 | 0 to 800(244) | 21 | 25 | 13 | | 33 | 31 |
| N06255 | 0 to 800(244) | 9 | | 9 | 24 | | 19 |

*Exposure Period

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| A | Installed | 04/13/84 | to | 10/28/84 | 198 days | C | Installed | 04/13/84 | to | 07/11/85 | 424 days |
| | Injected | 04/20/84 | to | 10/08/84 | 171 days | | Injected | 04/20/85 | to | 07/02/85 | 383 days |
| B | Installed | 11/27/84 | to | 07/11/85 | 226 days | | | | | | |
| | Injected | 11/27/84 | to | 07/02/85 | 212 days | | | | | | |

**Common name - no UNS Number assigned

rode through in only 8 years if made of a duplex material and would last 18 to 25 years if made of alloys # UNS N06255 or UNS N08825.

## IID 5

An 1800 ft. (549 m) string of 3½ x 0.254 in. (9 x 0.6 cm) wall tubing was installed in the Salton Sea IID 5 well in August of 1985. The string was pulled after 562 days, and finally after 908 days. *Table XII* shows the alloys tested, their position in the test string, and time of exposure.

Some of the joints of tubing and their couplings were cracked by chloride stress corrosion cracking. With one exception, UNS N08135, all the cracking was confined to the 22 Cr and 25 Cr duplex stainless steels.

The required factors for chloride stress corrosion cracking (Cl SCC) are: a susceptible alloy, a sufficient chloride ion concentration, elevated temperature, a sufficient tensile stress, and oxygen or low pH. If any of these factors is absent, Cl SCC will not occur. All of the factors are present normally in the injection system, except the oxygen. The pH is not sufficiently low to cause SCC. Since these injection wells take injectate on a vacuum, it is quite likely that air is drawn into the system. The operating pressure is low; so the stress level from internal pressure is probably not sufficient to cause cracking. However, the residual stress from cold working is certainly high enough to cause SCC. Although there is the possibility of drawing in air because the wells take injectate on vacuum, every time the oxygen level was measured (several times) the maximum detected was 15 ppb, hardly enough to cause SCC. Also there are so many ions and other species dissolved in the hot brine that any oxygen is used up rapidly, almost immediately, if oxygen does in fact enter the injection stream. So another corrodent is necessary to cause SCC. The injection fluid does contain about 30 ppb of Fe+3 ion which is a corrodent and may be the cause of the SCC that was seen. The Fe+2 is oxidized to Fe+3; oxygen would contribute to the oxidation of the Fe+2. The final comment on the SCC of the injection tubing is that there is not a good explanation for the SCC.

An alloy's nickel content is very important in determining its resistance to Cl SCC. As the nickel content increases, the SCC resistance increases. Duplex stainless steels have fairly good resistance to Cl SCC by nature of their microstructure, but they are more susceptible than the other alloys that have a nickel content of 35% or more. If duplex stainless steels are to be used in this service the residual stress from cold working would have to be eliminated or lowered drastically. This is necessary because eliminating the air in-leakage would be near impossible. An annealing heat treatment would eliminate the residual stress. The duplex stainless steels have an annealed yield strength of 70 ksi which is sufficient for the injection service; the 110 ksi yield strength used initially is not necessary. If one wanted to be conservative where Cl SCC is concerned, the higher nickel alloys should be used.

**Table XI** Salton Sea Field, IID6
Geothermal injector 3½ in. (9 cm) tubing string, 0.254 in. (0.6 cm) wall from surface to 800 ft. (244 m)

| UNS Number | Approx Depth ft.(m) | Opt. Corr. Rate, mpy | | | Prob. Corr. Rate, mpy | | |
|---|---|---|---|---|---|---|---|
| | | Exposure Period* | | | | | |
| | | A | B | C | A | B | C |
| S31803 | 0 to 800(244) | 27 | 40 | 23 | 58 | 65 | 29 |
| S31260 | 0 to 800(244) | 31 | | 14 | 57 | | 23 |
| 2025** | 0 to 800(244) | 33 | 13 | 18 | 60 | 26 | 25 |
| N08135 | 0 to 800(244) | 25 | 21 | 9 | 64 | 34 | 15 |
| N08535 | 0 to 800(244) | 19 | 16 | 14 | 47 | 30 | 22 |
| N08825 | 0 to 800(244) | 10 | 16 | 8 | 28 | 31 | 15 |
| N06255 | 0 to 800(244) | 10 | | 4 | 20 | | 10 |

*Exposure Period

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| A | Installed : | 03/28/84 | to | 10/27/84 | 213 days | C | Installed | 03/28/84 | to | 01/03/86 | 614 days |
| | Injected | 05/01/84 | to | 10/22/84 | 175 days | | Injected | 05/01/84 | to | 10/01/85 | 464 days |
| B | Installed | 11/28/84 | to | 01/03/86 | 401 days | | | | | | |
| | Injected | 11/28/84 | to | 10/01/85 | 289 days | | | | | | |

**Common name - no UNS Number assigned

**Table XII** Salton Sea Field IID 5
3½ x 0.254 in. (9 x 0.6 cm) wall, hangdown string surface to 1800 ft. (549 m)

| UNS Number | Inst Depth ft.(m) | Injection Time Days | Externa Optimistic Pit Rate (mpy) | Internal Optimistic Pit Rate (mpy) | Ext Crack |
|---|---|---|---|---|---|
| S31260 | 1764(538) | 562 | 21 | | CRACK |
| N08825 | 1738(530) | 562 | 1 | 12 | |
| N08825 | 1708(521) | 562 | 6 | | |
| S31803 | 1679(512) | 562 | 40 | 36 | CRACK |
| S31803 | 1650(503) | 562 | 39 | 22 | CRACK |
| S31803 | 1621(494) | 562 | 31 | 29 | CRACK |
| S31260 | 1589(484) | 562 | 23 | 16 | |
| S31260 | 1557(475) | 562 | 30 | 25 | CRACK |
| 2025* | 1528(466) | 562 | 10 | | |
| N08535 | 1375(419) | 562 | 0 | | |
| N08825 | 1346(410) | 562 | 0 | | |
| N08535 | 1005(306) | 562 | 10 | | |
| N08535 | 976(298) | 562 | 6 | 18 | |
| N08135 | 911(278) | 562 | 8 | 19 | CRACK |
| 2025* | 850(259) | 562 | 10 | 8 | |
| 2025* | 792(241) | 562 | 12 | | |
| S31260 | 759(231) | 562 | 11 | | CRACK |
| S31260 | 727(222) | 562 | 12 | 26 | CRACK |
| S31260 | 695(212) | 562 | 18 | | |
| S31803 | 665(203) | 562 | 12 | | CRACK |
| S31803 | 637(194) | 562 | 11 | | CRACK |
| S31803 | 608(185) | 562 | 16 | 32 | CRACK |
| S31803 | 679(207) | 562 | 14 | | CRACK |
| S31803 | 550(168) | 562 | 17 | | CRACK |
| S31803 | 522(159) | 562 | 11 | | CRACK |
| S31260 | 489(149) | 562 | 10 | 7 | |
| S31260 | 457(139) | 562 | 12 | | |
| S31260 | 425(130) | 562 | 1 | | |
| S31803 | SURF. | 346 | 47 | 220 | |
| S31260 | SURF. | 346 | 7 | 19 | |
| N08825 | SURF. | 346 | 23 | 71 | |
| N06255 | SURF. | 346 | 5 | 20 | |
| 2025* | SURF. | 346 | 6 | 15 | |
| N08135 | SURF. | 346 | 9 | 30 | |
| N08535 | SURF. | 346 | 2 | | |

*Common name - no UNS Number assigned

## Conclusions

1. The most obvious and pertinent conclusion that can be made from this data taken over a 2529-day (6 years +10 days) period is that short-term tests predict corrosion rates up to seven and a half times higher than the actual results after long-term tests. This overshadows all other conclusions.

2. As anticipated, the alloys having the higher combinations of nickel, chromium, and molybdenum have the higher resistance to corrosion.

3. The duplex stainless steels are susceptible to Cl SCC in this environment; however the cracking would most likely be eliminated if the alloys were used in the annealed condition.

4. Within the limitations of this test program, the brine chemistry did not seem to have an effect on corrosion rate. The brine temperature increases as the depth increases, and the pitting corrosion rates are greater at the higher temperatures.

5. There are several high nickel alloys that are virtually immune to pitting corrosion in these brines.

6. Based on short-term tests none of the alloys would be used. However, based on long-term (2220 days) all would be satisfactory. Therefore, initial pitting depth plus pitting rate must be considered in alloy selection.

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