Microbiologically Influenced Corrosion of Stainless Steels by Water Used for Cooling and Hydrostatic Testing

G. KOBRIN, Nickel Development Institute, Beaumont, Texas; S. LAMB, Nickel Development Institute, Huntington, West Virginia; A.H. TUTHILL, Nickel Development Institute, Blacksburg, Virginia; R.E. AVERY, Nickel Development Institute, Londonderry, New Hampshire; K.A. SELBY, Puckorius & Associates, Evergreen, Colorado

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Summary: Case histories from experience and the published literature illustrate factors which resulted in microbiologically influenced corrosion (MIC) of stainless steel piping, storage tanks and heat exchangers by waters used for hydrotesting, cooling and other purposes. Practices which will prevent or reduce potential for MIC, including material substitution, are discussed, along with efforts to heighten awareness of the problem.

INTRODUCTION

Corrosion of metals by micro-organisms, primarily bacteria, is a well known and ongoing problem in oil field production and transmission, natural gas transmission, pulp and paper industry, municipal and industrial wastewater treatment, power generation, metalworking and chemical process industries[1]. Documentation in the published literature from the early 1900s of cases of MIC of plain carbon steel and cast iron pipelines and other equipment by sulfate reducing and sulfur oxidizing bacteria is extensive[2, 3].

In recent years, numerous cases of MIC of austenitic (300 series) stainless steels (SST) in waters used for hydrotesting, cooling, settling, ballast, run-in, fire protection, etc. have been reported. Piping, storage tanks and heat exchangers along with other process equipment have been affected. Iron utilizing bacteria appear to be the dominating microbial species involved, although others have been implicated.

Industries hardest hit with high cost of repairs and replacements, plus lost revenues due to process downtime, are chemical process and nuclear power generation.

In virtually all cases, which are exceptions to the normally good performance of SST in natural fresh waters, stagnant or low water flow conditions prevailed for long periods of time, i.e.:

- Water not drained following a hydrotest or run-in procedure;
- Low water flow through horizontal pipelines and heat exchanger tube bundles;
- Water used as ballast during hurricane threats or for settling purposes in newly erected storage tanks;
- Water used for emergency situations such as fire protection, with little or no provision for continuous circulation;
- Water heel left in horizontal pipelines that were not sloped so low points between supports could drain readily.

In addition, almost without exception, the waters involved were raw (untreated) from fresh water sources such as reservoirs, rivers, bayous or wells, or fresh waters inadequately treated to prevent MIC.

Stagnant and low flow conditions promote attachment of bacteria to metal surfaces. Attachment is followed by colonization and formation of discrete deposits, starting as a film (biofilm) and frequently developing as a bulky deposit (biomound). Composition of the deposit is significantly different from and more corrosive than the bulk water environment. Thus, under-deposit corrosion occurs by formation of concentration cells and/or differential aeration cells. Localized attack manifests as:

- large, sub-surface cavities or tunnels, frequently at or adjacent to welds;
- as broad, open pits in crevices such as gasketed flanged joints;
- as broad, conical pits with terraced sides.

Penetration rates as high as one-eighth inch in one month for type 304L SST and in four months for type 316L SST have been reported".

Despite efforts to heighten awareness of MIC of stainless steels by technical societies and consortia such as NACE International, EPRI, MTI and others, failures continue to occur. Many could have been prevented by the simple practice of draining and drying immediately following a hydrotest or run-in procedure. Unfortunately, such practices have not been publicized as widely as believed, nor have appropriate warning statements appeared in consensus fabrication codes and standards. For example, only in the past few years have designers, constructors and operators of municipal potable water and wastewater treatment plants become aware of the problem, largely through seminars and publications by Nickel Development Institute consultants.

Following are case histories from the authors' experiences and published literature, highlighting factors which resulted in MIC of SST piping, storage tanks, heat exchangers and other equipment, in waters used for hydrotesting, cooling and other purposes. Methods used to inspect for and repair MIC damage and prevent recurrence are discussed. However, it is the desire for this paper that the information presented will receive widespread dissemination such that MIC failures will be prevented at the design, fabrication and

CASE HISTORIES - HYDROTEST WATER

CASE #1 - WELL WATER - TEXAS

Although this case history was reported more than 20 years ago,[5] it is repeated here because conditions leading to MIC were similar in many other cases, as were the biomounds and pitting characteristics. Unfortunately, much was lost in reproduction from the original brilliant color slides to black and white photos.

New production facilities at one plant site required austenitic SST, primarily 304L and 316L, for resistance to nitric and organic acids and to maintain product purity. Piping was shop fabricated, field erected and then hydrostatically tested. All of the large (50,000 gallons plus), flat bottom storage tanks were field erected and hydrostatically tested. During the early stages of construction, sodium softened but otherwise untreated well water (also used for boiler feed) containing 200 ppm chlorides was used for testing.

No attempts were made to drain the pipelines after testing. Tanks were drained, but then refilled to a depth of 2 to 3 feet for ballast because of a hurricane threat; the water was left to evaporate.

The problem surfaced when water was found dripping from circumferential butt welds in nominal 1/8 inch wall 304L and 316L piping approximately one and four months respectively after the hydrotest. Internal inspection showed pits in and adjacent to welds under reddish-brown deposits. Tank manways were uncovered and similar conditions were found. As shown in Figure 1, bulky, reddish-brown deposits were strung out along weld seams in the tank bottoms.

Figure 2 is a closeup of a typical mound-like deposit still wet with test water. The brilliantly colored deposit was slimy and gelatinous in appearance and to the touch, and measured 3 to 4 inches across. At one point during the investigation, a similar deposit on a weld which was covered with about 6 inches of water was thoroughly dispersed by hand. Twenty-four hours later, the "deposit" had returned in somewhat diminished form to exactly the same location!

Figure 3 shows a nearly dry deposit. After wiping the deposit clean, a dark ring-shaped stain outlining the deposit over the weld was noted, Figure 4. There was, however, no evidence of pitting or other corrosion, even after light sanding with emery. Finally, probing with an icepick revealed a large deep pit at the edge of the weld as shown in Figure 5.

Figure 6 is a radiograph of this weld seam showing the large pit which nearly consumed the entire width of the weld bead, plus several smaller pits.

A cross-section through a large pit in a 3/8 inch thick 304L tank bottom is shown in Figure 7.

The characteristics were a tiny "mouth" at the surface, and a thin shell of metal covering a bottle-shaped pit which had consumed both weld and base metal. There was no evidence of intergranular or interdendritic attack of base or weld metal respectively. However, pitted welds in a 316L tank showed preferential attack of the delta ferrite stringers, Figure 8.

This 316L tank was left full of hydrotest water for a month before draining. The bottom showed severe pitting under the typical reddish-brown deposits along welds. In addition, however, vertical rust-colored streaks, Figure 9, were found above and below the sidewall horizontal welds, with deep pits at the edges of the welds associated with each streak, Figure 10.

Analyses of the well water and deposits showed high counts of iron bacteria, Gallionella, and iron/manganese bacteria, Siderocapsa. Neither sulfate-reducing nor

sulfur-oxidizing bacteria were present. Deposits also contained large amounts (thousands of ppm) of iron, manganese and chlorides.

As indicated, nearly all deposits and pits were found at edges of, or very close to, weld seams. It is possible the bacteria in stagnant well water were attracted by an electrochemical phenomenon or surface imperfections -heat tint scale, oxide or slag inclusions, porosity, ripples, etc. - typically associated with welds. A scenario for the corrosion mechanism in this case was proposed:

- Attraction and colonization of iron and iron/manganese bacteria at welds;
- Microbiological concentration of iron and manganese compounds, primarily chlorides, because chloride was the predominant anion in the well water;
- Microbiological oxidation to the corresponding ferric and manganic chlorides, which either singly or in combination are severe pitting corrodents of austenitic SST;
- Penetration of the protective oxide films on SST surfaces which were already weakened by oxygen depletion under the deposits.

All affected piping was replaced in kind before the new facilities were placed in service. Demineralized water replaced well water as the hydrotest medium, and piping was drained and dried or placed in service immediately following the test. In the very few instances where demin water was inadvertently left in a pipeline for extended periods, inspection showed no evidence of MIC. The tanks were repaired by first sandblasting to uncover all pits, grinding out each pit to sound metal and welding with the appropriate SST filler metal. In lieu of re-hydrotesting, all repairs were examined for soundness with liquid dye penetrant. Piping and tanks have been in corrosive service for nearly 30 years to date with very few leaks, indicating the inspection, replacement and repair program was effective.

This scenario has been repeated numerous times in well waters and in surface waters all over the world. For example:

CASE #2 - RIVER WATER - IRAN

A chemical storage terminal consisting of several 304 SST and plain carbon steel tanks and a 2-1/2 mile 304 SST pipeline were constructed near the port of Bandar Shapur, Iran(". River water which was filtered but otherwise untreated was piped from about 100 kilometers inland for hydrostatic testing. A limited analysis of the water showed 320 ppm chlorides, 190 ppm calcium and pH between 8.0 and 8.6.

Following hydrotesting, the 8 inch x 0.109 inch wall pipeline was drained and blown with air but not checked for dryness. The tanks were drained but not dried out.

Observation of water dripping from a weld in the pipeline six weeks after hydrotesting led to extensive inspection by radiography which showed widespread pitting at circumferential butt welds only. Similar pitting was found at welds in the tanks. All pits were subsurface and cavernous, and associated with reddishbrown bio-mounds, virtually a carbon copy of Case #1. Once again, iron and/or manganese bacteria were suspect, although no microbiological analyses were made.

Piping was salvaged by replacing all welds plus an inch or two of base metal on either side, with new pipe. Tanks were repaired by sandblasting to uncover all pits which were then ground out to sound metal and rewelded.

CASE #3 - LAKE WATER - NORTH CAROLINA

Replacement of a steam generator at a nuclear power plant resulted in many systems out of service and/or in a wet layup condition for about one year[7]. Hydrotests performed prior to re-commissioning showed numerous leaks at circumferential butt welds in 304 SST service water piping. Inspection showed selective MIC of weld metal and weld heat affected zones (HAZ). Neither base metal nor longitudinal seam welds made in the pipe shop and solution annealed after forming, were affected.

Service water source was a man-made lake, an analysis of which showed only 3 ppm chlorides but a low pH of 5 and considerable organic material from decayed vegetation.

Temporary repairs were accomplished by welding 304L SST sleeves over the leaking welds. After re-commissioning, periodic radiographic examination showed progression of attack at the butt welds under the sleeves. Ultimately, all service water piping was replaced with a 6% molybdenum super austenitic SST welded with a high nickel-chromium-molybdenum alloy filler metal. This combination has shown excellent resistance to MIC. An additional requirement was removal of all surface oxides, including heat tint scale in the weld HAZs by grit or glass bead blasting followed by acid pickling.

CASE #4 - BAYOU WATER - FLORIDA

Two similar type 304L SST pipelines feeding raw water to a potable water treatment plant were hydrotested after installation with raw bayou water[8]. One line was placed in operation shortly after testing. The other line was left full for approximately 16 months, when weep type leaks were noted.

This line was then drained for inspection. External inspection showed the weeping leaks were in the lower half of circumferential butt welds that had been made in the field during installation. These circumferential welds were not pickled to remove the heat tint scale formed during welding. The longitudinal welds, made earlier in the shop, had been pickled to remove heat tint scale, and showed no signs of leaks.

The root cause of the weeps in the line left undrained was determined to be MIC in stagnant water despite pipe specs which required draining after hydrotesting. Placing the other line in operation after hydrotesting appears to have been sufficient to prevent MIC although the welding, heat tint scale, and other general aspects of the two lines were quite similar.

Additional cases with similar or identical characteristics are documented in the published literature, e.g. References 8-16.

How did these events occur? In all cases, a raw, naturally occurring fresh water used for hydrotesting, ballast, or wet layup was in stagnant contact with austenitic SST (304, 304L, 316, 316L) for long periods of time (weeks or months) at temperatures favorable for establishment and growth of microbiological deposits.

How could they have been prevented? In the case of hydrotesting, use of "clean" waters such as demineralized or steam condensate, or clarified, filtered and chlorinated potable waters are preferred over raw waters. In general, the cleaner the water, the less "food" there is for bacteria to grow and multiply. And regardless of the quality of the water, draining and drying and inspecting to assure dryness immediately following the test, i.e. within 3 to 5 days, virtually guarantees avoidance of MIC11[17].

In the case of ballasting or settling purposes, thorough cleaning after fabrication and use of "clean" waters are essential. Even so, periodic circulation, i.e. for an hour or two daily, plus monitoring by visual inspection should be employed throughout the time required for ballasting/settling.

In the case of wet layup, the easy answer is obvious - avoid wet layup! If wet layup cannot be avoided, the considerations for ballasting and settling apply as well.

Other considerations for prevention include the following:

- Make draining and drying immediately following a hydrotest (and monitoring to assure compliance) a requirement on all purchase orders, engineering specifications and fabrication procedures and drawings for SST piping, tanks and equipment.
- Avoid crevices where possible. They are preferred sites for attachment and growth of microbial colonies.
- Specify (and monitor to assure compliance) full penetration welds and removal of heat tint scale from weld HAZs by grinding, abrasive blasting, pickling or electropolishing. Susceptibility of heat tint scale to localized attack in numerous media including water is documented in the published literature[18-22].
- Chemically treat waters with biocides, dispersants, corrosion inhibitors and/or pH elevaters. Consult water treatment specialists for applicable treatments.

In the past 20 years, MIC of SST has been publicized widely and has been the focus of numerous research programs, as evidenced by the attached list of references (admittedly, only a partial listing). However, there continues to be a lack of awareness and concern to design around these issues. Attempts are in progress to address these issues.

One void has been the lack of statements in consensus fabrication codes and standards which provide users with guidelines for hydrotesting SST. The following paragraph appears in a Piping and Inspection Code, API 570, issued recently by the American Petroleum Institute[23]:

- Piping fabricated of or having components of 300 series stainless steel should be hydrotested with a solution made up of potable water (see note) or steam condensate. After testing is completed, the piping should be thoroughly drained (all high-point vents should be open during draining), air blown, or otherwise dried. If potable water is not available or if immediate draining and drying is not possible, water having a very low chloride level, higher pH (> 10), and inhibitor addition may be considered to reduce the risk of pitting and microbiologically induced corrosion.
  Note: Potable water in this context follows U.S. practice, with 250 parts per million maximum chloride, sanitized with chlorine or ozone.

Nickel Development Institute consultants are currently working with ASME subcommittees to have a similar statement incorporated in future revision of Section II, Part D, for reference by users of other

CASE HISTORIES - COOLING WATER

Prevention or mitigation of MIC of SST in cooling water systems poses considerations and challenges different from those involving waters used for hydrotesting, settling, etc. Obviously, draining and drying is an option only when the system must be shutdown for inspection, cleaning, equipment replacement or repairs.

Cooling water systems have evolved from:

- Once-through systems usually served by near-by rivers,
- To open recirculating systems with cooling towers for water conservation and mechanical and chemical treatments for control of corrosion and fouling,
- To the latter but with little or no treatment for environmental protection.

As a result, applications of SST for cooler and condenser shells, tube bundles and piping have increased because of inherent resistance to fouling and corrosion by natural fresh waters. For the most part, performance has been good, provided water velocities are high (i.e. greater than 6 ft./sec.), flows are continuous and proper design avoids zones where only partial wetting or alternate wetting/drying of SST surfaces occurs.

However, there have been some notable exceptions to good performance, which are covered by the following case histories taken from the published literature and experience. Hopefully, key learnings from these cases will heighten awareness of the problem such that MIC of SST by cooling waters can be avoided or at least mitigated in existing and new or proposed facilities.

CASE #5 - PROCESS CONDENSER

Two horizontal process condensers tubed with 304 SST failed by through-wall pitting from the cooling water (tube) side after only 13 months in service (24,25). Makeup water to the cooling tower serving the condensers was raw (unfiltered and unclarified) surface water containing a relatively high level of naturally occurring organic and inorganic substances. Initial treatment consisted of a chromate-zinc corrosion inhibitor, sulfuric acid for pH control, and gaseous chlorine for microbiological control. The chlorine treatment was replaced early in the program with bromochlorodimethylhydantoin because of safety concerns for handling the hazardous gas.

Examination showed severe biological fouling of the 304 SST condenser heads, channels, tube sheets, and tubes, as well as 2 to 3 ft. of biologically active sludge in the cooling tower basin. Fiberoptic video-probe inspection of internal tube surfaces after hydroblast cleaning showed random, discrete reddish-brown deposits or stains with pits inside the stains, Figure 11. A crosssection through a pitted area is shown in Figure 12.

Other observations:

- The heaviest concentration of deposits, pits and perforations was found in the coolest tube rows, tapering to slight and finally zero concentration in the hottest rows.
- Chemical analysis of deposits showed high concentrations of iron, manganese and chlorides.
- Sulfate-reducing bacteria were found in sludge in the cooling tower. Although no analysis was performed, both iron and manganese utilizing bacteria were believed to be present as well.

Conclusion? MIC; surprising, however, because of the relatively high water velocity of 8 to 10 ft./sec. through the tubes. It had been assumed that 5 to 6 ft. /sec. and greater is a "safe" flow velocity to prevent attachment and growth of microbiological colonies on metal surfaces. However, the cooling water in this condenser had a high organic and inorganic substance content which was concentrated further in the cooling tower, as well as a minimal treatment program, which contributed to the failure. Obviously, one cannot rely on water velocity alone to prevent MIC. Short-term remediation consisted of plugging all tubes that had pit depths of 80% of the tube wall or greater, thorough cleaning of the entire cooling water system, and implementation of an improved water treatment program.

The final long-term remedy was replacement with high nickel-chrome-molybdenum alloy tube bundles and water treatment with molybdate and orthophosphate anodic corrosion inhibitors coupled with zinc, polyphosphate, and tolytriazole; dispersants; and sodium hypochlorite, methylenebis (thiocyanate), and 2-(thiocyanomethylthio) benzotriazole for biological control.

Monitoring during operation and inspection during shutdowns have revealed no fouling nor any evidence of corrosion after eight years' service.

CASE #6 - UTILITY CONDENSER

Operation of a cooling water (lake) system serving a large horizontal utility condenser was interrupted for about 6 weeks[26]. Prior to startup, the 304 SST tubes were cleaned by high pressure water jetting and checked for leaks. Some 3 to 5% of the 28,000 tubes were found to be leaking slightly. Leakers were plugged and the condenser placed in service. Additional leaks occurred. The system was shutdown and retested, only to uncover more and more leakers. In fact, tube walls were popping open when a vacuum was pulled on the steam (shell) side!

Inspection showed severe attack from the water (tube) side, confined mostly to the bottom half and within four feet of the water inlet. Although the condenser was thought to be self draining, investigation showed the first few feet did not completely drain. Also, a considerable accumulation of decayed fish, mud and biological slime, a result of water intake screen deterioration, was found in the water inlet box. The water treatment program consisted of sodium hypochlorite for control of biofouling which was inadequate because of the excessive biomass accumulation.

Analyses of deposits indicated the presence of both slime-forming and sulfate-reducing bacteria, and sulfur as sulfide at pitted and perforated areas in the tubes. The combination of water holdup in the tubes during the outage with bacterial activity and an almost unlimited supply of nutrients resulted in severe corrosion in this short time period.

The unique repair procedure consisted of cleaning, sterilization and spray application of a quick-setting epoxy resin in the first 5 to 6 feet in each tube. The resin sealed perforations and developing pits, preventing leakage and further penetration. In addition, water intake screens were repaired and maintained, and water treatment was improved to control slime and silt deposition.

Successful applications for epoxy resin repair of MIC-damaged 304 SST heat exchanger tube sheets and water boxes are described in References 6 (p. 38-39 and p. 44 and 27).

CASE #7 - FLANGED CONNECTIONS

A river was the primary water source for a cooling tower serving a plant commissioned in eastern North Carolina[28]. As a result of environmental concerns, all water handling equipment and piping was fabricated from corrosion resistant alloys, mostly 304 SST, in lieu of corrosion inhibitor additions. Inspection of some equipment after 3 years in service showed severe crevice corrosion in and near flanged and gasketed joints. These corrosion sites, in low water velocity areas, were surrounded by voluminous bio-deposits, tan to brown in color and slimy to touch, Figure 13.

Corroded surfaces at the edges of gasketed surfaces were characterized as broad, open "gouging" type pits, bright and active under the deposits, Figure 14.

Adjacent corroded surfaces in contact with the asbestos gasket material were covered with black deposits which emitted hydrogen sulfide gas when treated with hydrochloric acid, Figure 15.

The brown bio-deposits were chemically and microbiologically analyzed. High concentrations of iron and silt were found, but chloride, manganese and sulfur compounds were either absent, or present in trace amounts only. Both slime-forming and iron bacteria were also found in these deposits, whereas sulfate-reducing bacteria were found only in the aforementioned black deposits.

These analyses were not too surprising in that the raw river water was high in iron and suspended and dissolved solids. Also, the high micro-organism counts were attributed to location of the plant downstream from a large paper mill. It was surprising, however, that chlorides were not involved, and that these bacteria survived the water treatment which consisted of continuous chlorination (0.5 to 1.0 ppm residual), caustic adjustment of pH to 6.5 - 7.5, continuous additions of a polyacrylate dispersant and a non-oxidizing biocide, quaternary amine plus tris tributyl tin oxide. The following corrosion mechanism was proposed:

1. Slime forming bacteria were attracted to, and colonized at, low water velocity sites such as gasketed joints;
2. The growing deposits trapped suspended solids rich in iron which harbored and sustained filamentous iron bacteria;
3. These aerobes consumed oxygen, leaving anaerobic conditions beneath the deposits which harbored and sustained sulfate-reducers, and shielded metal surfaces from biocide in the bulk environment;
4. The combination of oxygen depletion plus reduction of sulfates to sulfides destroyed the SST passivity, resulting in localized corrosion.

After considerable study and effort in water treatment, weld overlay repairs and alternate materials, all with only limited success, the solution to this problem was a combination of:

- Full face non-wicking hydrocarbon rubber (ethylene-epropylenediene terpolymer) gaskets in place of wicking asbestos types, and
- Filling in the pits and coating gasket surfaces with a proprietary metal-filled epoxy putty.

Additional cases of MIC of SST in cooling water systems are described in References 29-31.

Below are some key learnings from these and other cases which precluded successful applications of 300 series SST in cooling water systems:

Characterize the corrosivity and fouling potential of cooling water sources by appropriate chemical and microbiological analyses and corrosion tests, and select materials of construction accordingly. Design for and operate with high water flow rates, i.e. greater than 6 ft./sec.[32], but don't rely on high rates alone to prevent MIC. There are no substitutes for a good water treatment program with proper attention, control and monitoring, and sustained commitment by management and operations. When all else fails, consider replacements with MIC-resistant materials such as 6% molybdenum super austenitic SST, high nickel-chrome-molybdenum alloys, titanium or bi-metallics.

CASE #8 - BEHAVIOR OF WELDED SST IN LONG TERM EXPOSURE TO FRESH LAKE WATER

This last case,[8] although not directly associated with hydrotest or cooling water, is included as an example of excellent long term performance of welded SST in a relatively clean raw fresh water. Analysis of the water is shown in Table 1.

During the design stage of a dam on a river in California, the State Department of Water Resources realized that large sloped trash racks would be required to handle wide fluctuations in water level in the ensuing lake. Evaluation of coated carbon steel with and without cathodic protection vs. SST resulted in specification of cold worked (half hard) 304 SST for both racks. SST was determined to provide the lowest life cycle cost over the projected 50 to 100 years life of the dam and power plant.

The trash racks, each 680 feet long by 46 feet wide (Figure 16) were installed in 1968 and thoroughly inspected in 1991. There was no evidence of general corrosion, pitting or crevice attack on any component, including welds and fasteners (Figures 17-19). Surfaces covered with bulbous mounds, determined by analysis to be deposits of algae, and silt deposits were cleaned and examined for evidence of MIC; none was found. The only maintenance required during this period of 23 years was installation of bracing to solve a localized flow-induced vibration problem. It was concluded that the racks will remain in essentially their original condition for the projected 100 years life.

SUMMARY

These cases show that problems with MIC of SST in fresh waters, which, as stated previously, are exceptions to the normally good performance of SST in this service, can arise from a number of sources. Fresh waters high in dissolved and suspended solids and organic material are particularly susceptible. Other sources include improper operational practices and controls; inadequate water treatment; water contamination; inadequate design and fabrication practices; improper startup practices; and others. A summary of practices for prevention of MIC as discussed throughout this paper, follows:

- For hydrotest, ballast, settling and run-in procedures, use the cleanest water available, i.e. demineralized, steam condensate, potable, etc.
- Regardless of water quality, drain, dry and inspect to assure dryness immediately following a hydrotest, i.e. within 3 to 5 days. Make this a requirement on purchase orders, engineering specifications, fabrication procedures and drawings.
- Eliminate or at least minimize crevices in fabrication.
- Specify (and monitor to assure compliance) full penetration welds.
- Avoid heat tint scale in pipe weld HAZs with good inert gas backup procedures. Where unavoidable, remove heat tint scale by grinding, abrasive blasting, pickling or electropolishing.
- Slope horizontal pipelines and heat exchangers to make them self-draining.
- Use non-wicking gaskets at flanged connections.
- Design for highest possible water flow rates, i.e. in excess of 6 ft./sec.; however, don't rely on high flow rate alone to prevent MIC.
- Develop and implement a MIC-prevention water treatment program with proper attention, control and monitoring, and sustained commitment by management and operations.
- For severe/critical service, consider upgrades to more MIC-resistant materials like the 6 % super austenitic SSTs, high Ni-Cr-Mo alloys, and titanium.

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Table 1

Chemical Analyses of Water & Sediment

Constituent	*Symbol*	*Water 9/18/92*	*Water 10/15/91*	*Sediment 5/14/92*
Silica	SiO_2	11	-	-
Calcium	Ca	31	8	4
Magnesium	Mg	1	4	-
Sodium & Potassium	Na+K	10.1	1**	61.0
Iron	FE	0.07	0.0	28.4
Copper	Cu	0.06	-	-
Manganese	Mn	0.0	0.0	0.5
Carbonate	CO_3	0.0	-	0.0
Bicarbonate	HCO_3	104.0	-	178.0
Chloride	Cl	0.5	3	37.0
Sulfate	SO_4	7	2	5.0
Nitrate	NO_3	11	0.0	-
Total Hardness	$CaCO_3$	78	-	-
Total Alkalinity	$CaCO_3$	85	-	-
Total Dissolved Solids		125	-	-
pH @ 23.3°C		6.9	8.0	7.4
Elect. Cond.	Micromhos	193	-	-
Resistivity	Ohm-Cm	5181	-	6451
Total Bacteria		-	$2.7x10^3$*	

Results are reported in ppm unless noted otherwise.

* Organisms/ml of water

** Potassium only

Figure No. 1
Mound-like deposits along weld seam in bottom of Type 304L SST tank after several months exposure to well water at ambient temperature.

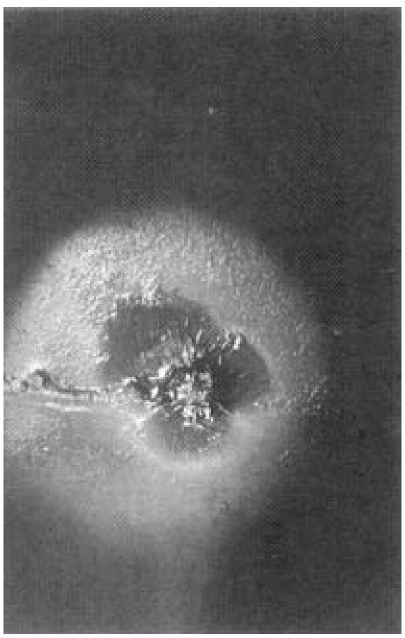

Figure No. 2
Closeup of a wet deposit

Figure No. 3
Closeup of a dry deposit.

Figure No. 4
After removal of deposit, showing ring-shaped stain around the weld.

Figure No. 5
Large pit at edge of weld in Figure 4 disclosed by probing with icepick.

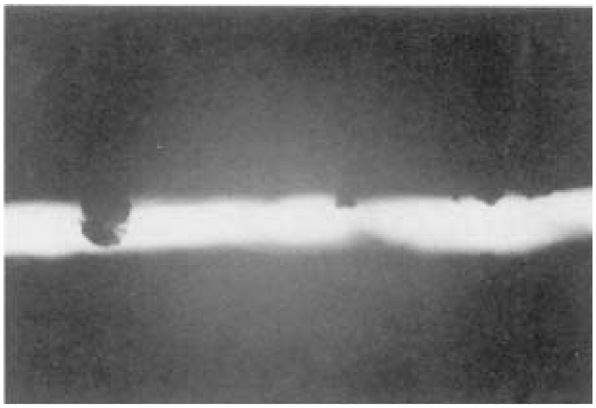

Figure No. 6
Radiograph of a pitted weld seam in a 304L tank.

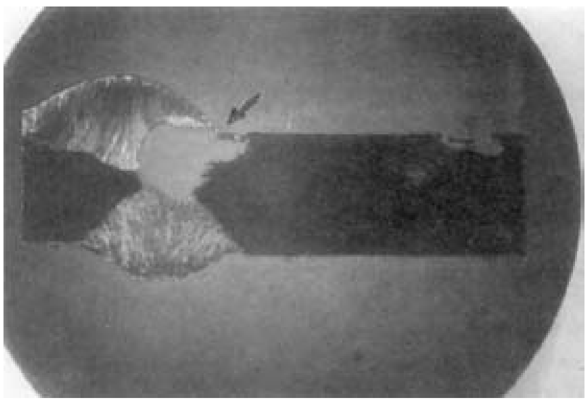

Figure No. 7
Metallographic mount of a cross section through a pitted weld seam. Arrow points to small "mouth" on surface.

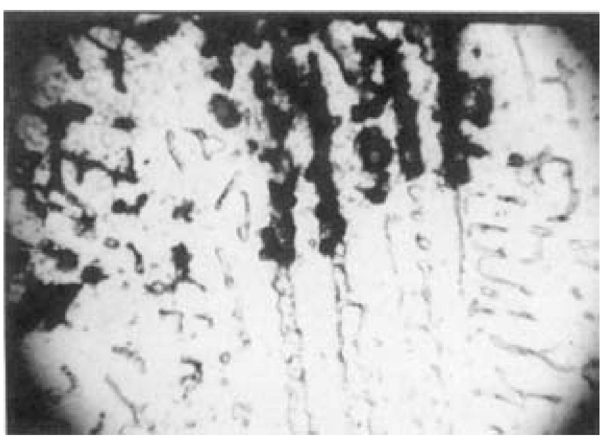

Figure No. 8
Photomicrograph showing preferential attack of delta ferrite stringers in 316L weld metal. 250X

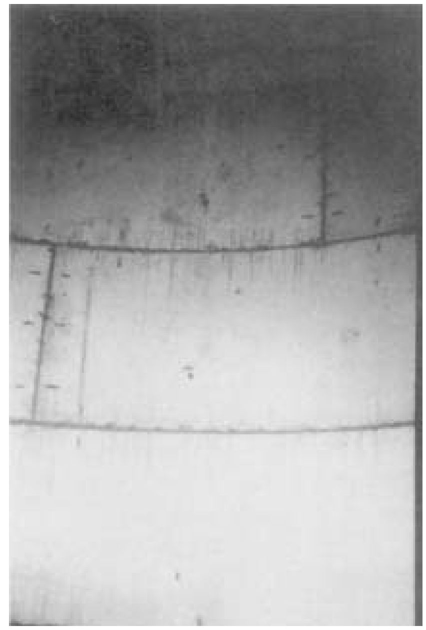

Figure No. 9
Rust-colored streaks normal to horizontal weld seams in sidewall of 316L tank.

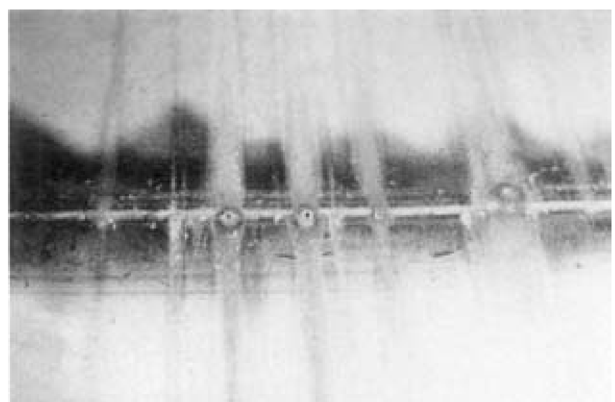

Figure No. 10
Closeup of streaks shown in Figure 9.

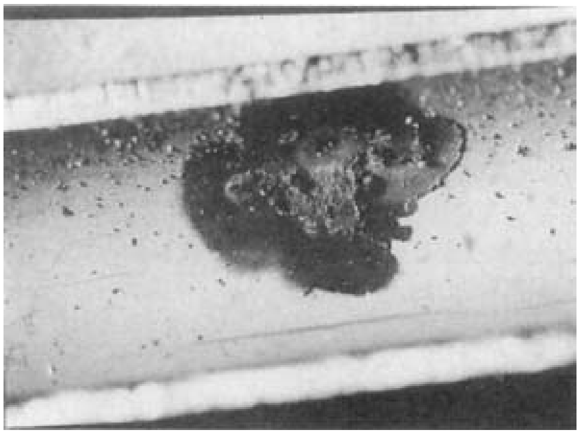

Figure No. 11
Reddish-brown deposit/stain and pits on internal surface

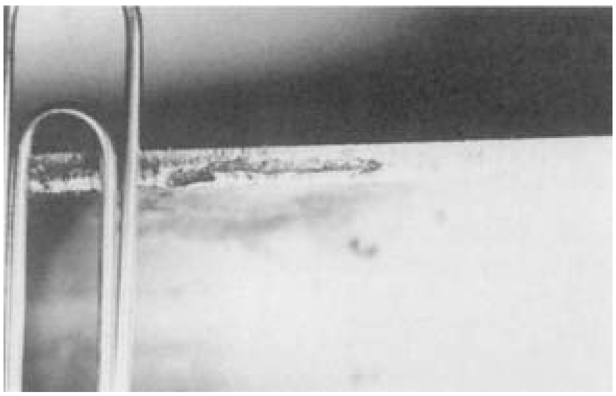

Figure No. 12
Cross-section through a pit in 304 SST tube showing sub-surface "tunnel".

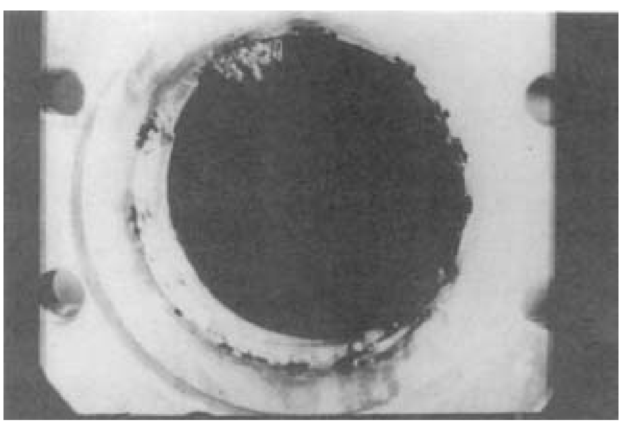

Figure No. 13
304 SST flange showing one remaining deposit. Numerous similar deposits were washed away when the joint was opened. This flange had been covered with an asbestos gasket and a SST blind flange.

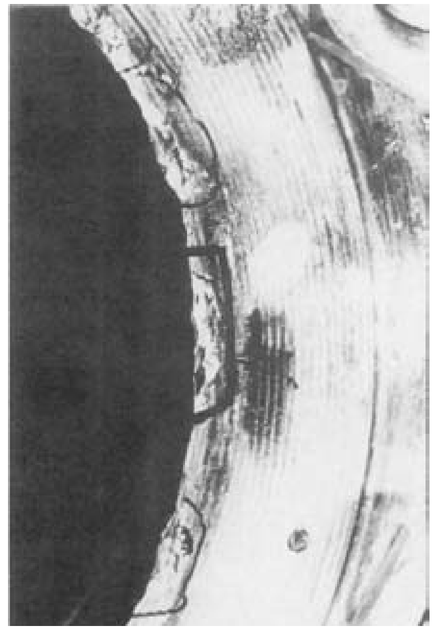

Figure No. 14
Closeup of flange in Figure 13 after cleaning. Shows open "gouging" corrosion that was directly under deposits.

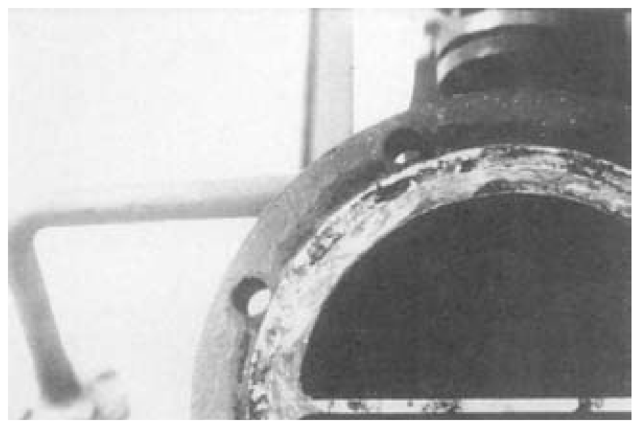

Figure No. 15
304 SST condenser head flange showing areas of crevice corrosion, some filled with black FeS, on gasket surface. Bacteria deposits covered the inside edge of the gasket in these areas.

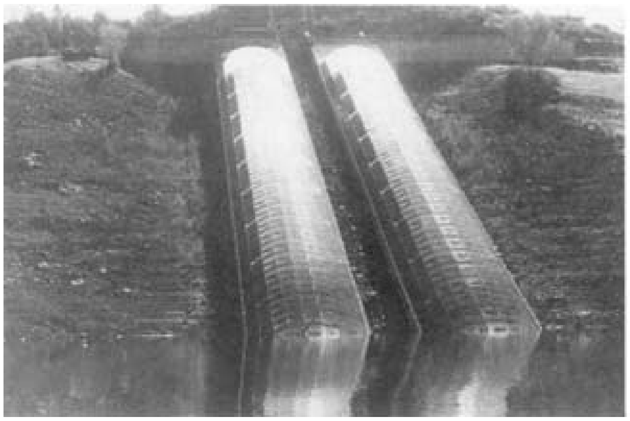

Figure No. 16
304 SST trash racks on a fresh water lake in California.

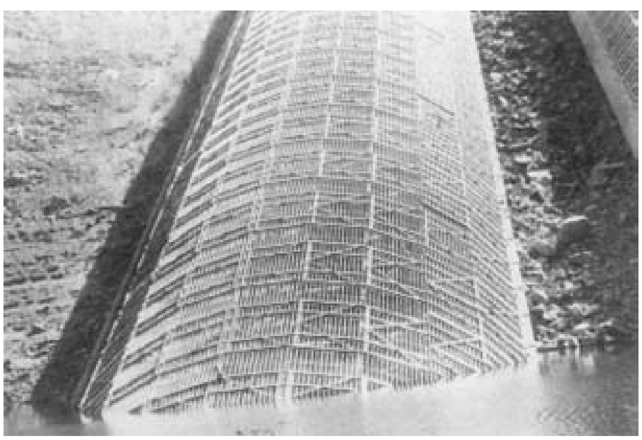

Figure No. 17
Closeup view of a trash rack showing half-hard 304 SST components.

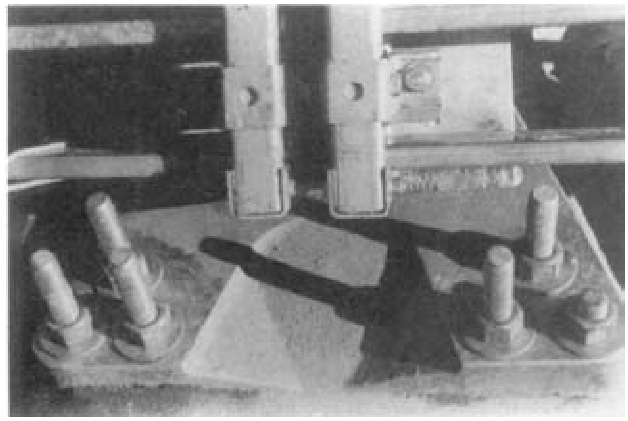

Figure No. 18
Trash rack weld; no evidence of corrosion.

Figure No. 19
Trash rack fasteners; no evidence of corrosion.