



Project Summary

Copper-Induced Corrosion of Galvanized Steel Pipe

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An investigation was conducted to determine the causes of rapid pitting failure of galvanized steel pipe used in consumer plumbing systems. The presence of copper in water and the character of the galvanized steel pipe were factors examined in detail.

Pipe manufactured in Korea, Australia, and in the United States was compared for pipe structure and zinc coating. The pipe manufactured in Korea by electrical resistance welding had a pronounced weld seam, whereas U.S. and Australian pipes manufactured with butt welding had only small or nonexistent seams. Furthermore, the zinc coating on the Korean pipe failed to meet the weight of coating standard (1.8 oz/ft²) in 11 of 14 samples. Examination of the iron/zinc interface on the Korean pipe revealed possible sites of poor adhesion of the coating to the base metal.

In pilot testing, increasing copper concentrations (from 0.0 to 5.0 mg/L) produced increased corrosion activity on the pipe surface, as measured by greater deposition of scale, calcium, iron, zinc, and copper. Also, the ratio of iron surface to zinc surface area increased. Other factors such as the mode of exposure and the addition of citrate had no measurable impact. The corrosion activity measured by scale formation was greatest on the Korean pipe, followed by the U.S. and Australian. Rapid pitting of the sort observed in several southern California homes did not occur under any of the conditions tested.

This Project Summary was developed by EPA's Water Engineering Research Laboratory, Cincinnati, OH, to

announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

Over the past two decades, several occurrences of accelerated pitting corrosion of small-diameter, galvanized steel pipe have been investigated. Pitting is a term used to describe a form of corrosion wherein a concentrated attack occurs at small sites, often perforating the pipe. Pitting typically causes leaks and destroys a pipe's usefulness long before the end of its rated economic life. Recent episodes of this type of corrosion have taken place in large housing tracts where widespread pitting failure of household plumbing occurred within 5 years of construction.

Several factors have been alleged to cause or enhance the corrosion problem, including the presence of copper in the water, the surface character of the pipe, base metal and/or zinc composition and integrity, and water temperature and quality. A common factor in failures that have occurred in a variety of water sources, building types, and in both hot and cold waters is the presence of copper in the water. A number of investigations into housing tract failures seem to bear out this hypothesis. Table 1 summarizes the conditions observed and failures investigated by several studies. As the table shows, copper in the water was associated with each case, either through its use as an algicide or through dissolution of copper piping. The variety of water sources included local well water, Owens River water with low total dissolved solids

Table 1. Summary of Copper-Related Corrosion of Galvanized Steel Water Pipes

Affected Units	Year	Source of Water Supply	Source of Copper	Copper Concentration in Water (mg/L)	Surface Copper Concentration on Pipe (mg/dm ²)	Corrective Action Recommended	Comment
Apartment Houses (9)	1961	Local wells and Colorado River	Reservoir algicide	N/A*	12-25	Install new copper pipes. Discontinue the use of CuSO ₄ algicide. Reduce dissolved O ₂ by blending.	Pipe failure through pitting corrosion in 18-36 months.
Lodge (75 units)	1962	Local wells	Reservoir algicide	N/A	11-26	Reduce reservoir aeration. Reduce intake of highly mineralized water. Reduce hot water temperature.	Hot (140-160°F) water system pipe failure through pitting corrosion in 18 months.
Motel (21 units)	1965	Local wells	Dissolution of copper pipe	0.01-0.08	0.84	Reduce velocity of circulation. Avoid mixing of copper and iron piping systems. Continue polyphosphate treatment.	Circulating hot (150°F) water system. Red water and iron particles from pitting corrosion in 18 months.
Apartment Hotel (44 units)	1968	Owens Valley	Copper tubes in heat exchangers	0.05	9.6	Replace corroded galvanized steel hot water piping with copper system.	Circulating hot (130°F) water system. Pipe failure through pitting corrosion in 108 months.
Tract Homes (39 units)	1973	Local wells	Reservoir algicide	0.029-0.063	N/A	Adjust pH to positive Langelier Index. Aerate supply to remove hydrogen sulfide. Cease use of polyphosphate inhibitor. Discontinue CuSO ₄ .	Pipe failure through pitting corrosion in 24-36 months.
Tract Homes (100+ units)	1973	Colorado River	Reservoir algicide	0.1-0.5	N/A	Replace galvanized pipe with copper pipe. Use greater care in application of copper sulfate-citric acid complex as algicide.	Pipe failure through pitting corrosion in 12-24 months.
Tract Homes (500+ units)	1977	Colorado River	Reservoir algicide	0.01-0.4	15-34	Replace galvanized pipe with copper pipe. Use greater care in application of copper sulfate-citric acid complex as algicide.	Pipe failure through pitting corrosion in 12-24 months.
Tract Homes (340 units)	1978	Colorado River & Northern California	Reservoir algicide	0.3-4.3	2.5-12.3	Replace galvanized pipe with copper pipe.	Pipe failure through pitting corrosion within 24-60 months; 90% of leaks in horizontal pipes, 72% of leaks in hot water pipe.

*N/A means not analyzed.

(TDS), and Colorado River water with high TDS. The latter four cases shown involved housing tracts with up to 500+ units affected.

To investigate further the factors that are important in this type of corrosion, a pilot-scale facility was designed, constructed, and operated in which the effects of copper dose, pipe type, mode of exposure of the pipe to test solutions, and water quality could be tested over a period of 3 years. During that period, ancillary bench and laboratory studies were also carried out on the effects of pipe structure, iron-zinc polarity reversal, and pipe surface anomalies. The full report contains findings made in each of these areas. Readers interested in obtaining the complete report with color illustrations should contact the senior author for details.

Results and Discussion

The first phase of this investigation concentrated on determining the characteristics of the galvanized steel pipe structure and the zinc coating. The results of this phase are summarized in Table 2. With respect to the elemental composition of the base metal, emission spectroscopy determined that the base steel used by each of the three manufacturers (Australian, Korean, and U.S.) was satisfactory for trace elements in the steel. The Korean pipe had a lower carbon content than either the Australian or the U.S. pipe, but this fact should not affect its corrosion potential. Microscopic examination of a cross-section of Korean pipe revealed a pronounced weld seam, probably produced during electrical resistance welding, whereas the U.S. and Aus-

tralian pipes had only a small or nonexistent seam, respectively. The weld seam on the Korean pipe produced a discontinuity in the otherwise smooth interior surface.

The zinc coating on pipe samples from each of the three manufacturers was examined by energy dispersive X-ray (EDX) to determine the elemental composition of the zinc/iron layers at the interface. No abnormal components were found in any of the three layers, which consisted primarily of zinc and iron with trace amounts of lead. The thickness of the zinc coating was determined by three tests: the weight of coating test (ASTM A90-81), the Preece test (ASTM A239-73), and microscopic examination. The Korean pipe failed to meet the weight of coating standard (1.8 oz/ft²) in 11 of 14 samples. The Aus-

Table 2. Summarized Characteristics of Galvanized Steel Pipe Structure and Coating

Characteristic	Pipe Manufacturer		
	Australian	Korean	U.S.
Pipe Structure			
Base metal chemical composition	Satisfactory	Satisfactory	Satisfactory
Fabrication anomalies	None	Pronounced weld seam	Slight weld seam
Pipe Coating			
Thickness			
Weight of coating test	Uniform coating All samples >1.8 oz/ft ²	Uniform coating 11 of 14 samples <1.8 oz/ft ²	Variable coating All samples >1.8 oz/ft ²
Preece test	Uniform, smooth coating 2 to 3 dips for 10 of 14 samples	Blemishes 1 dip for 12 of 14 samples	Variable coating More than 2 dips for 12 of 14 samples
Microscopic test	Average coating	Thin coating	Thick coating
Chemical composition	Satisfactory	Satisfactory	Satisfactory
Adhesion	Satisfactory	Separation zone between base metal and coating	Satisfactory

tralian and U.S. pipes met this standard in all instances. In the Preece test, 12 of the 14 Korean pipe samples required only one dip in copper sulfate solution to reveal the base metal. Ten of the 14 Australian pipe samples required two to three dips to reveal the base metal, and 12 of the 14 U.S. pipe samples required more than two dips to reveal the base metal. As would be expected from the weight of coating test and the Preece test, the microscopic examination of

three samples revealed that the total zinc coating on the Korean pipe was the thinnest. Furthermore, each of the three layers that make up the zinc/iron interface (the delta, zeta, and eta layers) were thinner for the Korean pipe than for the Australian or U.S. pipe. From these three tests, a picture emerged of the Australian pipe with a uniform, smooth coating of the proper thickness, the Korean pipe with a uniform thin coating containing occasional blem-

ishes, and the U.S. pipe with a more variable but thick coating containing occasional blemishes and irregularities.

Subsequent etching and microscopic examination of the iron/zinc interface on all three pipes revealed sites where the zinc coating adhered poorly to the base metal on the Korean pipe. In some instances, a thin gap appeared to exist between the zinc coating and the underlying base metal.

Because premature pitting failure of

Table 3. Results of Bench-Scale Testing for Potential Reversal and Unusual Corrosion at Pipe Surface Anomalies*

Characteristic	Water Source					
	Control Water+	State Water Project	Colorado River Water	Pasadena Tap#		
1. Potential Reversal	Reversal occurred	No reversal	No reversal	No reversal		
	Distilled Water Plus Constituent§					
	Control	CuSO ₄	Citrated CuSO ₄	Cu Plated		
2. Water Quality Impact						
Pipe Surface Anomalies						
Control	None	None	None	None		
Acid etched	None	None	None	None		
Acid etched and drilled	Localized	Localized	Localized	Localized		
Drilled	Localized	Localized	Localized	Localized		
	Pasadena Tap Plus Constituent#					
	Control	CuSO ₄	Citrated CuSO ₄	Azurite	CuSO ₄ with Azurite	Citrated CuSO ₄ with Azurite
3. Pipe Surface Anomalies						
Control	None	None	None	Zinc loss	Zinc loss	Zinc loss
Acid etched	None	None	None	Zinc loss	Zinc loss	Zinc loss
Drilled	None	None	None	Zinc loss	Zinc loss	Zinc loss
Black iron	Generalized	Generalized	Generalized	Generalized	Generalized	Generalized

* All tests used Korean galvanized pipe samples except as noted.

+ Distilled water plus 110 mg/L HCO₃, 10 mg/L SO₄, 10 mg/L NO₃.

Local groundwater source.

§ The same tests but with salts added to create high TDS (2000 mg/L) water showed no localized corrosion.

galvanized pipe has been demonstrated to occur as a result of potential reversal between the iron and zinc, bench-scale testing was conducted to determine whether such potential reversal was occurring at the elevated temperatures of hot water systems. Additional tests were run to determine whether unusual corrosion would occur at specially created pipe surface anomalies. The results of the bench-scale testing are summarized in Table 3. As shown, potential reversal occurred in the water solution matched to that used by earlier investigators. However, for water supplies currently available in southern California (the two surface water sources, State Water Project and Colorado River water, and one groundwater source, Pasadena tap water), no potential reversal occurred over the temperature range and time interval tested.

Pipe surface anomalies were created on Korean galvanized steel pipe by acid etching and/or by drilling a small hole into the zinc layer. While localized corrosion was enhanced in the drilled areas, the acid etching of the zinc surface had no measurable impact. Similarly, the addition of copper sulfate or citrated copper sulfate to the solution did not noticeably increase the localized corrosion over that recorded for the control, which consisted of distilled water. Copper plating portions of the sample (both clean and clean with acid etching) had

little effect. Similar results were recorded when Pasadena tap water was substituted for distilled water. Azurite crystals placed on the bottom of the interior pipe surface did accelerate the loss of zinc from the surface. In general, the addition of copper sulfate or citrated copper sulfate did not have corrosion impact that was obviously different from that of the control solution without these chemicals.

Pilot plant testing was undertaken to determine the impact of five major variables on the corrosion rate of galvanized steel pipe: copper dose (0.0 to 5.0 mg/L), pipe manufacturer (Australian, Korean, U.S.), initial mode of exposure (static, flowing), water quality (Colorado River water, State Water Project), and complexing agent (citrated, uncitrated). Table 4 summarizes the results of this pilot plant testing.

Pipes from all three countries were exposed to Colorado River water for up to 20 months and to increasing copper doses from 0.0 to 5.0 mg/L. The effect on the galvanized steel pipe was determined by measuring the extent of scale, calcium, iron, zinc, and copper deposition on the interior pipe surface. In addition, the iron-to-zinc ratio was determined for the interior surface area after the scale had been removed. Irrespective of the pipe manufacturer, increased copper doses invariably led to increased scale and increased iron-to-zinc

ratios. Increasing the exposure time from 8 to 20 months generally resulted in overall increased scale deposition, but the amount of calcium in the scale showed no difference. The iron-to-zinc ratios also showed no consistent increase with increased exposure time. Finally, the mode of exposure (static versus flowing test solution) made no apparent difference on the extent of corrosion.

As with the Colorado River water experiment, pipes from all the manufacturers exposed to State Water Project water with increasing doses of copper produced increasing deposition on the interior pipe surface. As the copper dose increased from 0.0 to 5.0 mg/L, the scale, calcium, iron, zinc, and copper deposition on the interior pipe surface similarly increased. The iron-to-zinc ratio of the exposed surface also increased. The addition of 2.5 mg/L of citrate to the solution containing 5.0 mg/L of copper produced no apparent difference compared with the solution containing only the 5.0 mg/L of copper. Finally, the mode of exposure (static versus flowing test solution) showed no difference in terms of the extent of corrosion.

The results from 8 months of exposure to Colorado River water were compared with those from 7 months' exposure to State Water Project water for all the pipe manufacturers. At each copper

Table 4. Results of Pilot Plant Testing of Galvanized Steel Pipe Corrosion*

Item tested and test conditions	Effects on Pipe					
	Scale Deposition	Calcium Deposition	Iron Deposition	Zinc Deposition	Copper Deposition	Surface Exposed Fe/Zn
1. Colorado River Water Exposure (all pipe manufacturers)						
Increase Cu dose (0.0 to 5.0 mg/L)	Increase	Increase	Increase	Increase	Increase	Increase
Increase exposure time (8 to 20 months)	Increase	Unchanged	Increase	Increase	Increase	Variable
Mode of exposure (static vs flowing)			No apparent difference	No apparent difference		
Section of pipe (top or bottom)			No apparent difference			
2. State Water Project Exposure						
Increase Cu dose (0.0 to 5.0 mg/L)	Increase	Increase	Increase	Increase	Increase	Increase
Addition of citrate (2.5 mg/L to 5.0 mg/L Cu)			No apparent difference	No apparent difference		
Mode of exposure (static vs flowing)			No apparent difference			
3. Comparison of Colorado River water (8 months' exposure) with State Water Project water (7 months' exposure)						
Increase Cu dose (0.0 to 5.0 mg/L)	CRW > SWP ⁺	CRW > SWP	CRW > SWP	Variable	CRW < SWP	CRW ≥ SWP
4. Comparison of Pipe Manufacturers						
Increase Cu dose (0.5 to 5.0 mg/L)	K > US > A [#]	K > US > A	US > K > A	K > US > A	K > US > A	Variable

* All tests were carried out using the pipe from Korea, Australia, and the United States.

⁺CRW = Colorado River water; SWP = State Water Project water.

[#]K = Korea; U.S. = United States; A = Australia.

dose, the scale formed in the Colorado supply was greater than the scale formed in the State supply, a result expected from the more positive Langelier Index of the Colorado supply. The extent of zinc removal and deposition varied among the different pipe manufacturers with no consistent pattern, whereas the extent of copper deposition was always less from the Colorado supply than from the State supply. The iron-to-zinc ratios for the exposed surface area indicated that the Colorado supply was at least as aggressive in removing the zinc layer as the State supply, and in some instances, it was more aggressive.

With respect to the different pipe manufacturers, the Korean pipe generally produced the greatest scale, calcium, zinc, and copper deposition, whereas the U.S. pipe deposition was between that of the Korean and Australian samples. The U.S. pipe appeared to produce the greatest iron deposition, with the Korean pipe between the U.S. and Australian samples. The iron-to-zinc ratio of exposed surface area varied between the different pipe manufacturers with no consistent pattern.

The pilot plant testing demonstrated increased corrosion activity associated with two variables—increasing copper dose (0-5 mg/L) and pipe manufacturer (Korean pipe showed the most corrosion and Australian the least). This corrosion activity was evidenced by the removal of zinc and iron from the pipe surfaces and the formation of deposits containing calcium, iron, zinc, and copper. Pits that did occur on the pipe surfaces were scattered over the entire surface of the pipe and were generally superficial, never becoming deep enough to warrant depth measurement. The 2 years of pilot testing produced no deep isolated pits of the type that originally motivated the study. Perhaps a longer test period or more severe test conditions (such as longer exposure time in hot water) would have resulted in eventual pitting failure, but such results are not clearly predictable.

Conclusions and Recommendations

Given past observations of the influence of copper on galvanized steel pipe and our findings regarding the differences in pipe quality among Korean, U.S., and Australian manufacturers, these results are unexpected. Based on the galvanic series, copper is known to

be aggressive to less noble metals such as zinc and iron, and pitting failure of galvanized, recirculating hot water systems as a result of copper contamination is quite common. The large-scale pitting failures that were found in houses during field studies and that precipitated this study appeared to match the failures of the recirculating hot water systems. However, our testing of copper in both pilot- and bench-scale facilities, coupled with a host of other variables, did not demonstrate this phenomenon. Use of Korean pipe with its substandard zinc coating did not produce this result either. Thus the recommendations below are directed toward re-evaluating field occurrences of this type of corrosion and attempting to determine whether flaws in the experimental designs of the pilot plant and bench tests precluded expected results.

1. Retain samples from bench and pilot testing for further analyses. Of specific concern is whether the rapid scale build up on the pipe during the pilot testing interfered with the action of copper on the pipe surfaces.
2. In this same context, a comparison is warranted of the form of copper precipitated on the pilot-plant pipes with the copper found on pipes that have failed in the field in housing tracts and in recirculating hot water systems. Possibly pilot-plant conditions resulted in a precipitate that is less intensively corrosive than that observed under these other conditions.
3. More thorough scrutiny should be provided for the conditions under which failures in housing tracts have occurred and may occur in the future. A group of experts from several fields such as chemistry, metallurgy, and corrosion should examine any future occurrences and concur as to the significant variables.

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Marvin Gardels is the EPA Project Officer (see below).

The complete report, entitled "Copper-Induced Corrosion of Galvanized Steel Pipe," (Order No. PB 86-208 717/AS; Cost: \$16.95, subject to change) will be available only from:

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