Comprehensive Evaluation of Aluminized Steel Type 2 Pipe Field Performance

G. E. MORRIS and L. BEDNAR

ABSTRACT

Results of 30-year field tests in 14 states, conducted by Armco on Aluminized Steel[TM] Type 2 and galvanized steel culvert pipe, have revealed a consistent and pronounced superiority of aluminized steel. The results were tabulated from 54 test sites where the materials were usually exposed together under climatic conditions ranging from very wet to very dry. Comparison of the field performance of the two materials revealed considerable differences in the basic coating corrosion-control mechanism. The aluminized steel coating imparted significantly better resistance to general corrosion and localized perforation. Analyses of pipe condition and environmental factors at every site resulted in usage guidelines for both materials. The results for aluminized steel indicated tolerance for substantially more severe environmental conditions. The technique by which the guidelines were derived has promise for predicting service life for the two materials as well.

Aluminized Steel[TM] Type 2 is a recently introduced material for drainage pipe applications, but it has a long history of field testing, which began in 1952. There were two separate test programs. One was a limited research program in which short lengths of pipe were joined in long strings and exposed in certain types of environments. The other program was a comprehensive one in which full-length pipes were installed at numerous sites by state and county highway departments in 20 states. In all field testing the primary goal was the comparison of performance between aluminized and galvanized steel, which is the standard accepted metallic pipe material. Aluminized steel displayed a pronounced superiority over galvanized steel in a series of inspections conducted at various times.

In 1982 a comprehensive evaluation was begun of all 30-year-old pipes in the highway department program. The results have revealed the significant long-term superiority of aluminized steel, which has been consistent in a wide variety of exposure conditions. This evaluation is the subject of this paper. Studies on basic corrosion behavior, pipe material performance, and pipe material environmental limitations are discussed herein.

COMPARATIVE BASIC CORROSION BEHAVIOR OF ALUMINIZED AND GALVANIZED STEEL

The reasons for the superiority of aluminized steel in field tests became evident during studies on pipe behavior and environmental conditions, as well as from published literature on basic aluminum and zinc corrosion behavior. The superiority of aluminized steel arises from differences in the manner by which long life is achieved.

Zinc Versus Aluminum

Zinc coatings are inherently highly corrodible in water and wetter soils. Fortunately, in most of these environments, galvanized steel performs well because corrosion is greatly retarded by the formation of protective-barrier scales, which are produced mainly by deposits of calcium and magnesium hardness salts (1,pp.98-100;2,pp.100-118;3,pp.4-132). Zinc corrosion products contribute to scale formation. Durability problems that occasionally arise are all associated with conditions that hinder barrier-scale development. Among the more significant of these are

1. Softer, nonscaling waters, which also contain corrosive-free acidity (CO_2 and organic acids);
2. Water or soil with excessive amounts of corrosion-accelerating salts (Cl^-, SO_4^{-2}, NO_3^-), which interfere with scale formation;
3. Turbulent, aerated waters that erode barrier scales and provide plentiful dissolved O_2, which accelerates corrosion; and
4. Moving, abrasive bedload that wears away scale and uncorroded metal.

Aluminum coatings are more durable than zinc. This is because of the formation of a thin, passive aluminum oxide film that is more protective than the scale on zinc (3,pp.4-9;4,pp.197-198,200-201). The film forms in both hard and soft water and is resistant to corrosion by SO_4^{-2}, NO_3^-, CO_2, O_2, and organic acids. The film also is resistant to erosion by turbulent water. In addition, if the film is damaged or removed by intermittent harsh abrasive or chemical influences, it is immediately repaired or reformed after the disappearance of these influences.

Behavior of Aluminized Steel Coating

The aluminized steel coating is a two-layer, metallurgically bonded composite with advantageous composite corrosion behavior. The coating consists of a protective layer of aluminum and an underlying layer of aluminum/iron alloy (Figure 1). The aluminum

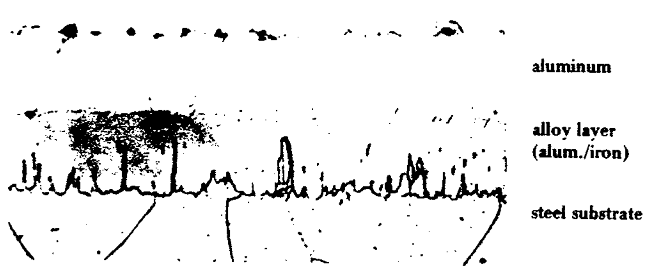


FIGURE 1 Modern aluminized steel microstructure (325X).

layer exhibits all of the aluminum corrosion-resistance characteristics noted previously.

Although the aluminum layer is subject to slow pitting corrosion, pitting is retarded by the alloy layer, where it tends to grow laterally (Figure 2). The alloy possesses high corrosion resistance and acts as a second line of defense against general corrosion in addition to acting as a pit arrestor.

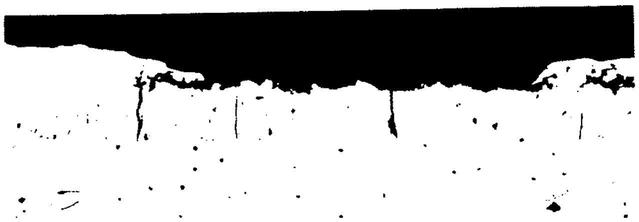


FIGURE 2 Arrest of pitting at alloy layer on pipe in service for 30 years.

On initial exposure at an aluminum layer pit, the alloy layer generates a protective, rust-colored scale that can stain the surrounding aluminum surface and give a false negative impression of coating condition (Figure 3). The alloy is extremely hard and imparts enhanced abrasion resistance under mildly or moderately abrasive conditions. Fabrication cracks that occur in the alloy layer are plugged and sealed by an initial reaction with the environment, so that substrate corrosion at crack bases is greatly retarded (Figure 4). Eventually the alloy will be undermined and deteriorated at coating pit sites, but the time required is considerably greater than that required for total loss of galvanized steel coatings.

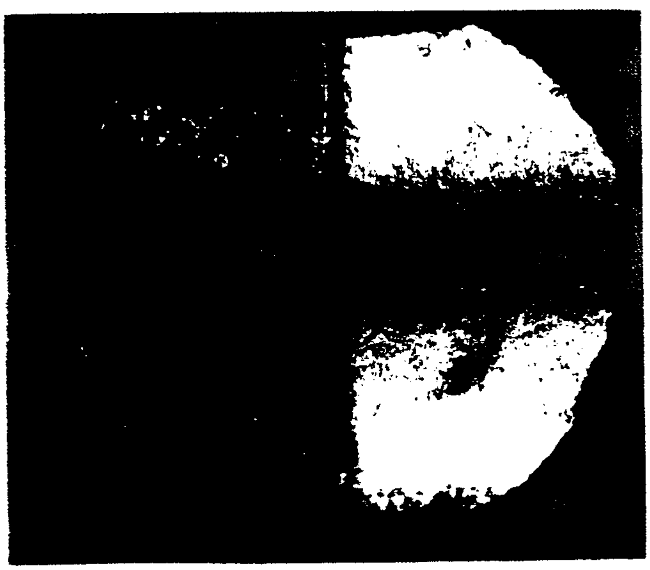


FIGURE 3 Aluminized steel coating intact beneath rust-stained invert surface.

Alloy cracking has only a minor effect on coating performance, judging by field-test results. In the 30-year-old field-tested material there was pronounced alloy cracking during corrugating, especially in corrugation valleys where lateral cracking occurred (Figure 5). The superiority of the old material over galvanized steel was achieved despite such cracking. A residual skin of alloy remained fully bonded to the substrate, even if lateral cracking caused spalling of the upper alloy portion (Figure 6).

Modern aluminized steel has improved coating ductility, and there is less cracking overall. At times there is no cracking tendency at all in corrugation valleys.

Galvanic Protection of Aluminized and Galvanized Steel

The aluminized steel coating affords more effective protection for exposed steel substrate than galvanized steel does, judging by the behavior of uncoated edges in 30-year field tests. Under conditions in which galvanized steel pipe edges and zinc-coated inverts have been destroyed, there has been little corrosion damage to aluminized steel edges after 30 years of service. Furthermore, on modern welded seam HEL-COR[R], the weld seams on aluminized steel have demonstrated superior performance to that of galvanized steel weld seams in more corrosive waters of lower scaling tendency (Figure 7).

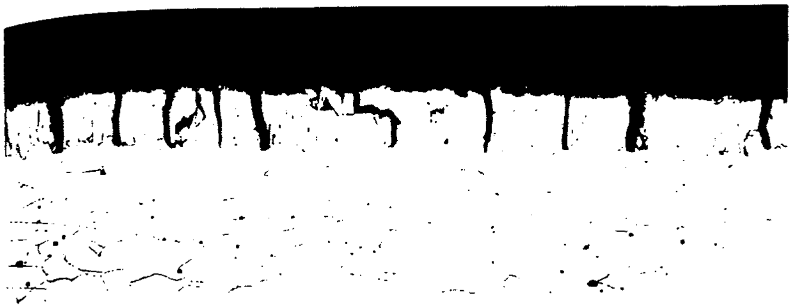
The basic limitation on performance of sacrificial zinc coatings is that in environments of low scaling tendency there is little restraint of coating corrosion. Galvanic protection is high, but coating life is shortened, so that exposed base metal is soon deprived of all protection. Coating loss occurs first around bare areas because coating corrosion there is accelerated by galvanic protection (Figure 7). However, in recommended environments for galvanized steel, coating corrosion is suppressed by formation of protective barrier scales (5,pp.637-639;6,p.204). In such environments galvanic protection of the steel substrate is achieved at extremely low coating corrosion rates.

FIELD-TEST PERFORMANCE

Program Background

In 1952 Armco supplied riveted pipe for installation at 137 culvert sites on secondary roads in 20 states for the highway department program. In most cases galvanized and aluminized steel pipe lengths were installed together in series. In 1982 Armco initiated a thorough program of locating and evaluating pipes from all those sites that were still functioning. By November 1983 a total of 58 sites had been located in California, Colorado, Idaho, Illinois, Iowa, Kansas, Michigan, Mississippi, New Mexico, Ohio, Oklahoma, Texas, Utah, and Washington. The other sites were lost because of urbanization, abandonment, or new construction. Of the 58 located sites, 4 have not been fully evaluated because of accessibility problems.

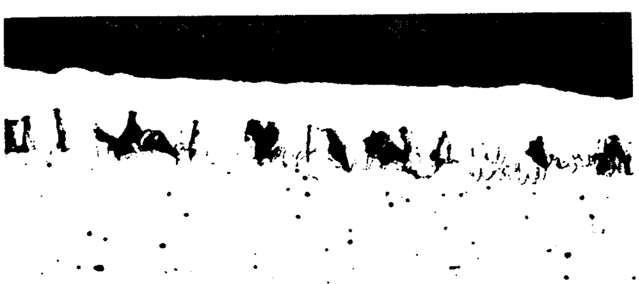
A wide variety of environmental conditions ranging from very wet (>50 in. of rain per year) to very dry (<15 in. per year) were represented. At several sites pipes were continuously or generally wet. A few sites were characterized by swampy, mucky conditions, including persistent stagnant water, and many were characterized by continuous or near-continuous water flow. Some were wet only during each rainfall or for a day or so afterward. Some pipes were subject to pronounced silting, and others were subject to little or none. There were widely varying



Thirty-year-old material at a site where the aluminum layer has been removed, exposing the alloy layer. Although cracks are uncovered, there is no steel substrate corrosion. (200X)

Steel substrate protection is the result of crack plugging with alloy-reaction products. The crack on the right and the central crack are sealed and still dormant, whereas the crack on the left has begun to permit slow substrate corrosion. (1,500X)

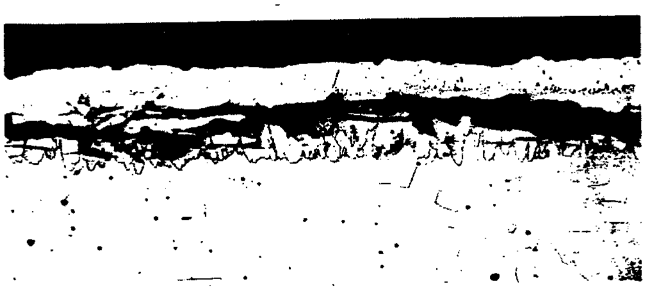
FIGURE 4 Protection of the steel substrate by the cracked alloy layer on 30-year-old field-exposed material.



30-year-old aluminized steel

Modern aluminized steel

Alloy Cracking on Corrugation Crests



30-year-old aluminized steel

Modern aluminized steel

Alloy Cracking on Corrugation Valleys

FIGURE 5 Comparative alloy condition at corrugations on old and modern aluminized steel (192X).

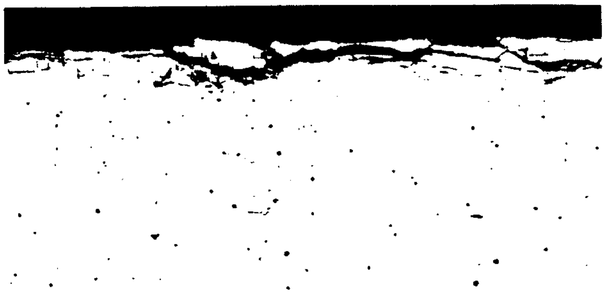


FIGURE 6 Protection of the steel substrate by alloy layer with lateral cracking. Thirty-year-old material at a site where the aluminum layer has been removed locally is illustrated. Although cracks are uncovered over a substantial area, there is no alloy layer spalling and no steel substrate corrosion.

pipe and terrain slopes. Site soils included many loamy, clayey, and sandy types.

The evaluation included an assessment of environmental conditions through analysis of water and soil specimens. Environments were classified as severe, moderate, or mild in accordance with their effect on galvanized steel and their water chemistry, soil pH, and resistivity. A list of water and soil pH and resistivity values obtained is given in Table 1.

Pipe evaluation also included cleaning, visual inspection, and photographing of inverts. Metal trepan specimens of 1.5 to 2 in. in diameter were taken from the invert at or near the six o'clock position, near the pipe ends in both aluminized and galvanized steel pipes. Where possible, pipe ends were uncovered at the crown, and then cleaned and photographed to permit evaluation of soil-side performance. Additional information about soil-side performance was obtained by acquiring trepans from the three or nine o'clock positions on aluminized and galvanized steel at locations remote from pipe ends. At three sites pipes were excavated because of special circumstances and a complete evaluation of soil-side behavior was possible.

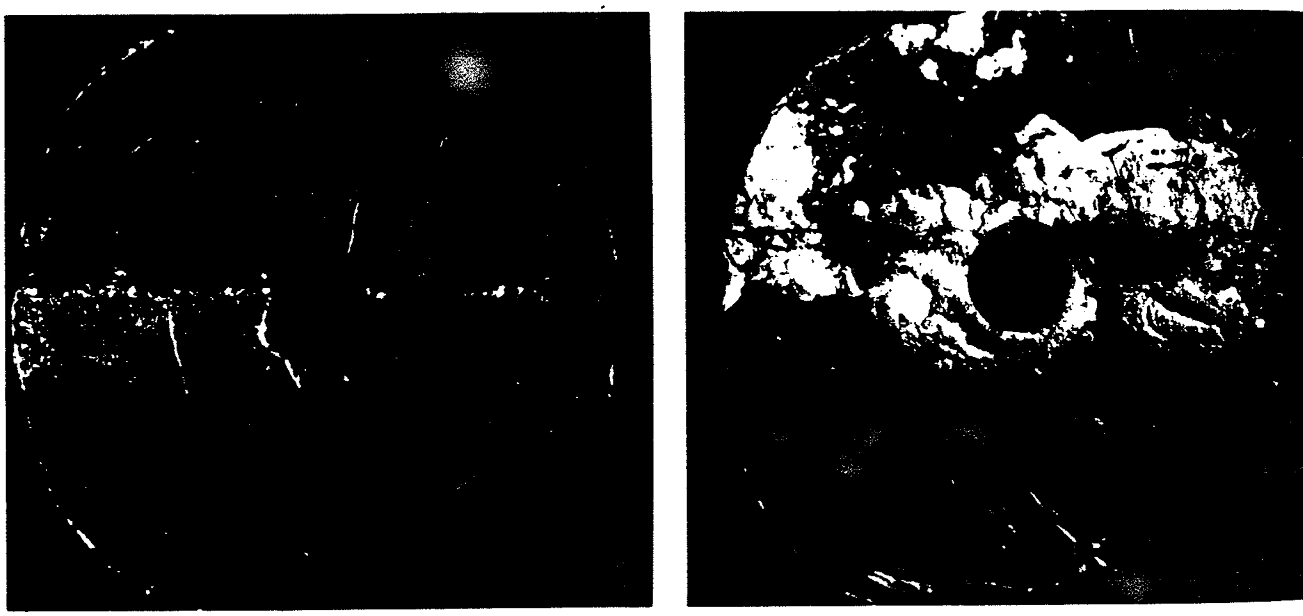
Evaluation Results

Aluminized steel was considerably superior to galvanized steel in resistance to both overall attack and localized corrosion on both the invert and the soil side at every evaluated site where no extreme conditions existed. All results are summarized generally in the following sections.

Invert Behavior

1. Severe environments: At sites with severely corrosive water, galvanized steel pipe inverts were destroyed or thinned to the point of extensive perforation. By contrast, at these sites there was only mild attack to the aluminized steel, which was in the form of small coating pits (Figure 8). In some cases pits extended into the steel substrate to a minor degree. There were sometimes general rust-colored stains on the aluminized steel inverts, which might appear to be indicative of general coating loss. However, invert cleaning and microscopic examination indicated that the coating was intact overall, as shown in Figure 3. A total of 18 sites were designed severe. Thirteen of these had aluminized and galvanized steel pipes. Five had only aluminized steel, and water chemistry was comparable to that at other sites where galvanized steel corrosion was severe.

2. Moderate or mild environments: At sites with moderately or mildly corrosive waters, there was typically overall loss of coating and minor penetra-



Aluminized steel

Galvanized steel

FIGURE 7 Comparative weld-seam condition in the inverts of aluminized and galvanized steel pipe exposed together in Maine. The pipes are connected in series. Inverts constantly are exposed to severely corrosive nonscaling water. The aluminized steel shows no discernible deterioration of the weld or of the coated surface. The galvanized steel pipe shows loss of the zinc coating throughout the invert and scattered pitting in the substrate. The extruded weld metal on galvanized steel is attacked and the substrate attack around the weld is due to earlier coating loss.

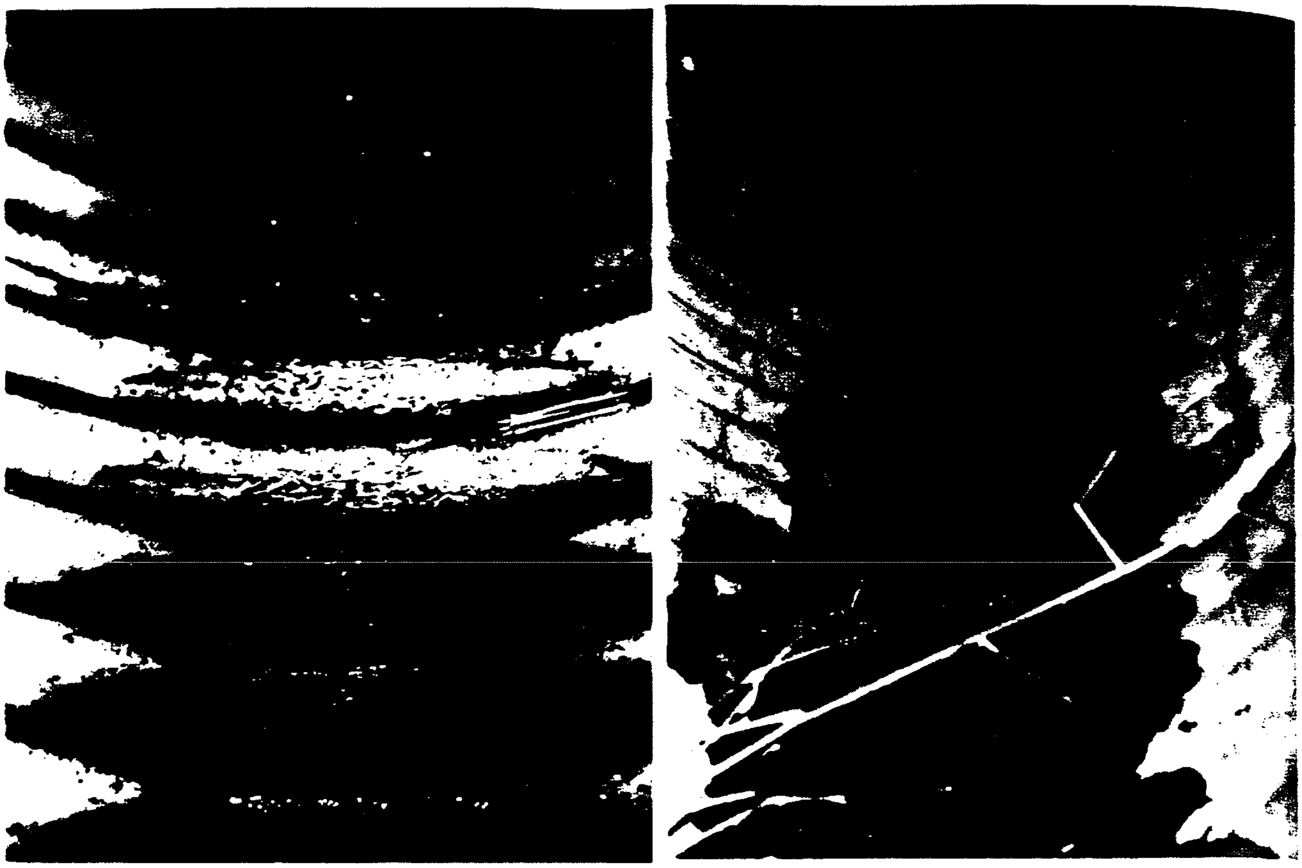
TABLE 1 Minimum Resistivity and pH Data

			Soil		Water	
State	County	Original Site No.	Resistivity (ohm-cm)	pH	Resistivity (ohm-cm)	pH
Illinois	Morgan	1	2,500	6.75	2,700	7.94
	Sangamon	2	2,200	6.95	6,570	7.04
	Morgan	3	2,500	7.27	1,540	8.10
	Greene	4	3,600	7.39	260	7.90
	Adams	6	2,600	7.10	3,300	7.24
Kansas	Decatur	7	2,550	7.56	-	-
	Dickinson	10	1,500	6.95	-	-
	Pratt	11	3,600	5.34	-	-
Iowa	Marshall	13	2,300	7.24	1,885	7.15
		14	2,800	7.29	-	-
		15	2,300	7.32	-	-
		16	1,800	7.14	-	-
		17	2,800	7.11	-	-
		18	2,300	7.12	1,470	7.73
		19	2,900	7.17	1,370	7.15
		20	2,400	7.56	1,450	7.02
	Jefferson		2,350	7.48	1,020	7.70
Colorado	Fairplay	23	7,100	7.41	-	-
	Mesa	24	1,150	7.06	245	7.30
	Weld	26	1,050	7.21	-	-
California	Napa	34	1,600	5.90	3,030	6.97
	El Dorado	37	18,000	5.60	-	-
	Placer	45	27,000	4.85	1,560	6,25
	San Benito	46	3,300	5.20	2,440	7.27
	Marin	48	2,600	6.70	2,175	6.50
Utah	Piute	57	8,106	7.90	-	-
Michigan	Van Buren	63	1,250	7.52	2,000	7.38
Ohio	Delaware	70	1,800	7.46	2,270	7.40
Mississippi	Tate	81	4,700	5.15	11,110	5.55
	Benton	82	5,600	4.25	-	-
	De Soto	93	7,700	4.65	-	-
Texas	Montgomery	96	6,000	4.90	3,450	7.18
Oklahoma	Oklahoma	103	4,700	7.39	-	-
		104	4,600	7.31	-	-
		105	4,600	6.96	-	-
		106	11,400	7.34	-	-
		107	4,500	8.29	-	-
Missouri	Carter	108	2,900	7.62	2,630	-
		109	4,400	6.54	-	-
	Livingston	110	1,900	7.42	830	7.01
		111	1,750	7.34	2,000	7.09
	Lafayette	112	1,700	7.26	2,440	7.38
		113	2,150	6.52	3,075	7.11
	Nodaway	114	2,100	7.49	1,850	6.72
		115	1,100	6.95	4,255	6.55
		116	2,000	7.48	2,040	6.82
		117	2,400	7.36	2,630	7.10
		118	1,500	7.12	2,060	6.70
		119	1,500	7.04	1,540	6.80
Washington	Clallum		17,000	4.70	43,500	4.60
	Snohomish		1,850	4.00	11,110	6.60
	San Juan[a]	A	-	6.0	-	-
		B	1,400	5.7	1,600	7.1
		C	700	6.0	1,300	7.0
		D	1,600	6.2	1,750	6.7
New Mexico		29	3,200	7.65	-	-

[a]Data are for Waldron Island, taken from Washington State Department of Transportation Report 173, September 1981.

tion of the steel substrate of the galvanized steel inverts. Penetration ranged from a few mils in milder environments to 10 to 30 mils in moderate environments. By contrast, for the aluminized steel after 30 years of service, there was typically only pitting of the aluminum layer; the pitting was arrested at the alloy layer. Invert rust staining occurred in some cases, but several inverts were essentially free of staining.

3. Abrasive environments: Several sites had obvious abrasive conditions in that invert attack occurred primarily on corrugation crests and upstream sides. Abrasion was mild at most of these, but was moderate at one site and severe at one other.



Aluminized steel type 2 Galvanized steel

FIGURE 8 Comparative invert performance of aluminized and galvanized steel pipe exposed together for 30 years in a severe environment in Missouri (saline 830 ohm-cm resistivity water).

In all but the one case involving severe conditions, aluminized steel exhibited superior invert abrasion resistance when compared with galvanized steel. Aluminized steel superiority was always associated with the hard alloy layer. At mild sites the soft aluminum layer was preferentially removed over large areas on the upstream sides of corrugation crests, whereas the underlying hard alloy layer was intact and unaffected. For the galvanized steel there was total coating loss and significant substrate penetration at corrugation crests.

At the one moderate site the galvanized steel invert was destroyed in one section and there were severe overall thinning and localized perforations on the upstream side of corrugation crests elsewhere. For aluminized steel at this site there was loss of the aluminum and alloy coating layers on the upstream sides of crests, but only slight substrate penetration (Figure 9).

At the one severe site the corrugation crests in the inverts were destroyed for both galvanized and aluminized steel.

Soil-Side Behavior

No sites had severe soil-side influences on galvanized or aluminized steel, but aluminized steel behavior was superior in every case where there was some soil-side corrosion of the galvanized steel. Typically, in soil-side areas above the waterline there was only loss of the galvanized steel coating; there was no substantial penetration of the steel substrate. Below the waterline there was a tendency toward more severe soil-side corrosion of galvanized steel, and substantial, though not important, substrate penetration often occurred there (Figure 10).

At two locations where there were no galvanized steel pipes for comparison, there was more significant substrate penetration of the aluminized steel at small coating pit sites. These pits were about 10 mils deep in one case and 18 mils deep in the other.

Sites with Interference Complications

There were four sites where the performance of aluminized steel was not typical because of complicating interference conditions. At one of these sites poor coating quality, in the form of severe lateral alloy cracking, caused widespread spalling of the coating. At two sites evidence indicated severe intermittent chemical contamination. At the fourth site there was severe abrasion.

EFFECT OF ENVIRONMENTAL PARAMETERS ON THE DURABILITY OF ALUMINIZED AND GALVANIZED STEEL

Field-test results led to a determination of pipe material performance as a function of controlling environmental parameters. This is highly desirable from the standpoint of comparing the environmental limitations of different materials and predicting material performance. The problem is the identifica-

Aluminized steel type 2 Galvanized steel

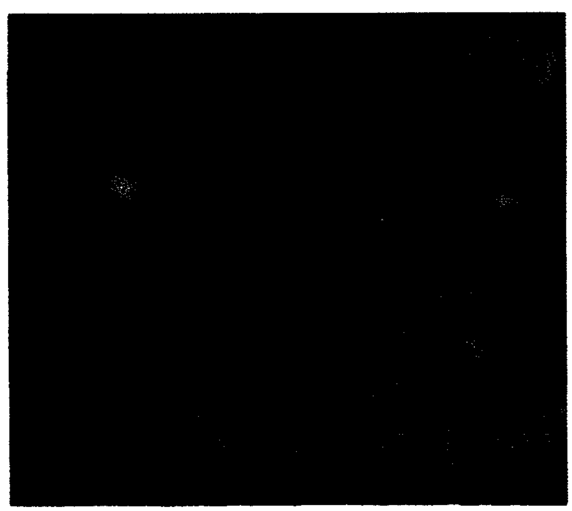
FIGURE 9 Invert specimens from a moderately abrasive site in Placer County, California. Aluminized steel has lost all coating on upstream sides of corrugations, but shows little substrate penetration. Galvanized steel shows loss of all coating and about 75 percent penetration of the substrate generally, plus some localized small perforations. There was one section in which galvanized steel shows invert destruction. Galvanized steel is about 7 years younger than aluminized steel at this site (late addition).

tion of controlling environmental parameters and their interrelationships. Armco simplified the matter by using primary parameters only. Armco investigators then determined whether a realistic, highly consistent result could be attained.

The primary simplification is the assumption that any corrosion problems will result mainly from water-side conditions in the invert. Studies by Armco and various highway departments, among others, indicate that this is generally the case for galvanized steel (7-13). The results indicate that corrosion that affects galvanized steel structural integrity is likely to occur sooner on the invert than on the water side. There are certain exceptions, the most significant being cases involving high-salinity soils in dry climates. However, most earlier corrosion problems that occasionally occur on galvanized steel are the result of water-side corrosion, and Armco concentrated on defining the conditions that give rise to such problems.

Of course, soil parameters do control water parameters, but it is best to concentrate on water because soils are highly heterogeneous. Local soil chemistry is often vastly different from water chemistry because the water traverses a variety of soil conditions over a watershed of any significant size.

Corrosion of zinc and steel in water is usually dependent on dissolved oxygen, and oxygen tends to accelerate corrosion in direct proportion to its concentration, up to a point. A certain minimum amount of inhibiting salt ions (including Ca^{+2}, Mg^{+2}, HCO_3^-, and to a lesser extent SiO_3^{-2}) is needed to form protective barrier scales, or corrosion at higher O_2 levels will be severe (1,2). Thus soft high-resistivity surface water is usually quite



Aluminized steel type 2 Galvanized steel

FIGURE 10 Comparative soil-side behavior below the waterline level in Snohomish County, Washington. Galvanized steel shows loss of coating and moderate substrate penetration, whereas aluminized steel shows mild spotty attack with no significant substrate penetration.

corrosive to galvanized steel. Dissolved CO_2 and other sources of H^+ (above certain levels) accelerate corrosion by retarding scale formation and by lowering the pH. Certain salt ions, including Cl^-, SO_4^{-2}, and NO_3^-, are inherently corrosive, and these ions along with Na^+ and K^+ all interfere with protective scale formation. At higher levels of inhibitors, increased levels of all accelerators can be tolerated. Low-resistivity water also will be low in corrosivity when inhibitors are predominant, and high in corrosivity when accelerators are predominant.

It is necessary to know the prevalent water chemistry at a pipe site in order to classify site corrosivity. Chemistry changes somewhat throughout the year, but a degree of stability exists as a result of stable prevalent climatic conditions and soil strata composition. These two predominant factors determine whether surface water will be hard or soft, saline or nonsaline, and alkaline or acidic.

The time of sampling is important with regard to rainfall. Dilution of groundwater discharge with softer surface runoff occurs during and shortly after rainfall periods. The prevalent water chemistry at normally wet sites can be obtained only by sampling at least a few days after the last rainfall.

Some galvanized inverts are exposed to more severe conditions near the high watermark because of contact with well-aerated and diluted softer mixtures of runoff with groundwater. This is true, even though the time of water contact above the low waterline is usually much less than that below. Time of contact is usually of lesser importance in the lowest invert areas, which are subject to continuous or prolonged contact with undiluted groundwater that is usually scale forming. Protective scale in this area tends to persist through periods of rainfall dilution.

Occasionally, in wet climates, pipes that are wet only during and shortly after rainfall periods are severely corroded, despite limited contact time. This is because of the relatively severe conditions produced by aerated, softer runoff that is extremely low in scaling salt ions because of little groundwater input.

Once a suitable water specimen is obtained, concentrations of the necessary ions can be determined reasonably well by a few simple quick titration and meter tests. A total hardness titration gives Ca^{+2} + Mg^{+2}, and a total alkalinity titration gives HCO_3^- and some of the SiO_3^{-2}. A pH measurement gives H^+ that, in conjunction with total alkalinity, gives excess or free CO_2, which is usually more useful. A conductivity measurement gives an approximate measure of the total dissolved salt content that, in conjunction with the total inhibitor content (total alkalinity + total hardness), gives an idea of the total accelerator salt content.

The total scaling tendency of a water is established reasonably well by a determination of alkalinity, hardness, and H^+ (1,pp.29-34). By adding alkalinity and hardness values and subtracting H^+ (in the form of free CO_2, which is usually the primary source of H^+), the scaling tendency is quantified in a relative sense. Plotting the result on one axis of a graph and conductivity (or resistivity) on the other axis permits graphing of pipe performance as a function of the primary water parameters. Thus zones of satisfactory and unsatisfactory performance can be determined.

By using this approach on sites in the two aluminized and galvanized steel field-test programs and sites from other galvanized-steel-only field-inspection programs Armco constructed Figure 11 for performance guidelines. One-time water samplings, taken at least 2 days after the last rainfall at normally wet sites, were used, and samples included 81 waters from 16 states.

Satisfactory performance was designated as less than 30 mils penetration over sizable invert areas after exposure for 30 years. This would be expected to result in a minimum service life of 50 years for 16-gauge material.

Line AB in Figure 11 marks the limit of increasingly severe conditions that galvanized steel normally can tolerate while providing satisfactory performance. Increasing severity is encountered from top to bottom and from left to right, and crossing line AB in either direction results in encountering problematic conditions. Traversing the graph from left to right shows the effect of constantly increasing corrosion-accelerator salt concentrations (Cl^-, SO_4^{-2}, and so forth) at a fixed level of total inhibitors and free CO_2; line AB marks the limit of accelerator salt tolerance at this inhibitor/CO_2 level for galvanized steel. Traversing the graph from top to bottom shows the effect of decreasing inhibitor and increasing free CO_2 at a fixed accelerator salt level; line AB marks the limit of inhibitor decrease or CO_2 increase tolerable at this accelerator level for galvanized steel.

Consistent results with a rather well-defined boundary between satisfactory and unsatisfactory performance for galvanized steel were found. There was some overlap at the boundary, most likely caused by somewhat nonrepresentative water chemistry in a few cases, but the results are generally consistent and realistic in defining the suitability of galvanized steel.

The anticipated detrimental effects of water softness, acidity, and corrosion accelerators on galvanized steel are evident. The superior tolerance of aluminized steel for more severe conditions is also evident. Superior tolerance for soft acidic water is evident and well defined. Superior tolerance for higher corrosion-accelerator salt concentrations is suggested, as would be anticipated, but the number of pertinent data points is small at present and additional sites with high-conductivity water must be studied to help establish this.

The position of the limiting line for satisfactory aluminized performance (CD) is only tentative at present, but it is evident that the limit is considerably beyond line AB in the directions of increasing severity. The deterioration of aluminized steel was only minor at all sites with compound aluminized and galvanized steel pipe lengths, where galvanized steel performed poorly. Thus considerably more severe conditions than these would be necessary to produce the same degree of deterioration on aluminized steel in the same exposure time, and line CD must be located well beyond line AB. However, its location cannot be known accurately until the material exhibits considerable deterioration.

At one severe site in the research test program there was substantial localized attack on aluminized steel, with a few tiny pit perforations, but even there the overall deterioration was modest. At one other site there was severe overall deterioration of aluminized steel because of extremely high salinity, but accelerator salt content there was far too high to be useful in locating line CD.

Four test sites, where the performance of aluminized steel was not typical because of unusual complicating conditions, cannot be used to help locate line CD. One of these cases involves severe abrasion, another poor coating quality, while the other two apparently involve severe intermittent chemical conditions far beyond line CD.

Obviously, the designation of zones of satisfactory and unsatisfactory pipe durability, based on water chemistry, affords the prospect of predicting

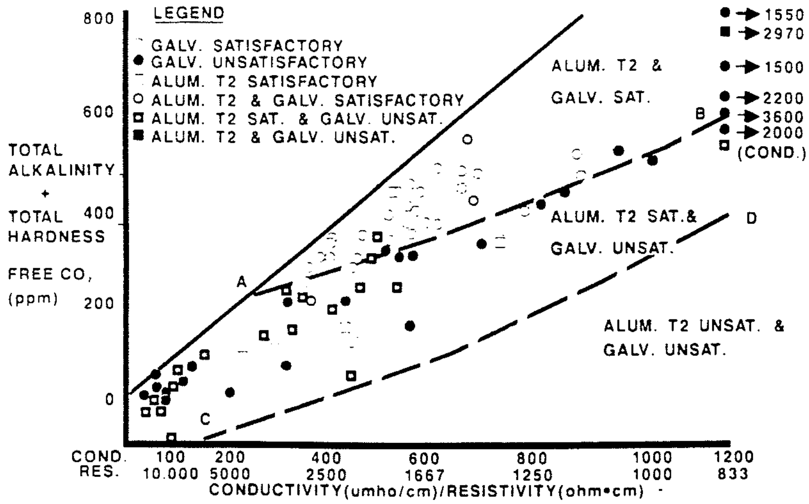


FIGURE 11 Effect of water chemistry on performance of aluminized and galvanized steel.

pipe life. In its present form, the graph provides a useful guideline for pipe performance, although it is expected to be conservative. It is extremely conservative for drier climates because the graph is based on data from wetter climates. It is also conservative in that the worst portion of a pipe length was used to designate the pipe condition. In addition, it is conservative for stagnant-water sites because lower dissolved oxygen contents in such water produce lower overall corrosion loss (when acidity is not extreme); most of the wet sites in this study had flowing water. The graph is very conservative for material thicker than 16 gauge and for situations that do not require 50 years of maintenance-free life for 16-gauge material.

Discussion

T. J. Summerson*

This discussion has three main points:

1. Type 2 aluminized steel (Al/Fe) culvert performed better than galvanized steel, as determined by an evaluation of exposed 30-year-old riveted pipe from sites in 20 states.
2. Alloy cracking has only a minor effect on coating performance. The modern Type 2 aluminized steel product is superior in coating ductility and exhibits less cracking than the 30-year-old coating.
3. New environmental guidelines are proposed to define usage of both galvanized and aluminized steel. (These are based on the scaling tendencies of the water effluent.)

I have some reservations and concerns about the practical significance of these points.

*Center for Technology, Kaiser Aluminum and Chemical Corporation, P.O. Box 877, Pleasanton, Calif. 94566

POINT 1

As many know, in 1981 Kaiser Aluminum made an independent survey of as many of the original 137 test sites as it could. Although it was concluded in the Kaiser report that Type 2 aluminized steel had performed better than galvanized steel culvert in these tests, it was believed that the generally good performance of the galvanized steel, as well as that of the aluminized steel, was because of the nonaggressive nature of the test sites. For example, it was found that water and soil pH were in the neutral 6 to 9 range and resistivities were relatively high (i.e., >2,000 ohm-cm). These are the ranges in which galvanized steel is normally used (see FHWA Technical Advisory T 5040.12, October 22, 1979).

To fully define the performance parameters for Type 2 aluminized steel, additional testing in a broader range of environmental conditions is needed. Such tests should include asphalt-coated corrugated steel pipe (CSP), polymeric-coated CSP, and aluminum so that the relative performances of these various metal pipe products can be assessed.

It is my understanding that Armco agrees that Type 2 aluminized steel pipe should not be used over the entire range of soil and water conditions in which aluminum pipe is used. However, it is important to the end user to know how the performance of Type 2 aluminized steel compares with that of asphalt-coated CSP and polymeric-coated CSP, as well as that of aluminum. In some states this issue is clouded because the guidelines for various materials recommended by these states differ from those recommended by material producers or other government agencies.

POINT 2

Alloy cracking had only a minor effect on performance, and the modern Type 2 aluminized steel product has superior coating ductility and exhibits less cracking than the 30-year-old coating.

In the 30-year test the significance of coating cracking was not fully evaluated because the test sites were nonaggressive. The modern Type 2 aluminized steel product has a lock-seam joint, whereas the coating, although more ductile than the 30-year-old coating, is heavily fractured during the manufacture of the lock-seam and the base steel is exposed. Although the authors showed cross sections of the corrugations, they did not show the more severely formed lock-seam in cross section, where fracturing of the coating does occur.

With the welded-seam product, the aluminum coating is destroyed at the weld.

Again, to support the authors' contention that the modern Type 2 aluminized steel is a superior product to the old riveted Type 2, considerably more field-test data are needed, in terms of longer exposure times and in a broader range of environmental conditions.

POINT 3

In this section new environmental guidelines for galvanized and Type 2 aluminized steel are discussed. The "scaling tendency" system proposed appears similar to what the Georgia Department of Highways used some years ago, based on a cumulative point-count rating of hardness, acidity ($CaCO_3$), conductance plus chlorides, sulfates, and industrial wastes at each site (14,pp.95-96).

Although the authors should be commended for considering this approach, much more data are needed to confirm the effectiveness of the concept for predicting service conditions for galvanized steel, let alone for Type 2 aluminized steel. Moreover, the possibility of soil-side corrosion is not taken into consideration. (This may be more important for aluminized steel than galvanized steel, particularly in western and southern states, where some soil-side corrosion has been observed.)

In 1981 Kaiser Aluminum measured water pH and resistivity at 24 sites where riveted aluminized steel pipe had been in test for 30 years. All but one water registered a pH between 6 and 8. Moreover, the resistivity of the water was greater than 2,500 to 3,000 ohm-cm at more than half of the sites.

If the data in Figure 11 on scaling versus resistivity are tabulated, it is clearly evident that there are not enough data points provided for aluminized steel to put confidence on the validity of line CD, which purports to claim that aluminized steel is satisfactory, whereas galvanized steel is not. For example, more than 50 percent of the waters at the 28 aluminized steel sites shown have resistivities greater than 2,500 ohm-cm and a scaling tendency of 200 or less. Although this adequately covers the lower end (C) of the line, the upper end toward D is wide open and undefinable. For example, there are only five of the aluminized steel sites where the water resistivity is 1,667 ohm-cm or less and the scaling tendency is 200 or greater.

For scientific reasons I would have liked to have seen the authors include a table containing all of the raw data from which Figure 11 was derived. This table would have given the pH and resistivity values, as well as total hardness, total alkalinity, and the CO_2 content for the water at each site. In addition, it would have been appropriate to have shown a second graph in which water pH (instead of scaling tendency) and resistivity--the current conventional parameters used by most agencies for guidelines--were related to the performance of aluminized and galvanized steel.

Finally, I have reservations on the reproducibility and accuracy of CO_2 values in water analyses. Unless the CO_2 concentration is taken immediately on site, the results do not truly reflect actual conditions. Correspondingly, because total alkalinity is based in part on carbonic acid, there will be an error in this value as well. The authors point out that hardness, alkalinity, and carbon dioxide were determined from all sites 2 days after samples were taken. This should make such results comparative, within themselves, but the values will be different from those taken at each site. Perhaps this is of no major concern in routine analysis for a given location. However, when attempting to provide a data base for a new system, this could be critical, particularly in those instances where the water is corrosive because of dissolved gases such as carbon dioxide.

Authors' Closure

POINT 1

Kaiser Aluminum has not made any significant evaluation of corrosivity at the test sites. The Kaiser report of its investigation of the sites (2CFT-82-35-TJS, May 28, 1982) indicates that of the 58 sites still in existence, it found only 23. In the report Kaiser reported pH and resistivity values for several other sites where no aluminized steel was found. Obviously, Kaiser was at the wrong sites in several cases because the aluminized steel pipe is present at the actual sites. In several other cases pH and resistivity values were reported for sites no longer in existence. Kaiser did not inspect any of the 12 existing sites in Missouri or the 6 in Washington, and it missed all three still existing in Mississippi. Also numerous pipes in several other states were missed. Among the 23 verified sites Kaiser visited, there were 17 at which no water testing was done and only soil pH and resistivity measurements were taken. The statement that the Armco test sites are nonaggressive is based on just soil pH and resistivity measurements at 17 verified sites and soil and water pH and resistivity measurements at 6 others.

Armco determined site severity on the basis of the effect of the environment on galvanized steel and also on the basis of comprehensive water chemistry as well as soil pH and resistivity measurements. The severe sites we found included 13 where there was severe water-side corrosion of the galvanized steel for the 30-year exposure time. These sites also included five nongalvanized steel sites where water chemistry was comparable with that of sites where there was severe water-side corrosion of the galvanized steel. The Armco finding that water-side corrosion is the major concern with galvanized steel is in accord with the findings of several highway departments and other investigators, as noted in our paper. Kaiser's water pH and resistivity measurements for six verified sites do not constitute any significant basis for evaluating the primary water-side corrosion factor.

Any reader who wishes to see the pH and resistivity values Armco obtained for all sites has only to refer to Table 1. A sizable proportion of soils and waters had values outside the ranges normally recommended for galvanized steel (pH 6 to 9 and resistivity lower limit of 2,000 ohm-cm). Actually, even if all values had been within the galvanized steel ranges, it would still be evident from the comparative condition of the two materials that aggressive conditions outside these ranges would be necessary to induce in aluminized steel the degree of deterioration exhibited by galvanized steel.

Comparative tests on various materials suggested by Summerson would be interesting, but obviously they were not part of the scope of Armco's desires

30 years ago. The Armco program already represents the longest and most comprehensive field-test results available for any newer pipe material.

POINT 2

Lock-seam coating cracking can be more severe than that indicated by the 30-year-old test material at corrugations. The point we were making is that coating cracking in the old material at corrugations was severe because of low coating ductility, and the superior performance of aluminized over galvanized steel was achieved despite severe cracking. We did not state that modern aluminized steel is superior in durability to the old material because this is something that cannot be known until the modern material has been in service for 30 years. We simply stated that lesser corrugation cracking in the new material indicates that it has superior coating ductility. This property should prove useful for lock-seam performance, judging by the satisfactory performance of old material with severe coating cracking. At any rate, the good galvanic protection for uncoated weld seams noted in our paper should certainly apply also to steel substrate at coating cracks on lock-seams.

Contrary to Summerson's belief, old aluminized steel with severe corrugation cracking was exposed at severely corrosive sites where it performed well. He simply is not aware of the full extent of site conditions because of the limited nature of the Kaiser investigation.

POINT 3

Our graph (Figure 11) denotes the comparative environmental limits of the two materials on the basis of all sufficiently comprehensive data currently available to Armco. It reflects relative performance as revealed by these data. The data are comprehensive enough to be indicative of trends. The graph is preliminary, and some limited changes may be made as more data become available.

The graph deals only with water-side corrosion simply because this is the major problem nationwide for galvanized steel, and we have noted the effectiveness of aluminized steel in addressing this pronounced problem. Nationwide, galvanized steel seldom shows soil-side corrosion that causes early problems. In all of our field tests, aluminized steel was superior to galvanized steel on the soil side everywhere; therefore we currently see no basis for widespread concern about soil-side behavior with either material. There are some local western regions where salty soils would cause local early problems for either material, and some method, such as the California chart, is needed to determine material limitations in such cases. An asphalt coating is a simple solution to most problems of this type for either material, so both materials are broadly applicable in such circumstances. We have not tried to produce a graph that compares material behavior under all conditions, but have simply dealt with the situation that causes most galvanized steel problems nationwide, with the aim of preventing most of these problems in the future.

As we have stated in our paper, the position of line CD, which depicts the limitations of aluminized steel water chemistry tolerance, is tentative at present. We stated that there is a need for more data in lower resistivity water to help establish the position of line CD to the right of the graph. Because the data points are clearly plotted on the graph, the reader can clearly see how limited our data are in this region. There are just five graphed aluminized steel pipes in water less than 2,000 ohm-cm, and two of these are in milder high hardness and high alkalinity water. The performance of three aluminized steel pipes in lower resistivity waters that are severely corrosive compared with galvanized steel is indicative of considerable superiority of aluminized steel under such conditions (Figure 8 illustrates the degree of superiority in one water at 830 ohm-cm). We also had one ungraphed aluminized steel pipe that performed well in water at 245 ohm-cm (it did show advanced corrosion after 30 years), which further indicates enhanced performance in lower resistivity water. Although the data are quite limited for lower resistivity water, the trend toward enhanced performance in such water is quite significant, and we have estimated the degree of superior resistance as well as possible with the limited present data.

With regard to Summerson's reference to Kaiser water data for the Armco test sites, they have water pH and resistivity values for only six verified sites, as previously noted. Other values are for unverified sites. Their report includes values for water at 16 unverified sites at which they found no aluminized steel. Six of the 16 sites were obviously the wrong sites because the aluminized steel pipe is present at the actual sites. Data for 9 of the remaining 10 sites are not from the actual sites because these sites no longer exist.

We did not state that water chemistry tests were conducted 2 days after sampling. What we said was that water specimens were taken at least 2 days after the last rainfall. We agree that the best testing is that conducted on site, and some practical simple field kits are available for this purpose. Actually, it is possible to test for alkalinity and hardness several days after sampling because some simple techniques and calculations can be used to approximate the on-site values, but pH and conductivity must be measured on site. It is not necessary to conduct the relatively difficult test for CO_2 because this can be calculated from the pH and alkalinity measurements.

REFERENCES

1. G. Butler and H.C.K. Ison. Corrosion and Its Prevention in Waters. Reinhold, New York, 1966.
2. C.J. Slunder and W.K. Boyd. Zinc: Its Corrosion Resistance. Zinc Institute, Inc., New York, 1971.
3. L.L. Shreir. Corrosion. Wiley, New York, 1963, Volume I.
4. F.L. LaQue and H.R. Copson. Corrosion Resistance of Metals and Alloys. Reinhold, New York, 1963.
5. U.R. Evans. The Corrosion and Oxidation of Metals. St. Martins Press, Inc., New York, 1960.
6. H.H. Uhlig. Corrosion and Corrosion Control. Wiley, New York, 1963.
7. R.P. Brown and R.J. Kessler. Performance Evaluation of Corrugated Metal Culverts in Florida. Florida Department of Transportation, Tallahassee, Nov. 1975.
8. J.E. Haviland, P.J. Bellair, and V.D. Morrell. Durability of Corrugated Metal Culverts. Research Report 66-5. New York State Department of Transportation, Albany, Nov. 1967.
9. R.A. Holt. Durability Design Method for Galvanized Steel Pipe in Minnesota. National Corrugated Steel Pipe Association, Washington, D.C., 1967.
10. E.A. Bearg, R.L. Pepple, and M. Prise. Durability Design Method for Galvanized Steel Pipe in Nebraska. Armco, Inc., Middletown, Ohio, 1968.

11. Performance Evaluation of Corrugated Metal Culverts in Georgia. Southeastern Corrugated Steel Pipe Association, April 1977.
12. V.E. Berg. Culvert Performance Evaluations. Research Project HPR-1-2. Washington State Department of Transportation, Olympia, April 1965.
13. H.E. Worley. Corrosion of Corrugated Metal Pipe. Research Division, State Highway Commission of Kansas, Tokepa, 1971.
14. R.J. Krizek, R.E. Parmelee, J.N. Kay, and H.A. Elnaggar. Structural Analysis and Design of Pipe Culverts. NCHRP Report 116. HRB, National Research Council, Washington, D.C., 1971, 153 pp.

Publication of this paper sponsored by Committee on Corrosion.

Metal-Loss Rates of Uncoated Steel and Aluminum Culverts in New York

PETER J. BELLAIR and JAMES P. EWING

ABSTRACT

In this paper a laboratory evaluation is described of three techniques to determine metal loss on 1-in. coupons extracted from corrugated metal pipe, a field evaluation of 30 pipes to determine the sample size (number of coupons) and sampling location necessary to characterize metal loss, and a statewide survey of steel and aluminum culverts in New York. It is concluded that a pin micrometer can be used to measure metal loss and that eight coupons extracted randomly along the "worst straight line" of a pipe will provide the accuracy needed for large-scale field surveys. Results of a field survey of 190 galvanized steel culverts and 35 aluminum culverts are presented, and implementation of these results in New York is discussed.

In 1964 New York State began a study of the durability of corrugated metal pipe culverts. The ultimate objective was to provide designers with reliable data on corrosion and abrasion rates of corrugated aluminum and galvanized steel culverts under environmental conditions encountered in the state.

Initial findings were reported in 1967 (1). In that paper metal loss for 111 uncoated galvanized steel culverts was estimated. The values were obtained by striking the pipe with a geologist's pick and then estimating the amount of metal remaining. This method was thought to provide realistic values because early in the investigation a favorable correlation was found between measured thicknesses of 1-in.-diameter cores from 67 culverts and estimates made by soundings with the pick.

These estimates of metal loss were used in conjunction with subsequently developed data to derive a durability design for New York (2). This was based on annual metal losses of 1 mil for diameters up to 48 in. and 2 mils for larger sizes (1 mil = 0.001 in.). In addition, a rating system was designed to determine the need for asphalt coating and paving. The rating system included such factors as surface water corrosiveness, abrasive character of the bedload, and frequency of flow.

Beginning in 1968, a series of 1-in.-diameter cores was taken from many uncoated galvanized steel culverts throughout the state. A single core was taken in each pipe to represent average conditions along the invert or water line, whichever had the greatest apparent deterioration. Results of thickness measurements on these cores indicated that metal-loss rates were considerably higher than the earlier data suggested. This led to concern about the adequacy of the assumptions made in the design procedure.

Several theories have been advanced to account for the discrepancy between the 1965 estimates and the more recent data:

1. In the 1965 survey no cores were taken from the pipes. Metal loss was visually estimated, aided by soundings with a geologist's pick.
2. The original data were collected toward the end of a 5-year drought, which could tend to reduce indicated corrosion rates.
3. Many pipes included in the first survey were young (less than 10 years old).
4. Both sets of data had weaknesses in sample sizes and distribution of samples throughout the state.
5. The methods used in collecting both sets of data to characterize metal-loss rates within each pipe may not have provided reasonable accuracy.
6. The technique of measuring coupons with a pin micrometer may have overestimated metal loss.
7. The 1-in. samples may have been too small for accurate determination of metal loss at a given location within a pipe.
8. Lack of true randomness in selecting pipe