have the nodular bacterial colonies been observed on aluminum or concrete.

CONCLUSIONS

Examination of culvert pipe in Wisconsin has indicated that bacterial activity, both soil and water related, is a significant cause of corrosion of galvanized steel culvert pipe in Wisconsin. The examination also noted that corrosion at most culvert sites can be related singly or in combination to bacterial activity, low pH, and low electrical resistivity of soil or water or both at a culvert site.

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Galvalume Corrugated Steel Pipe: A Performance Summary

A. J. STAVROS

ABSTRACT

Laboratory and field tests have been used to characterize the performance of Galvalume corrugated steel pipe. Galvalume, galvanized, and aluminum-coated Type 2 sheet were subjected to laboratory tests designed to measure corrosion resistance in salt spray (ASTM B 117), cyclic standing water, and full immersion. Abrasion resistance and asphalt adhesion were also tested. In all tests Galvalume sheet demonstrated the best relative performance. Results of field tests that compared nearly 1,000 ft each of Galvalume and galvanized corrugated steel pipe at 16 sites in the northeastern United States substantiated the laboratory predictions. After 9 to 9.5 years, the Galvalume inverts and intermittently wet zones inside the pipe, where service is most severe, were overall in much better condition than those of the galvanized pipes.

Aluminum-zinc (Al-Zn) alloys have been developed into a hot-dip coating for steel that provides superior corrosion resistance. A 55 percent Al-Zn coated sheet is available in the United States from Bethlehem Steel and other companies under the trade name Galvalume. Worldwide, the annual production capacity for 55 percent Al-Zn coated sheet exceeds 2 million tons.

Galvalume sheet has become a growing factor in the preengineered metal building, appliance, agriculture, and automotive markets. Its phenomenal success in these markets is due to the significant improvement in atmospheric corrosion resistance when compared with standard galvanized sheet.

Based on 13-year exposure test results of sheet samples in severe marine, marine, industrial, and rural atmospheres, 55 percent Al-Zn coating is 2 to 4 times more durable than a galvanized coating of the same thickness [see Figure 1 (1)].

Corrugated steel pipe is another traditionally galvanized product that can benefit from Galvalume sheet. In order to develop meaningful performance behavior, Bethlehem, in cooperation with nine state highway agencies, established field trials for full-sized Galvalume corrugated steel pipe. Subsequently, a number of laboratory tests were conducted to supplement the field trial data. The results of these

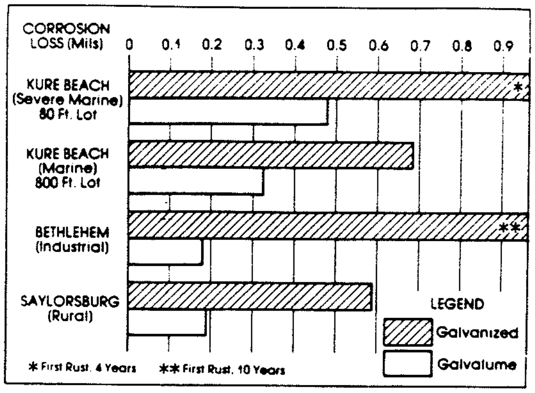

FIGURE 1 Corrosion losses of Galvalume and galvanized sheets after 13 years of exposure in the atmosphere (average top and bottom surfaces) *(1)*.

laboratory and field tests are the subject of this paper.

LABORATORY TEST PROGRAM

The objective of laboratory testing is to simulate service behavior at an accelerated rate. Because corrugated steel pipe may be exposed to a variety of environmental conditions, no single laboratory test can represent all service conditions.

A test program was developed to compare Galvalume sheet with other metallic-coated sheet steels both in the standard accelerated salt spray (fog) test and in other tests designed to simulate specific aspects of culvert service (e.g., standing water, soil contact, abrasion, and asphalt adhesion).

Salt Spray (Fog)

Three coated culvert materials were evaluated: galvanized, aluminum-coated Type 2, and Galvalume. Test coupons (1 x 1 ft) were cut from commercial 0.064-in., 2-2/3 x 1/2 in. corrugated, spiral wound, lock-seamed pipe with rerolled ends. A typical test panel is shown in Figure 2.

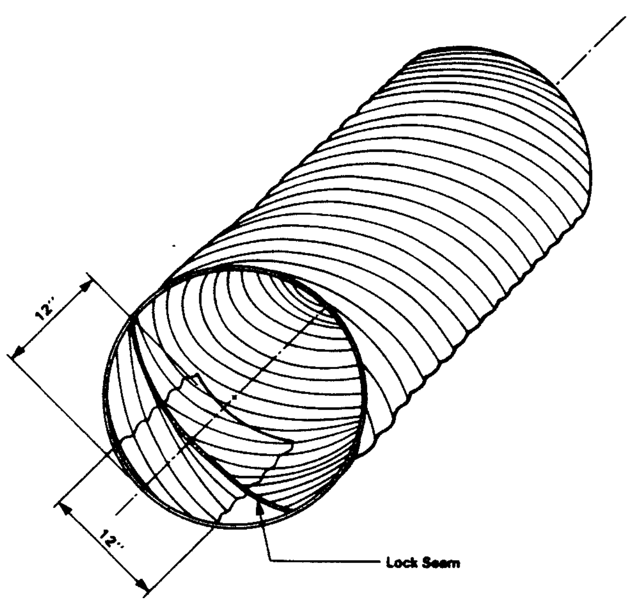

FIGURE 2 Test panel cut from corrugated pipe.

Panels were degreased, cleaned, and tested with and without the cut edges exposed. Test conditions conformed to ASTM B 117. Inspection occurred at weekly intervals. Results are given in Tables 1 and 2.

In salt spray, rust is initiated on galvanized sheet in a random pattern. Behavior is approximately

TABLE 1 Salt Spray Resistance of Culvert Materials, Exposed Edges

Time (hr)	Surface Rust (%) Zn	55 Percent Al-Zn	Al, Type 2
335	0	0	0
670	10	Tr	1
1,000	25	2	20
1,500	40	30	50
1,850	60	40	60

Note: Tr = trace.

TABLE 2 Salt Spray Resistance of Culvert Materials, Protected Edges

Time (hr)	Surface Rust (%) Zn	55 Percent Al-Zn	Al, Type 2
335	0	0	0
670	1	Tr	1
1,000	20	Tr	1
1,500	30	Tr	1
1,850	40	Tr	1
2,350	50	<1	2
3,000	60	<1	3
3,530	75	<1	5
4,000	90	1	10

Note: Tr = trace.

the same for exposed or protected edges. On both Galvalume and aluminum-coated Type 2 sheets rust usually initiates at the edges, so that with protected edges the rate of rusting is significantly retarded.

For panels with exposed edges, rusting had initiated on all three coatings in about 4 weeks (670 hr). At the conclusion of the test after 11 weeks (1,850 hr), 55 percent Al-Zn had a lower percentage of rust than the other coatings, but all three coatings were extensively rusted.

Results were significantly different when the panels had protected edges. The 55 percent Al-Zn had the best corrosion resistance of the three coatings. After 24 weeks (4,000 hr) when the test was concluded, only 1 percent of the 55 percent Al-Zn was rusted, 10 percent of the aluminum-coated Type 2 was rusted, and 90 percent of the galvanized was rusted.

Standing Water

Because water can remain in pipe corrugations for many days after actual flow has stopped, resistance to standing water is important. A laboratory test was designed to measure this resistance.

Test panels cut from galvanized, Galvalume, and aluminum-coated Type 2 corrugated steel pipe were made into troughs by damming the ends (Figure 3). The troughs were filled with 750 mL of either distilled water or 0.05 percent NaCl solution (brackish water). Filled troughs were stored at ambient tem-

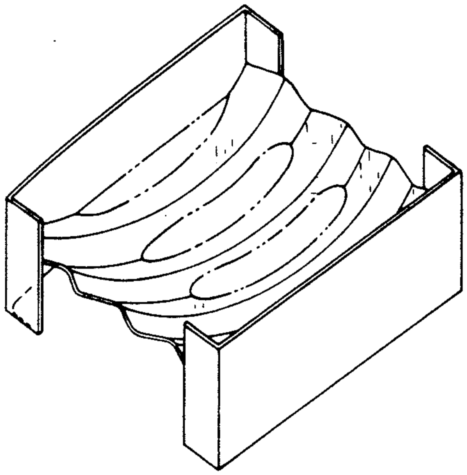

FIGURE 3 Troughs for standing water tests.

perature until the solutions had dried completely. They were then scrubbed with a soft bristle brush to remove corrosion products and refilled with solution. This procedure simulates the condition where a culvert is subjected to abrasive flow, yet dries completely. The average time between the addition of fresh solutions was 9 to 12 days. Testing was ended after 260 days (24 cycles).

The results of the standing water tests are given in Tables 3 and 4. In distilled water galvanized and Galvalume troughs demonstrate similar behavior: small pinpoints of rust gradually develop at the high watermark (somewhat earlier on Galvalume). After 260 days there are still only a few pinpoints of rust, although the galvanized trough has undergone more general corrosion than the Galvalume trough.

The aluminum-coated Type 2 trough also exhibited rust specks after several cycles. These specks, distributed throughout the exposed surface, gradually increased in size and number to cover about 3 percent of the exposed surface after 260 days. The exposed surface was also very rust stained.

In the 0.05 percent salt solution Galvalume troughs had the best performance. By 135 days only a few rust specks had developed within the generally corroded area. This situation had not changed appreciably after 260 days.

The galvanized troughs quickly developed rust specks, initially at the high watermark. Although the entire exposed area was corroded, only 10 percent was rusted at the conclusion of the test. This rust was mostly at the high watermark.

Aluminum-coated Type 2 troughs had the poorest performance. Rust specks began at the high watermark after a few cycles and increased in size and number until 100 percent of the exposed surface was rusted at the end of the test.

Underwater Corrosion

Underwater immersion was used to determine the effect of pH on aqueous corrosion. Galvanized and Galvalume panels (with ASTM G 90 and AZ 50 coatings, respectively) and protected edges were immersed in water containing 45 parts per million (ppm) of sulfate-ion and 10 ppm of chloride-ion for 3 months. (Aluminum-coated Type 2 sheet samples were not available for this test.) The pH was adjusted as needed to the desired value by additions of H_2SO_4 or NaOH.

The results in terms of coating thickness loss are given in Table 5. In the pH range of 5 to 9, which is typical of most natural waters, a 55 percent Al-Zn coating is significantly more resistant to corrosion than a zinc coating. In the acid range both the zinc and 55 percent Al-Zn coatings were completely corroded away. At the alkaline pH, where zinc had its lowest value, 55 percent Al-Zn corroded at a still lower rate.

Soil Tests

To simulate the long-term burial of culverts, test panels were placed in artificially compounded soils that were expected to provide higher corrosion rates than typical of natural soils. These artificial soils are described in Table 6.

Panels were obtained from 0.064-in., 0.5 oz/ft^2 Galvalume (0.7 oz/ft^2 culvert stock was not available) and 2 oz/ft^2 galvanized sheet. Aluminum-coated Type 2 sheet was not included because it was not sold for culvert use when these tests were initiated.

Corrosion data have been compiled for test panels removed at 0.6, 1.6, and 2.8 years (Figure 4). In the mildest Soil 1, the percent coating weight loss for the galvanized panel is less than that for the Galvalume panel, but both are low and nearly identical.

Galvanized and Galvalume panels buried in the more aggressive Soils 2 and 3 have much higher weight losses. In both soils the losses for Galvalume panels are much less than those of galvanized panels.

These burial tests suggest that Galvalume may be more resistant to aggressive soils than galvanized sheet.

Abrasion Resistance

The California Department of Transportation designed test apparatus (2) was used to tumble corrugated panels in a water slurry of sharp flint pebbles. Test panels, cut from corrugated pipe, were mounted so that the corrugations were at right angles to the rotation of the apparatus (i.e., the abrasive slurry flows across the corrugations as occurs in service).

A nondestructive thickness gauge was used to measure coating thickness at five positions across a

TABLE 3 Resistance to Standing Distilled Water

Duration		Surface Condition		
Cycles	Days	Zn	55 Percent Al-Zn	Al, Type 2
2	18	OK	OK	Slight stain
5	61	OK	Rust specks	Rust specks, stain
7	81	OK	Rust specks, stain	Rust specks, stain
10	109	Rust specks	Rust specks, stain	1 percent rust specks, stain
13	135	Rust specks	Rust specks, stain	1 percent rust specks, stain
16	165	Rust specks	Rust specks, stain	1.5 percent rust specks, stain
19	196	Rust specks	Rust specks, stain	2 percent rust specks, stain
24	260	Rust specks	Rust specks, stain	3 percent rust specks, stain

TABLE 4 Resistance to Standing 0.05 Percent NaCl Solution

Duration		Surface Condition		
Cycles	Days	Zn	55 Percent Al-Zn	Al, Type 2
2	18	Rust specks	OK	Rust specks
5	61	Rust specks	OK	Rust specks
7	81	Rust specks	OK	2 percent rust
10	109	Rust specks	OK	5 percent rust
13	135	Rust specks	Rust specks	10 percent rust
16	165	1 percent rust	Rust specks	20 percent rust
19	196	1 percent rust	Rust specks	30 percent rust
24	260	10 percent rust	Rust specks	100 percent rust

TABLE 5 Underwater Corrosion of Galvalume and Galvanized Panels

pH	Coating	Calculated Thickness Loss (mil)	Three-Month Appearance
3	Zn	1	Rust
	55 percent Al-Zn	0.79	Rust
5	Zn	1	Bare
	55 percent Al-Zn	0.19	Mottled
7	Zn	0.92	Bare
	55 percent Al-Zn	0.13	Mottled
9	Zn	1	Bare
	55 percent Al-Zn	0.12	Mottled
11	Zn	0.58	70 percent bare
	55 percent Al-Zn	0.43	Bare spots

TABLE 6 Test Soils

Soil	Description	pH	Resistivity (ohm-cm)
1	Native shale, clay: wet and dry	5	70,000
2	Native shale, clay treated with $CaCl_2$ NaCl, $MgSO_4$: wet and dry	4	35,000
3	Native shale, clay, bentonite treated with $CaCl_2$, NaCl, $MgSO_4$: wet	6	1,700

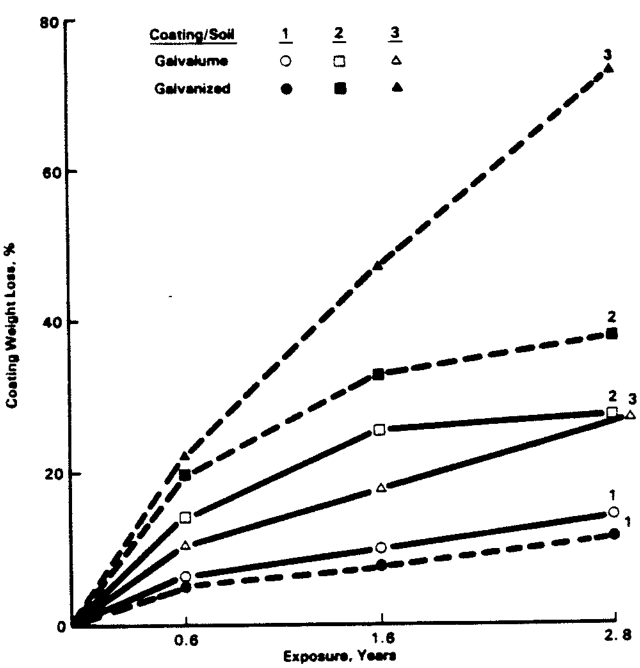

FIGURE 4 Coating loss in burial tests.

corrugation, repeated over four corrugations on each sample (Figure 5). Measurements were made initially and after each 15,000 revolutions when the slurry (16 L water, 5 kg flint pebbles) was also changed. Abrasion severity was changed by varying the number of panels exposed to the slurry.

The results of the most severe abrasion test are given in Table 7. All three coated steels were judged to provide about equal abrasion resistance based on the time (or revolutions) needed to expose base steel at position A, which had the highest rate of coating loss. Less severe abrasion tests indicated similar results.

Asphalt Adhesion

Asphalt adhesion was measured by both impact resistance and freeze-thaw cycling. Both flat and corrugated test panels were coated on one side with asphalt. A standard two-dip practice at 410°F was followed to build up the specified 50-mil asphalt thickness. Some asphalt-coated panels were aged at room temperature for 10 months; others were artificially aged at 150°F until the asphalt had significantly hardened.

Impact resistance was determined by reverse impacting the test panels at 80 in.-lb with a Gardener Impact Tester using a 0.625-in.-diameter ball at 20° and 40°F, and then measuring the extent of delamination.

For freeze-thaw cycling, the asphalt was grooved through to the metal to produce 1-in. squares. These panels were then cycled at -20°F for 8 hr and room temperature for 16 hr. Spalling or loss of adhesion was noted.

The results of asphalt adhesion in the impact test are given in Table 8. Galvanized and Galvalume sheets had about the same amount of delamination, which was observed to be directional about the point of impact.

Although aluminum-coated Type 2 sheet appears to be more prone to delamination, a direct comparison may not be possible because the galvanized and Galvalume test panels were smooth, whereas the aluminum-coated Type 2 panels were corrugated.

After 5 weeks of freeze-thaw cycling, no differences were noted among the three coating materials in the room-temperature-aged condition. Aging at 150°F, however, increased the delamination relative to the room-temperature-aged condition.

Laboratory Test Results

The data in Table 9 summarize the relative performance in the laboratory tests of the three coated sheet steels commonly available for corrugated steel pipe. Relative performance is indicated by the numerals 1, 2, and 3, where best performance is 1 and worst performance is 3. NT indicates the coating was not tested.

Based on the results of the laboratory tests, Galvalume sheet would be expected to provide a service life equal to or better than that of galvanized or aluminum-coated Type 2 sheet.

FIELD SERVICE TESTS

Shortly after the introduction of Galvalume sheet steel, Bethlehem Steel Corporation in cooperation with nine state highway departments in the northeastern United States established field service tests for Galvalume corrugated steel pipe. The primary purpose was to document behavior under

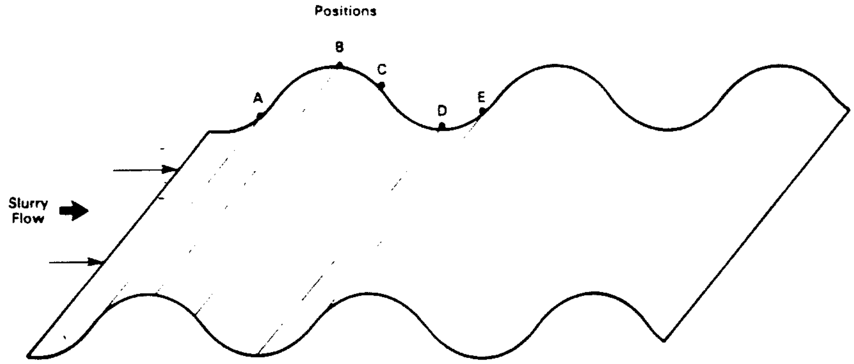

FIGURE 5 Coating thickness measurement positions in abrasion tests.

TABLE 7 Abrasion Test Results

Coating Type	No. of Rotations	Thickness Loss (mils) A	B	C	D	E	Avg	Visible Steel
Zn	15,000	1.58	0.17	0.32	0.31	0.64	0.60	
	30,000	1.65	0.22	0.43	0.52	1.12	0.79	Trace at A
	45,000	1.98	0.10	0.35	0.60	1.59	0.92	At A
55 percent Al-Zn	15,000	0.77	0.23	0.02	0.03	0.47	0.30	
	30,000	0.85	0.41	0.07	0.08	0.68	0.42	
	45,000	0.88	0.49	0.11	0.10	0.80	0.48	At A
Al, Type 2	15,000	1.01	0.56	0.26	0.16	0.44	0.49	
	30,000	1.08	1.00	0.11	0.21	0.75	0.63	
	45,000	1.33	0.97	0.24	0.36	0.88	0.76	At A

TABLE 8 Asphalt Adhesion Impact Test

Test Temperature (°F)	Aged Condition	Asphalt Delamination (mm) Zn (smooth)	55 Percent Al-Zn (smooth)	Al, Type 2 (corrugated)
20	RT aged	13, 10	10, 15	50, >50
	150°F aged	15, >50	12, 12	50, >50
50	RT aged	1, 1	1, 5	10, 0
	150°F aged	10, 8	9, 11	40, 12

Note: RT = room temperature.

TABLE 9 Laboratory Testing of Metallic Coating for Corrugated Steel Pipe

Test	Relative Performance[a] Zinc	55 Percent Al-Zn	Al, Type 2
Salt spray	3	1	2
Standing distilled water	2	1	3
Standing 0.05 percent NaCl	2	1	3
Immersion (pH)	3	1	NT
Soil resistance, 3 years	3	1	NT
Abrasion resistance	1	1	1
Asphalt adhesion	1	1	3

[a]1 = best performance, 2 = intermediate performance, 3 = worst performance, and NT = not tested.

actual service conditions, comparing the performance of Galvalume corrugated steel pipe with that of galvanized corrugated steel pipe.

Additional field service tests in other sections of the United States have recently been established to broaden geographic coverage and to include service conditions not available in the northeast. Because these sites are only 2 to 4 years old, they will not be discussed.

Galvalume corrugated steel pipe has also been used commercially in numerous installations. Sheet and pipe meet AASHTO Specifications M 289 and M 36, and ASTM Specifications A 806 and A 760 (under revision).

Installation

From October 1973 to October 1974, 16 service tests using corrugated pipe made from 0.6 oz/ft^2 Galvalume and 2 oz/ft^2 galvanized sheet were placed in service at five sites in Maine, three sites in New Hampshire, two sites in Rhode Island, and one site each in Maryland, Massachusetts, New York, Vermont, and Virginia. At the time these tests were established, the heavier 0.7 oz/ft^2 55 percent Al-Zn coating now required in ASTM and AASHTO specifications was not made on Bethlehem's Sparrows Point Galvalume coating line.

The location, use, configuration (parallel or tandem), and length of each installation are given in Table 10. About 1,000 ft each of Galvalume and galvanized corrugated steel pipe were installed.

A wide range of environmental conditions is encompassed by these 16 sites, including drainage from farmland, forests, bogs, highways, and highway maintenance yards. Nine of the sites usually have

TABLE 10 Description of Installations

Site	Location	Date Installed	Pipe Configuration	Pipe Length (ft)		Drainage From
				Galvalume	Galvanized	
1	Milford, Conn.	11/73	Parallel	100	100	Highway maintenance yard
2	Brewer, Maine	7/74	Tandem	20	20	Springs
3	Kenduskeag, Maine	7/74	-	54	0	Rural road, springs
4	Levant, Maine	10/73	Parallel	40	40	Bogs
5	Milford, Maine	11/73	Parallel	40	40	Bogs
6	Newburgh, Maine	10/73	Tandem	20	20	Rural roads, bogs
7	Hereford, Md.	11/73	Tandem	6	6	Highway maintenance yard
8	Chelsea, Mass.	10/73	Tandem	90	90	Interstate, urban roads
9	Danbury, N.H.	6/74	Parallel	80	80[a]	Rural roads, bogs
10	West Ossipee, N.H.	10/73	Parallel	40	40[a]	Rural road
11	Thornton, N.H.	11/74	Parallel	74	74[a]	Streambed
12	Woodbury, N.Y.	10/73	Parallel	200	200	Interstate, rural roads
13	Lincoln, R.I.	12/73	Tandem	20	80	Rural road
14	Cranston, R.I.	9/74	Tandem	50	50	Parking lot
15	Ferrisburg, Vt.	10/73	Parallel	78	78	Streambed
16	Fredericksburg, Va.	11/73	Parallel	50[a]	50[a]	Streambed

[a]Asphalt coated.

continuous flow, primarily spring-fed. The remaining seven sites have intermittent flow after storms and especially during the spring thawing cycle. Twelve sites have a minimum slope of less than 0.5 percent. Two sites have slopes of 1 to 2 percent, and two sites are greater than 2 percent. Many of the installations carry bedloads of soil, sand, gravel, and large rocks to varying degrees. Three of the installations are also subject to salt-laden flows.

Numerous inspections of these sites have been carried out since installation. These inspections have been primarily visual, with photographs recording the progressive reaction of each pipe to its particular environment. Soil and water samples were often taken to record any changes in properties (Table 11).

Results

The performance of a buried corrugated steel pipe can be best followed by focusing on the behavior of (a) the invert, (b) the soil side, and (c) the zone of intermittent wetness between the low and high water levels.

The Invert

This portion of a culvert usually suffers the greatest degree of corrosion. The frequent or continuous contact with water, along with any abrasion or erosion, can penetrate a metallic coating in a short time under severe conditions.

Within the first year of service rust indications were found on the galvanized inverts at Sites 1 and 5 and on the Galvalume invert at Site 12. By 2 years of service there were indications of rust on the galvanized invert at Site 12, and also on the Galvalume invert at Site 1. All inverts had measurable indications of rust at 5-year service inspections, with the exception of Site 7 (usually dry) and those pipes that were asphalt coated. Generally, the Galvalume pipe inverts took 0.75 to 1 year longer to show measurable rust.

The most recent inspections at 9 to 9.5 years of service found that, with the exception of Site 12 (where there is a larger amount of invert rust on the Galvalume pipe, but both galvanized and Galvalume pipe have perforated), Galvalume inverts are equal or, more often, are in much better condition than the galvanized inverts (Figure 6).

The most severely corroded inverts (Sites 1, 5,

TABLE 11 Soil and Water Properties of Service Test Sites

Site	Soil		Water							
					Chemical Analysis (mg/L)					
	pH	Resistivity (ohm-cm)	pH	Resistivity (ohm-cm)	Ca^{++}	Mg^{++}	HCO_3^-	Cl^-	$SO_4^=$	Acidity (mg/L) as $CaCO_3$
1	6.1	300	5.7	1,200	300	62	83	879	127	8
2	8.2	168,000	7.2	12,000	24	7.8	29	5	23	-
3	6.5	61,000	6.8	9,500	40	8.7	48	5	21	8
4	5.2	26,000	5.4	10,000	24	5.8	22	<5	11	16
5	7.9	82,000	4.9	44,000	8	3.9	10	<5	7.7	40
6	7.9	25,000	6.7	20,000	16	4.9	10	<5	15	-
7	6.6	20,000	-	-	-	-	-	-	-	-
8[a]	6.8	2,100	6.6	700	192	64	90	199	77	24
9	4.6	36,000	5.5	8,900	-	-	-	14	7	-
10	5.1	4,000	5.2	31,000	3.2	1	10	<5	25	8
11	6.0	132,000	6.3	27,000	8	1.9	10	<5	15	12
12	6.5	6,200	7.1	1,200	119	18.5	80	98	55	8
13	7.0	19,000	6.9	2,700	-	-	-	-	-	-
14[a]	-	-	6.7	-	-	-	-	-	-	-
15	6.9	22,700	7.0	1,400	139	64	145	<5	63	<4
16	6.1	14,300	5.8	4,800	-	-	-	-	-	-

Note: Original values unless significant change found during a subsequent measurement.
[a]Inaccessible since installation because of high water.

FIGURE 6 Comparison of galvanized (top) and Galvalume (bottom) pipe inverts after 9.5 years exposure at Newburgh, Maine.

and 12) are explained by continuous wetness. These aggressive flows are of low pH (Sites 1 and 5) or low resistivity (Sites 1 and 12), contain aggressive ions (Cl^- at Sites 1 and 12), or are abrasive (all three sites).

Soil Side

Soil conditions can vary from something typical of atmospheric exposure to that comparable to complete immersion (3,pp.90-99). Many types of chemical, electrochemical, or even bacterial attack are possible.

Compared with the pipe inverts, experience has indicated that soil-side corrosion in the northeastern United States is usually not significant. Soil-side corrosion was monitored only by removing backfill from around the culvert where it protruded into the atmosphere. The more rigorous method of drilling core samples from the pipe at a position well removed from the pipe ends was not justified.

Little change was noted on either the galvanized or Galvalume pipes until recently. It is possible to directly compare soil-side behavior at nine sites. Eight of these sites were inspected in 1983. At three sites both the galvanized and Galvalume pipes were in about the same condition: some rust at Site 1, and in good condition at Sites 7 and 12.

The Galvalume pipe has corroded to a greater extent at four sites (2, 4, 5, and 15), where there is some degree of rust, whereas the galvanized pipe is only darkened slightly, except at Site 15 where it is also rusting. At Site 6 the Galvalume pipes shows better soil-side behavior than the galvanized pipe, although both are in good condition.

Soil-side condition does not appear to correlate with soil pH and resistivity. In no instance, however, was the soil-side corrosion comparable with that found on the inverts.

Zone of Intermittent Wetness

In this zone between the high and low water levels, where the coating is intermittently wet, the 55 percent Al-Zn coating was found to be much superior to a zinc coating. Most of the galvanized pipes showed rust much earlier than their Galvalume companions and continued to degrade much more rapidly with age (Figure 7).

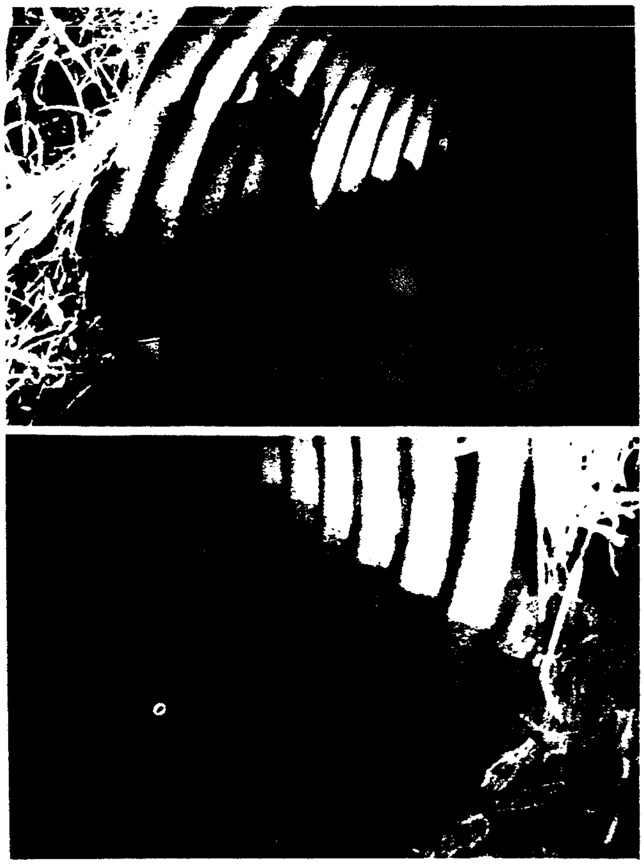

FIGURE 7 Comparison of galvanized (top) and Galvalume (bottom) intermittently wet zones after 9.5 years of exposure at Levant, Maine.

Discussion of Results

Galvanized culverts have been used successfully since early in this century. There have been numerous studies into their durability, with the aim of relating service life to measurable environmental properties (4), particularly soil and water pH and resistivity.

Although there have been successful correlations of durability with pH and resistivity, other studies have found different factors to be more important. Generally, pH and resistivity along with a consideration of abrasion can provide guidelines for the successful use of galvanized culverts. The National Corrugated Steel Pipe Association Selection Guide (5) indicates that galvanized coatings are satisfactory over a pH range of 5 to 12 if resistivity is greater than 10,000 ohm-cm with no more than moderate abrasion. If resistivity drops down to 2,000 ohm-cm, the suggested pH range is 5.8 to 10.

The data in Table 11 indicate that water and soil conditions of many of the service test sites lie at the extreme or even outside of these guidelines. Particularly severe conditions would be expected to exist at Sites 1, 5, 8, 9, 10, 12, and 15. Also, the highest chloride concentrations occur at Sites 1, 8, and 12; the highest sulfate concentrations at Sites 1, 8, and 15; and the highest acidity at Sites 4, 5, and 8.

Inspections over the past 9 years found that Site 12, which is very abrasive, has indeed suffered the most intense corrosion. The inverts of both the Galvalume and galvanized pipes perforated at their entrance ends in between 8 and 9 years. Sites 1 and 5 also show severely corroded inverts. At Site 1 both the Galvalume and the galvanized pipe inverts are essentially devoid of coating and exhibit large shallow pits in the steel base. At Site 5, however, the extent of rust is much greater in the galvanized pipe than in the Galvalume pipe.

A similar situation exists at Sites 4 and 15, but the total extent of invert corrosion is much less in both pipes. Site 8 has never been inspected after installation because of high water levels. Site 9 was only recently classed as a severe site because of a drop in pH. There is still substantial coating on the Galvalume invert, but because the galvanized pipe is asphalt coated, no comparison is possible. At Site 10, which is only occasionally wet, both pipes are still in excellent condition.

At the remaining test sites, which fall within the guidelines for galvanized coatings, corrosion has been less severe, even though some sites are continuously wet. At Sites 2, 6, and 7, where Galvalume and galvanized can be directly compared, the Galvalume inverts range from as good as the zinc invert at Site 7 (both are still free of red rust) to substantially better at Site 6.

Laboratory testing suggested that Galvalume corrugated steel pipe should be more resistant than galvanized corrugated steel pipe to aqueous corrosion, especially when Cl^- or $SO_4^=$ ions are present, and to corrosion by aggressive soils. Where abrasion is the dominant factor, both Galvalume and galvanized corrugated steel pipes should perform equally well.

The field tests tend to substantiate these predictions. The inverts and intermittently wet zone of the Galvalume pipes took longer than galvanized pipes to show first rust and remain in equal or usually better condition.

Where abrasion is significant, both coatings show much more but about equal deterioration. Unfortunately, the most chemically aggressive test sites were also the most abrasive, so that the two factors cannot be separated.

Soil conditions are mild at most sites, and there is no clear indication that either coating is markedly superior. At the one aggressive site where bare pipes could be evaluated, both were in the same condition.

Field Performance Summary

After nearly 10 years of service testing about 1,000 ft each of galvanized and Galvalume corrugated pipe, the following conclusions are obtained:

1. The inverts of the Galvalume pipes are overall in much better condition than those of the galvanized pipes;
2. In the area between the high and low water levels, above the invert, corrosion resistance of Galvalume pipes is superior to galvanized pipes; and
3. Galvalume and galvanized corrugated steel pipes provide about equal resistance to soil corrosion; however, the soil corrosion rate is much lower than that obtained on the inverts and is not a significant factor in overall pipe durability.

CONCLUSIONS

Galvalume, galvanized, and aluminum-coated Type sheet steels were subjected to laboratory tests designed to simulate various aspects of corrugated steel pipe service. In all tests Galvalume sheet demonstrated the best relative performance.

Results of field tests comprising approximately 1,000 ft each of Galvalume and galvanized corrugated steel pipe at 16 sites in the northeastern United States have substantiated the laboratory predictions by demonstrating that Galvalume pipe is in better condition after 9 to 9.5 years of service. The Galvalume inverts and intermittently wet zones on the inside of the pipe were overall in much better condition than those of the galvanized pipe. Additional field tests are under way to broaden these conclusions.

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