



BIEC International Inc.
1111 Main Street, Suite 545
Vancouver, WA 98660 USA

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Thirty-Year Atmospheric Corrosion Performance of 55% Aluminum-Zinc Alloy-Coated Sheet Steel

Herbert E. Townsend

Bethlehem Steel Corp., Homer Research Laboratories, Bethlehem, PA 18016

Angelo R. Borzillo

BIEC International Inc., Park Plaza, 3400 Bath Pike, Bethlehem, PA 18017

In 1964, a series of aluminum-zinc (Al-Zn) alloy coatings were applied to steel sheet on a laboratory continuous hot-dip coating pilot line. The coated sheets were exposed in outdoor corrosion tests in severe marine, moderate marine, rural, and industrial atmospheres. Following eight years of testing, the 55% Al-Zn composition was selected as the optimum composition because it combined excellent long-term durability with the ability to provide cut-edge protection to the steel substrate. Now, after 30 years of continued outdoor testing, the results show conclusively that the 55% Al-Zn alloy coating has better than twice the life of an ordinary zinc coating of equal thickness, and that it provides enduring cut-edge protection. Following identification of the optimum composition in 1972, steel sheet with the 55% Al-Zn alloy coating was produced commercially by Bethlehem Steel. Large quantities of this material have been put in service as unpainted roofing on metal buildings. Inspections of these buildings show that the corrosion performance is excellent for roofs that have been in service for up to 22 years in a variety of US environments. These results confirm the conclusions of the earlier outdoor tests.

In 1962, Bethlehem Steel's Research Department initiated a screening program to look at coatings based on alloys of aluminum (Al) and zinc (Zn). This work was aimed at developing an im-

proved coating for the corrosion protection of steel. Specifically, it was anticipated that the well-known durability of Al coatings could be combined with the unique galvanic property of galvanized coatings.

However, it was quickly recognized that it is impossible to coat steel sheet by hot dipping in Al-Zn alloy baths approaching the 50% Al composition. An excessive alloying reaction takes place between the coating metal and the steel substrate. This reaction is so extreme that it exothermically consumes steel sheet, producing a pile of intermetallic rubble.¹

In 1963, a breakthrough occurred when it was discovered that a small amount of silicon (for example, 3% of the Al content) added to the Al-Zn bath effectively suppresses the alloying reaction. This was the key discovery that enabled development to proceed. The next step was the coating and testing of small steel coupons in the laboratory.

In 1964, a series of Al-Zn alloy coatings in the range 0 to 70% Al were applied to 6-in.-wide steel strip on a continuous hot-dip pilot coating line. Long-term atmospheric testing of these materials was initiated at four

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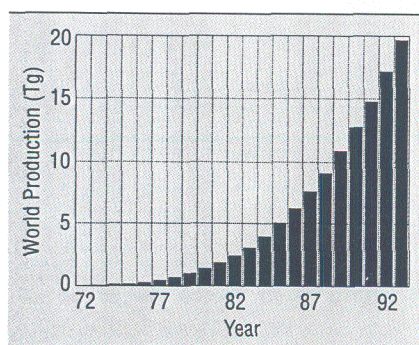


FIGURE 1

Cumulative worldwide production of steel sheet coated with 55% Al-Zn alloy (One Tg is equal to 1 million metric tons or 1.1 million short tons).

outdoor test sites representing industrial, rural, marine, and severe marine environments.

After eight years of atmospheric testing, the results indicated that 55% Al-Zn alloy is the optimum coating composition. It was shown to be at least two to four times more corrosion resistant than an equal thickness galvanized coating. It also provided good protection at the cut edges of the steel sheet.² The results of continued outdoor corrosion testing has been reported after 13, 20, 22, and 25 years.³⁻⁶ One purpose of this report is to present the results after 30 years of continued outdoor exposure.

The 55% Al-Zn coated sheet was also found to have superior corrosion resistance to galvanized sheet when exposed underneath vehicles driven in the snow belt.⁷ The material has been successfully used for a variety of undercar parts and school-bus floors. It was also found to have heat reflectivity that is superior to aluminum-coated sheet,⁸ thus making it well-suited for applications ranging from automotive heat shields to internal components of household toasters.

In 1972, the No. 3 galvanizing line at Bethlehem's Sparrows Point Plant was converted for the start of commercial production of 55% Al-Zn alloy coated sheet. The material was sold under the tradename, Galvalume sheet[†]. Since then, production of steel sheet coated with 55% Al-Zn alloy has spread throughout

[†]Trade name.

TABLE 2
Atmospheric Corrosion Test Sites

Location	Environment	Longitude, Latitude
Kure Beach, NC (25-m lot)	Severe marine	78W, 34N
Kure Beach, NC (250-m lot)	Moderate marine	78W, 34N
Saylorsburg, PA	Rural	75W, 41N
Bethlehem, PA	Industrial	75W, 41N

the world. The remarkable growth of this product is shown in Figure 1. For the year 1993, annual worldwide production was 2.5 Tg (2.8 million short tons).

From the beginning, one of the largest applications of 55% Al-Zn coated sheet has been unpainted roll-formed roofing for pre-engineered metal buildings. Earlier, we described the behavior of 34 roofs that had been in service in the US for up to 13 years.⁵ A second purpose of this report is to document the performance of roofing that was inspected in 1994 after being in service for up to 22 years.

Experimental Procedures

Materials

Steel sheet was coated with the alloys shown in Table 1 to evaluate the effect of composition on the corrosion resistance of a wide range of Al-Zn compositions. Silicon was added to these alloys in an amount equal to 3% of the Al content to avoid the catastrophic alloying phenomenon described above.

The coatings were applied to low-carbon (0.06% C) steel strip on a pilot-scale, continuous hot-dip coating line. In this laboratory facility, coils of full-hard, cold rolled strip (0.4-mm thick by 152-mm wide) were uncoiled, scrubbed in an alkaline cleaner and rinsed. They were next annealed in a gas-fired Selas-type furnace, cooled in hydrogen gas, and dipped in a coating bath. Coating thickness was controlled to 20 to 25 μ m by use of coating rolls as the strip was withdrawn from the bath. The coating was solidified by forced-air cooling. The coated sheet was water cooled to room temperature and rewound into a coil.

For purposes of comparison with the pilot-line materials, two commercially produced coated sheet products were also tested: (1) Z275 (formerly G90) galvanized containing 0.2% Al and 0.1% lead on 0.69-mm sheet, and (2) Type 2 Al-coated 0.55-mm sheet.

Roofing sheet was coated with AZ165 55% Al-Zn alloy coatings on the No. 3 line at Bethlehem Steel's Sparrows Point Plant. The process on this line is similar to that described

TABLE 1
Compositions of Al-Zn Alloy Coatings Applied to Steel Sheet on a Pilot-Scale Hot-Dip Coating Line

Composition (%)		
Al	Si	Pb
0.2	0	0.2
1.0	0.03	0
4.0	0.12	0
7.4	0.22	0
12.2	0.37	0
16.6	0.50	0
21.0	0.63	0
35.1	1.05	0
44.6	1.34	0
69.6	2.01	0

All compositions given in this article are stated in wt%.

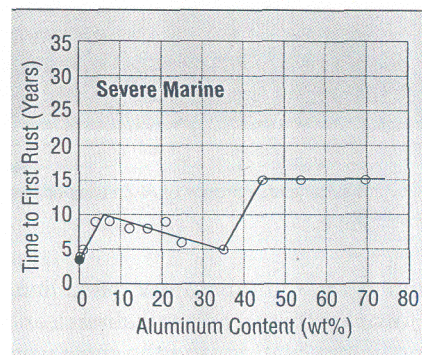


FIGURE 2

Effect of Al content on coating life in a severe marine environment. Open circles: pilot line product. Solid circle: commercial product.

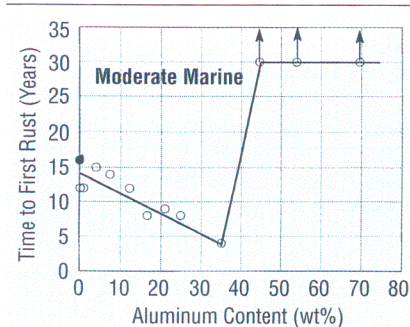


FIGURE 3

Effect of Al content on coating life in a moderate marine environment. Open circles: pilot-line product. Solid circle: commercial product. Arrows indicate that there is no failure for this composition and the test is continuing.

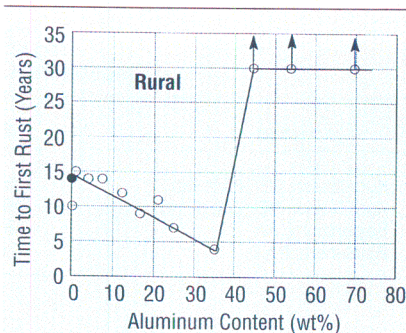


FIGURE 4

Effect of Al content on coating life in a rural environment. Open circles: pilot-line product. Solid circle: commercial product. Arrows indicate that there is no failure for this composition and the test is continuing.

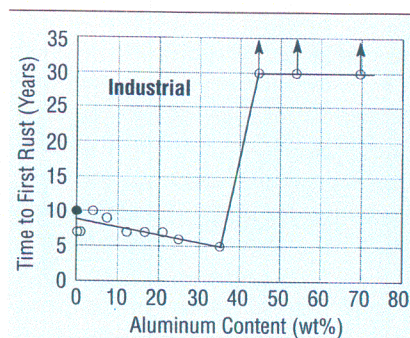


FIGURE 5

Effect of Al content on coating life in an industrial environment. Open circles: pilot-line product. Solid circle: commercial product. Arrows indicate that there is no failure for this composition and the test is continuing.

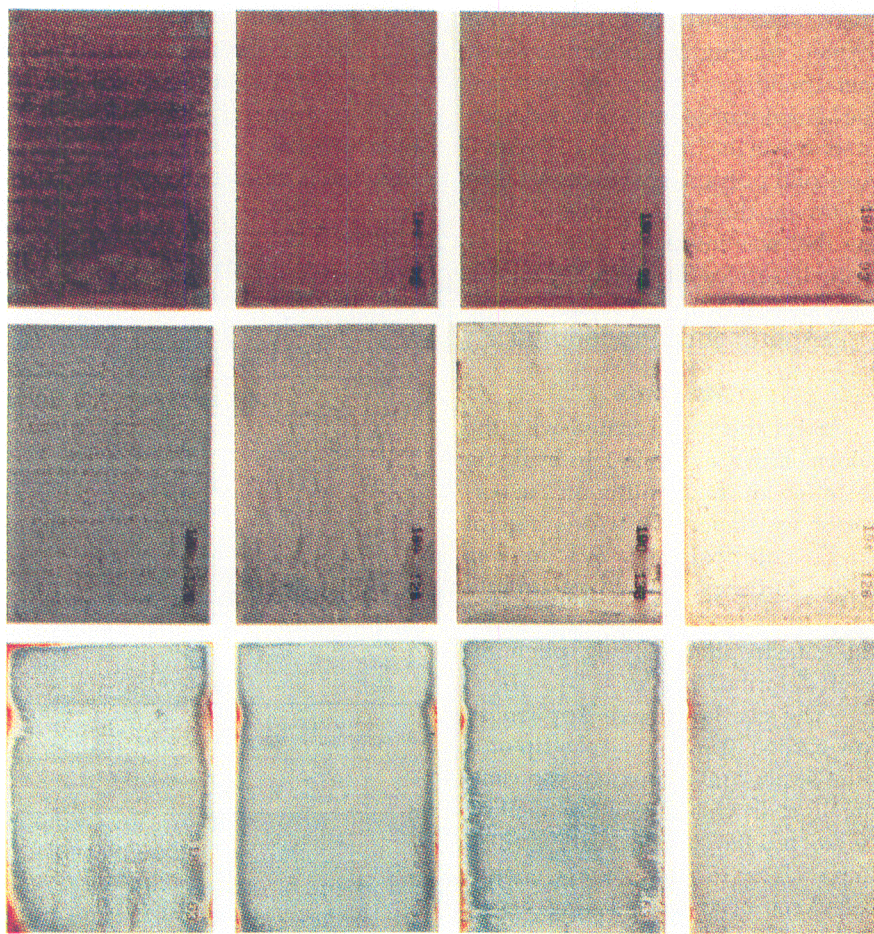


FIGURE 6

Skyward surface appearance of Al-Zn alloy-coated sheet steels remaining in test after 30 years of outdoor exposure.

above for the laboratory pilot line. However, there was no alkaline cleaning before coating, and the sheet was chromate passivated after coating to avoid wet storage staining.⁹ The coated sheet was roll formed into

roofing panels and installed on the roofs of metal buildings.

Atmospheric Corrosion Tests

Coated strip was sheared into 102- by 152-mm test panels and ex-

posed with unprotected cut edges. The panels were mounted on racks inclined at an angle of 30 degrees to the horizontal at the four outdoor corrosion test sites described in Table 2. These sites represent a range of environments including severe marine, moderate marine, rural, and industrial. Upper surfaces of the test panels faced eastward toward the Atlantic Ocean at the severe marine site, and toward the south at the other three locations.

The marine sites are operated by the LaQue Center for Corrosion Technology, and are described in detail elsewhere.¹⁰

The rural site is located in the Pocono Mountains about 50 km north of Bethlehem, PA. The industrial site is located on South Mountain in Bethlehem, about 3 km from a plant at which steel was produced until late 1995. This location is within sight of coke ovens which continue to be operated. These sites are maintained by Bethlehem Steel Corporation, and have been previously characterized in terms of the corrosion rates of steel and pure Zn.¹¹

Panels were inspected regularly to determine the time to first rust, defined as the number of years until red rust had spread over about 2% of the coated surface.

Corrosion Potentials

Corrosion potentials were measured in the laboratory on atmospheric corrosion test panels that were

removed from test following 30-year outdoor exposure. After placing a drop of 5% NaCl solution on the surface of a panel, the tip of a saturated calomel reference electrode was inserted into the drop. The potential between the reference electrode and the panel was recorded for up to 60 minutes. During this period, the corrosion potentials typically started at about -0.92 V and then gradually became more negative with time. The values reported are the levels reached after 30 minutes.

Roofing Inspections

A total of 82 buildings with unpainted 55% Al-Zn coated steel roofing sheet were inspected during 1994. Fifty roofs were in service for at least 17 years, and 21 were in service for 20 to 22 years. The buildings are located in 18 states throughout the Midwestern, Northeastern, and Southwestern US, including Iowa, Illinois, Wisconsin, Massachusetts, Maine, Michigan, Indiana, Ohio, and Pennsylvania, Mississippi, Louisiana, and Florida.

Results and Discussion

Effects of Composition on Coating Life

At the severe marine test site (Figure 2), Zn coatings (galvanized) show first rust after four to five years. Coatings containing 4.7 to 7% Al show longer lives, but the degree of improvement appears to decrease as Al increases in the range 7 to 35.1%. The largest increase in coating durability occurs in the range 44.6 to 69.6% Al. These coatings exhibit a threefold improvement over ordinary Zn coatings.

Similar features are noted at the moderate marine, rural, and industrial locations (Figures 3 through 5, respectively). There is a range of coating life for the Zn and low-Al-Zn alloy coatings. The life of the alloy coatings generally diminishes, with increasing Al content up to 35.1%.

However, coating life increases dramatically to more than 30 years for coatings containing Al in the range 44.6 to 69.6%. At the moderate marine and rural sites, coatings in this range have already lasted twice as

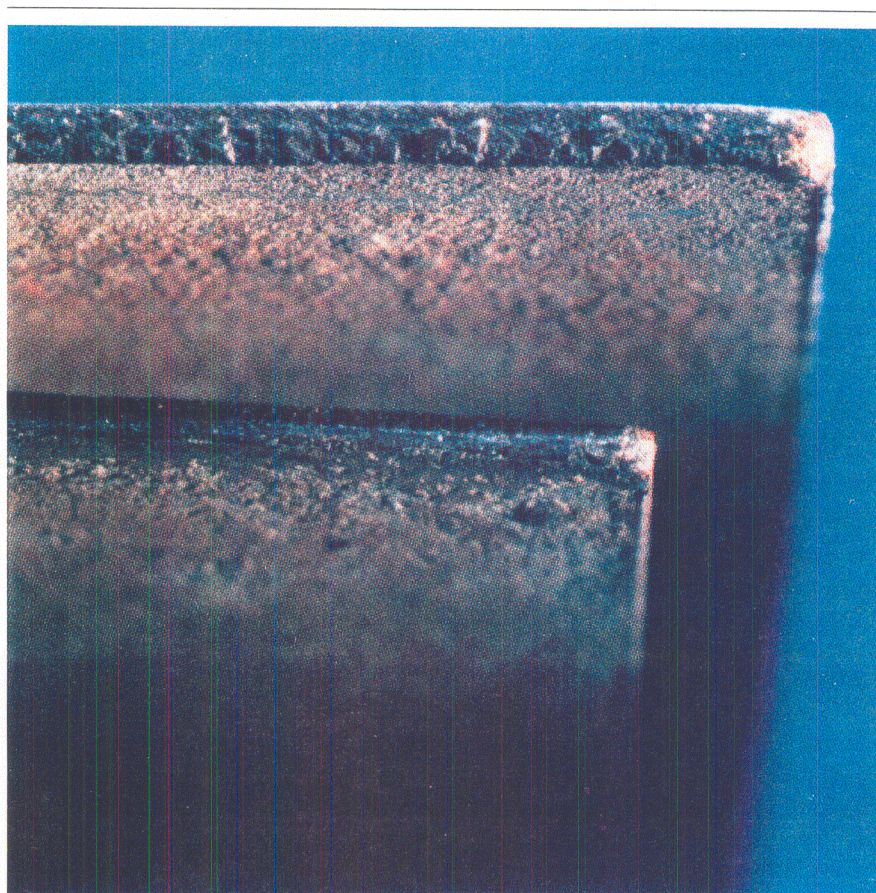


FIGURE 7

Appearance of Cut Edges. Upper: Type 2 Al-coated. Lower: 53.9% Al-Zn Coated.

long as a zinc coating. At the industrial site, the degree of improvement is threefold.

Based on 13-year quantitative weight-loss data,³ the life of the 55% Al-Zn coating was estimated to be,¹² respectively, 35, 41, and 53 years in the moderate marine, rural, and industrial environments. The present results are consistent with those projections.

Appearance of Aluminum-Zinc Alloy-Coated Steel Sheet After Thirty Years of Outdoor Exposure

During the course of the 30-year outdoor tests, most of the original coatings failed completely. Many of the steel panels have been completely consumed by rust, particularly at the marine test sites. The only panels remaining in test without rust after 30 years are those coated with alloys containing 44.6% or more Al. These were

exposed at the moderate marine, rural and industrial sites. The skyward surfaces of these panels is shown in Figure 6. Generally, these specimens are in remarkably good condition, except as follows.

In the industrial environment, the remaining test panels are covered with deposits that are the result of fallout from the nearby steelmaking operations. The discoloration from these deposits is superficial and should not be mistaken for rust. The undersides of specimens exposed at the industrial, rural, and moderate marine sites, are free of these deposits.

In the moderate marine environment, evidence of more rapid attack is apparent on the edges of the panels at the four ceramic insulators that hold the specimens to the test rack. This phenomenon is attributed to the effect of crevices formed at these points.

TABLE 3

Corrosion Potentials of 54% Al-Zn Coated Sheet After 30-Year Exposure

Site	Corrosion Potential (V_{SCE})
Unexposed	-1.00
Moderate marine, 30 y	-0.92
Rural, 30 y	-0.95
Industrial, 30 y	-0.95
Bare steel, unexposed	-0.45
Pure Zn, unexposed	-1.00

Appearance of Cut Edges

The appearance of the cut edges of the 53.9% Al-Zn alloy coated and the Type 2 Al-coated sheet panels are shown magnified in Figure 7. Cut edges of the 53.9% Al-Zn alloy-coated panel show only a superficial stain and remain free of rust deposits after the 30-year exposure in all environments. The same is true of the Type 2 Al-coated in the moderate marine environment, but not in the rural and industrial environments where the Al is passive and serves only as a barrier.

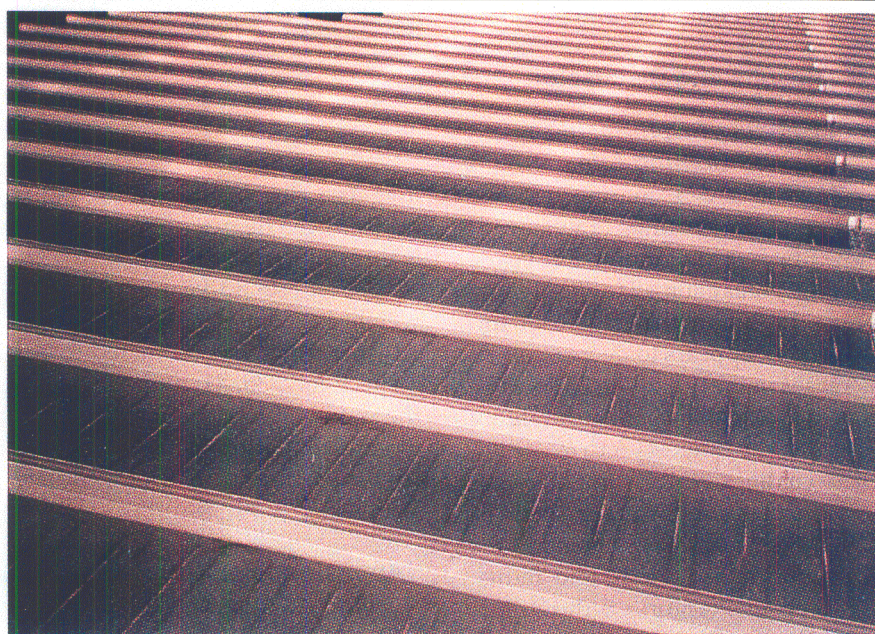
Corrosion Potentials of 53.9% Aluminum-Zinc Alloy Coatings

Corrosion potentials of 53.9% Al-Zn alloy-coated sheet are given in Table 3 as measured after 30-year exposure at the outdoor sites. The potential of an unexposed 53.9% Al-Zn coating is $-1.00 V_{SCE}$. This value is identical to that of an unexposed Zn coating. It is also much less than the value of about $-0.45 V_{SCE}$ exhibited by steel under similar conditions. This clearly indicates that the coating is capable of providing sacrificial protection to steel exposed at cut edges. Although the coating potential has become slightly less negative after the 30-year exposure, it is still much more negative than steel, and is able to provide continuing sacrificial protection to the steel substrate. The Zn coatings on the galvanized panels exposed at these has been totally consumed for many years. It is clear that the 53.9% Al-Zn coating provides more enduring sacrificial protection.

A slow increase in corrosion potential of 55% Al-Zn coating has been

**FIGURE 8**

Typical building with 55% Al-coated steel sheet roof after 20 years in Appleton, Wisconsin.

**FIGURE 9**

Appearance after 20 years of low-slope (1/2:12), standing seam roofing made from 55% Al-Zn coated steel sheet in Appleton, Wisconsin.

observed during laboratory immersion tests. The phenomenon is explained in terms of the corrosion mechanism as previously reported,² namely preferential dissolution of the Zn-rich interdendritic regions of the

coating microstructure. As Zn corrodes at the surfaces of these regions, it is replaced by precipitated Zn corrosion products. The Zn remaining deeper within the interstices is screened. Therefore, the surface po-

tential is reduced by the IR drop through the corrosion-products in the interdendritic channels.

Long-Term Performance of 55% Al-Zn Alloy-Coated Roofing Sheet

A typical building with 55% Al-Zn alloy-coated steel roofing sheet is shown in Figure 8. The roof panels were installed when the building was first constructed in 1974.

The overall excellent appearance of this roof after 20 years of service is evident in Figure 9. The roof is a Butler MR-24 standing-seam system with a slope of 1/2:12 (2 degrees from the horizontal). This slope is much shallower than that of the 30-year test panels (30 degrees from horizontal). This is significant because shallower slopes drain more slowly and receive the sun's rays at a shallower angle. Consequently, shallower slopes are subject to a greater time of wetness which tends to increase corrosion.

The roofing panels are joined and sealed end-to-end by use of Al alloy straps and 302 stainless steel studs and nuts. They are sealed with butyl rubber caulk. The compatibility of the 55% Al-Zn coated sheet with the other materials of the roofing system is seen in Figure 9.

An interesting observation made on this roof concerns the condition of the Z275 galvanized gutter hangers. This component is a strap that is bolted to the roof to support the rain gutters. As shown in Figure 10, the Zn coating on the gutter hanger has been totally consumed. The surface was covered with rust. This condition was noted frequently on older roofs. The rusted galvanized hanger provides a striking contrast to the intact surfaces of the adjacent roofing sheet. It provides a conclusive demonstration of the superior durability of the 55% Al-Zn coated steel sheet. We note that to upgrade the performance of the gutter hanger, the manufacturer of this roofing system has now switched from galvanized to 55% Al-Zn coated.

One of the buildings inspected led to the fortuitous discovery of a

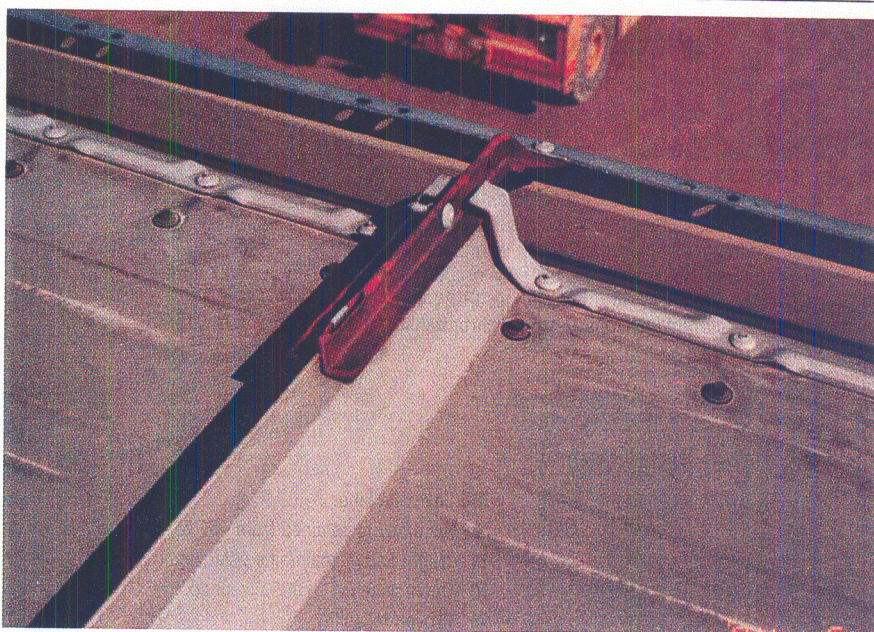


FIGURE 10

Comparison of the appearance of 55% Al-Zn coated steel roofing sheet with rusted galvanized gutter hanger after 20 years in Appleton, Wisconsin.

small section of roofing that had been previously cut out to allow penetration of a stack subsequent to the initial construction. This finding provided a unique opportunity for preparation of a metallographic cross section and laboratory examination of the 55% Al-Zn coating after long-term exposure on the roof. As seen in Figure 11, most of the original coating is still intact. Only scattered regions of localized interdendritic corrosion are evident. It is also clear that the cut edges are free of rust, demonstrating the good cut-edge protection afforded by this coating.

Summary

Thirty years of outdoor corrosion testing in marine, rural, and industrial environments show conclusively that the durability of the 55% Al-Zn coating is more than two times that of an equal-thickness Zn coating.

The outdoor corrosion tests also demonstrate that cut edges of 55% Al-Zn coated sheet are well protected, and corrosion potential measurements show that the coating remains galvanically active during these long-term outdoor exposures.

The excellent durability and cut-edge protection of the 55% Al-Zn coated steel sheet is confirmed by the performance of roofing panels that have been in service on buildings in the midwestern, northeastern, and southeastern US for up to 22 years.

Acknowledgment

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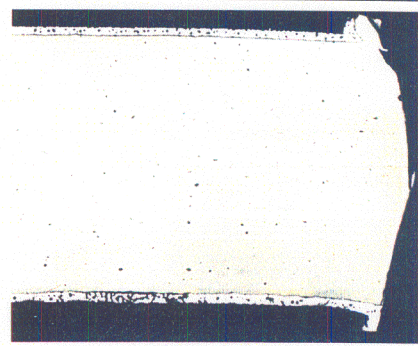


FIGURE 11

Cross section showing edge of 55% Al-Zn coated sheet exposed on roof for 15 years in Appleton, Wisconsin. Original mag. x100; reduced 44%.

for the corrosion potential measurements; and BIEC consultant W.D. Barker for conducting the on-site evaluations of roofing; and to Butler Manufacturing Company for identifying and arranging access to the buildings.

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