NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
SYNTHESIS OF HIGHWAY PRACTICE 112

COST-EFFECTIVENESS OF HOT-DIP GALVANIZING FOR EXPOSED STEEL

TRANSPORTATION RESEARCH BOARD
National Research Council

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FOR EXPOSED STEEL

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TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL
WASHINGTON, D.C.   DECEMBER 1984

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway and Transportation Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full co-operation and support of the Federal Highway Administration, United States Department of Transportation.

The Transportation Research Board of the National Research Council was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as: it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communications and cooperation with federal, state, and local governmental agencies, universities, and industry; its relationship to the National Research Council is an assurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

The program is developed on the basis of research needs identified by chief administrators of the highway and transportation departments and by committees of AASHTO. Each year, specific areas of research needs to be included in the program are proposed to the National Research Council and the Board by the American Association of State Highway and Transportation Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are the responsibilities of the National Research Council and its Transportation Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

NOTICE

A vast storehouse of information exists on nearly every subject of concern to highway administrators and engineers. Much of this information has resulted from both research and the successful application of solutions to the problems faced by practitioners in their daily work. Because previously there has been no systematic means for compiling such useful information and making it available to the entire highway community, the American Association of State Highway and Transportation Officials has, through the mechanism of the National Cooperative Highway Research Program, authorized the Transportation Research Board to undertake a continuing project to search out and synthesize useful knowledge from all available sources and to prepare documented reports on current practices in the subject areas of concern.

This synthesis series reports on various practices, making specific recommendations where appropriate but without the detailed directions usually found in handbooks or design manuals. Nonetheless, these documents can serve similar purposes, for each is a compendium of the best knowledge available on those measures found to be the most successful in resolving specific problems. The extent to which these reports are useful will be tempered by the user's knowledge and experience in the particular problem area.

FOREWORD

By Staff
Transportation
Research Board

This synthesis will be useful to materials engineers and others interested in the use of hot-dip galvanizing for protection of exposed steel. Information is presented on the performance of hot-dip galvanizing and on economic considerations in selecting a coating for exposed steel.

Administrators, engineers, and researchers are continually faced with highway problems on which much information exists, either in the form of reports or in terms of undocumented experience and practice. Unfortunately, this information often is scattered and unevaluated, and, as a consequence, in seeking solutions, full information on what has been learned about a problem frequently is not assembled. Costly research findings may go unused, valuable experience may be overlooked, and full consideration may not be given to available practices for solving or alleviating the problem. In an effort to correct this situation, a continuing NCHRP project, carried out by the Transportation Research Board as the research agency, has the objective of reporting on common highway problems and synthesizing available information. The synthesis reports from this endeavor constitute an NCHRP publication series in which various forms of relevant information are assembled into single, concise documents pertaining to specific highway problems or sets of closely related problems.

Most highway agencies use hot-dip galvanizing extensively for guardrails, bridge railing, fencing, and other appurtenances, and some have used galvanizing for steel bridge members. This report of the Transportation Research Board contains information on the performance of hot-dip galvanizing, explains the galvanizing process,

and describes procedures for determining if galvanizing is cost-effective in a particular application.

To develop this synthesis in a comprehensive manner and to ensure inclusion of significant knowledge, the Board analyzed available information assembled from numerous sources, including a large number of state highway and transportation departments. A topic panel of experts in the subject area was established to guide the researcher in organizing and evaluating the collected data, and to review the final synthesis report.

This synthesis is an immediately useful document that records practices that were acceptable within the limitations of the knowledge available at the time of its preparation. As the processes of advancement continue, new knowledge can be expected to be added to that now at hand.

CONTENTS

COST-EFFECTIVENESS OF HOT-DIP GALVANIZING FOR EXPOSED STEEL

SUMMARY   Zinc has been used as a protective coating for steel for more than 100 years, although major uses have been in areas other than highway structures and appurtenances. Highway applications of hot-dip galvanized steel have included bridges, bridge railings, and guardrail. A number of bridges erected in Quebec between 1963 and 1970 were reported to be performing well after up to 17 years of maintenance-free service. The first hot-dip galvanized bridge in the United States was at the Stearns Bayou in Michigan in 1966. After 18 years, the galvanizing on this bridge is reported to be performing well. An experimental project was begun in 1970 on a pair of parallel Interstate bridges in Indiana, one hot-dip galvanized and the other painted with their standard paint. A report by the Indiana DOT on these bridges in 1983 indicated that the galvanized bridge has been performing satisfactorily whereas the painted bridge has shown progressive rusting over the years.

Bridge railings in Michigan have been hot-dip galvanized since an investigation begun in 1956 showed that a 20- to 25-year service life could be expected. Michigan also concluded that galvanizing of guardrails was more economical than painting. In Pottawattamie County, Iowa, rails on existing bridges are removed, hot-dip galvanized, and replaced during a normal work week; the galvanized coating is expected to last 20 to 30 years.

Hot-dip galvanizing has been used extensively in industrial environments, such as wastewater treatment plants, refineries, and chemical plants. Investigations have shown that galvanizing has given excellent service under these severe service conditions.

Atmospheric exposure tests indicate that the weight loss of zinc plates is linear and correlates well with weight loss of galvanized panels. Thus, the performance of a hot-dip galvanized structure in a particular location may be predicted by exposing weighed zinc plates in the location for 1 to 3 years.

The hot-dip galvanizing process begins with immersion in a solution to remove oil and grease. This is followed by an acid bath to remove mill scale and rust. The item is then rinsed, fluxed, and immersed in molten zinc until it comes up to bath temperature. The iron in the item will then have reacted with the zinc to form several iron-zinc alloy layers. These layers are covered with a layer of pure zinc. The zinc' and alloy layers provide a barrier protection to the steel. In addition, the zinc offers sacrificial protection; if the galvanizing is scratched, the zinc will corrode to protect the steel.

Many large structural members are not candidates for galvanizing because they are too large for available galvanizing tanks or there are difficulties of transporting them to galvanizing facilities. Also, steel should not be welded after it is galvanized

and this may limit its attractiveness in some applications. Careful attention to design and construction of galvanized items will minimize problems such as distortion, embrittlement, or tensioning high-strength bolted connections.

Hot-dip galvanizing has proved to be a cost-effective treatment in many cases. Although it generally requires a greater expenditure than does painting, it has frequently paid back this additional expense through the savings implicit in longer life. The key factors that influence the relative cost-effectiveness of hot-dip galvanizing have changed over time and vary with circumstances. Further, as paints have been improved in recent years, their effectiveness relative to galvanizing may have improved. The effectiveness of paints varies widely with method of application, as described in a synthesis, "Protective Coatings for Bridge Steel," to be published in late 1985. Thus, meaningful comparisons between competing coatings can only be made when alternatives are compared in specific circumstances.

In comparing the costs of coating alternatives, it is the life-cycle costs that should be considered. These costs include the initial costs and the costs of future maintenance. The maintenance costs should be estimated assuming an inflation factor. The comparison of the costs of alternatives should be done either by comparing the future value of all costs over some period of time or by comparing the net present worth of these costs.

In many instances, economic analysis will show that galvanizing is cost-effective, particularly in areas where the climate is severe and where suitable galvanizing facilities are nearby. This synthesis uses numerous illustrative examples from Ohio, Michigan, Indiana, Iowa, and Quebec where these conditions are found. In other conditions, notably in arid climates or in situations where suitable galvanizing facilities are not nearby, economic analysis may show that painting is more cost-effective.

Thus, an economic analysis that includes both initial costs and future maintenance costs and that considers interest, inflation, and net present worth, should be used to select the most cost-effective protective coating system.

CHAPTER ONE

INTRODUCTION

The purpose of this report, as required by Section 110(b) of the 1982 Surface Transportation Assistance Act, is to present information concerning the cost-effectiveness of the hot-dip galvanizing process for the protection of exposed structural and miscellaneous steel. This report presents information to enable the reader to understand the properties that characterize the galvanizing process, its applications and economics.

PAINT AS A PROTECTIVE COATING

The term "paint," which is commonly used for the decorative and lightly protective material used to coat housing interiors, does not adequately describe the contemporary protective coatings used on bridges, which are complex systems. Because of the complexity of the subject, an NCHRP Synthesis (Topic 15-09, "Protective Coatings for Bridge Steel") dealing with protective coatings in greater detail is being prepared. However, to properly compare and contrast hot-dip galvanizing, a cursory treatment of protective coating principles and performance is included where necessary.

According to a practicing professional engineer, 75 to 80 percent of premature coating failures are attributable to improper application (1). Failures are caused by a variety of circumstances such as inadequate thickness, environmental degradation, a porous coating, incomplete coverage, application over contamination, blistering, and insufficient adhesion to the substrate.

A study was performed for the Federal Highway Administration (FHWA) to evaluate coating performance to date and to develop effective selection techniques (2). The purpose of the study was to gather data on costs related to corrosion of highway structural steel. Sources of information included (a) the open literature, (b) service data on coating performance from four representative states, (c) information from paint suppliers and a paint inspection firm, (d) galvanizing cost data from a trade association, and (e) reports of experience from a wide variety of practicing highway engineers.

The information was categorized in elaborate form so that a simulation computer model could be built to analyze and predict corrosion and maintenance costs. An appendix was devoted to the use of 1979 cost data applied to the full spectrum of factors involved in pricing the painting of bridges. The appendix lists the elements involved and the cost figures that make it helpful in understanding the role played by each step in arriving at the final cost per square foot of surface protection. The elements considered included the following:

1. Type of bridge (truss or girder)
2. Elements of cost (square foot of surface per ton of steel)
3. Prevailing weather conditions
4. Traffic control requirements
5. Location of bridge (local or remote)

6. Labor rates
   a. Hourly
   b. Premiums
   c. Benefits
   d. Insurance and taxes
   e. Travel/Subsistence
   f. Supervision (crew personnel)
7. Coating materials
8. Equipment (leased in part)
9. Overhead
10. Profit
11. Bonds and Insurance
12. Rigging
13. Shop estimating

In addition, the study identified such additional variables that affected coating performance as the local environment, type of coating applied, thickness of coating, and size of bridge, among others. The study established that nondurable systems require frequent painting and costs accumulate through the life of the bridge. To establish the model, data were gathered on 2,052 bridges from California, Louisiana, Massachusetts, and Washington. The dependent variable was the number of years between painting. For an oleoresinous oil-base system, the study found the following average life expectancy in years (there were insufficient data for California and Louisiana):

State	Marine	Industrial	Rural	Desert
Washington	9	11	12	13
Massachusetts	12	15	17	—

The study found that the majority of states have been using oil-based paints containing lead. However, there is a growing trend toward the use of zinc-rich primers with an organic top coat. There is a growing concern with regard to repainting programs because of the pollution being created by the removal of old lead-based coatings and the methods being used to prepare the surface (3).

ZINC AS A PROTECTIVE COATING

In 1742, the French chemist, Melouin, reported that he had succeeded in applying a coating to iron by immersing it in molten zinc. In 1836, another French chemist, Sorel, patented a means for the coating of iron with zinc after cleaning it in nine percent sulfuric acid and fluxing it with ammonium chloride. By 1850, the galvanizing industry in Britain was using 10,000 tons of zinc a year for the protection of iron products.

In 1981, zinc use for the protection of steel reached a level of two million tons worldwide. Among the major uses of gal-

vanized steel products are farm building roofs and siding, feed troughs for livestock and poultry, farm fencing and barbed wire, gutters and downspouts, heating and air conditioning ductwork, numerous electrical applications, and fencing. The product has been used almost exclusively by utilities for substation structures as well as for a substantial portion of transmission tower requirements.

It should be appreciated, however, that no one system of corrosion protection fits all needs; various systems complement one another and some are used in conjunction with one another.

HOT-DIP GALVANIZING—PERFORMANCE AND APPLICATIONS

This chapter presents data on the performance of galvanized steel in various applications and environments. The information given herein was drawn from published reports, some of which make comparisons between galvanizing and painting. However, these reports often did not identify the specific type of paint used for comparison and, therefore, this information is not given in this synthesis. Moreover, as paints have changed over the years from lead and chromate to alternative pigments, the comparisons made may or may not still be valid.

PERFORMANCE OF GALVANIZED STEEL

In 1967 Sisler (4) reported that, on the basis of performance and cost per square foot per year, Monsanto Chemical Company preferred to use hot-dip galvanized structural steel wherever size and configuration made it possible to be galvanized. Their second choice was a topcoated inorganic zinc-rich coating.

Vickers (5) pointed out that in the corrosive Houston area the transmission towers belonging to Houston Lighting and Power have served effectively from as far back as 1925 and 1930 to the time of writing (1962). In a second article published in 1964 (6), he promoted the idea that hot-dip galvanizing and inorganic zinc-rich compositions can be used in a complementary sense on many jobs. He described how galvanizers have trouble with such items as boxed plate sections, unequal sections, mixed types of material, and oversized lengths and widths.

A number of reports have appeared depicting the performance of protective coating systems in different industrial environments in the corrosion journal of the National Association of Corrosion Engineers. The authors generally reported on the performance of a number of contemporary coating systems in such specific aggressive environments as fertilizer manufacture, pulp and paper processing, caustic and chlorine production, and the petrochemical industry, among others. The resulting service data have proved valuable to those operating in less aggressive environments because the coating systems have, in a sense, been evaluated and rated by those specific exposures.

Since the mid-1970s, reports on this subject have leaned more toward an economic analysis of the resulting service data. For example, before 1975, the major economic concern of mainte-nance engineers dealt with the initial cost per gallon of a protective coating formulation that led, in turn, to the cost per square foot of protection. Little heed was given to the service life of the coating and less heed was given to the fact that the cost of the protective coating materials was a relatively small portion of the total project, which included rigging, surface preparation, application, and the various other factors cited previously (2). It was only when maintenance funding was reduced that maintenance engineers recognized that the more significant criterion of coating performance was the cost per square foot per year. That kind of an analysis quickly resulted in the recognition that a protection system that costs more initially may be less expensive in the long run.

Among the pioneering investigators expounding this philosophy for handling the maintenance dollar more effectively was Tator (7), who developed a test panel that incorporated a number of features found on structural steel, such as a channel to retain water, weld spatter, sharp edges, scratches, etc. Evaluation of competitive coating systems on such a test panel permitted the best economic choice in a specific environment. Tator, in 1961, was among the first to recognize that use of a galvanized base would extend the service life of a topcoat that had to face an aggressive chemical environment.

Also, the FHWA report (2) indicates that:

> Zinc coatings are very resistant to normal atmospheres; however, in acidic or coastal atmospheres their life can be extended through painting. Painting systems on galvanized steel perform differently than paint systems on bare steel, because spreading of rust beneath the paint film, a major factor contributing to the deterioration of paint films, is no longer a problem. . . . Demands on surface preparation are significantly decreased as one goes from painting of bare steel to painting of galvanized steel.

For high performance paints, such as vinyls, epoxies, and urethanes, a brush blast or solvent wipe of a new galvanized surface is sufficient, or hand cleaning for a reapplication will be adequate according to these studies. According to the FHWA report (2), there are two options for painting galvanized steel: (a) painting can be deferred for up to 33 years in a normal environment before surface preparation can become rather costly, and (b) the combination of longer paint life combined

with the long service life of the zinc makes an excellent combination and therefore, it might be prudent to paint the galvanized structure in the shop while it is being fabricated.

The FHWA report (2) also addresses the service life of coatings on different types of bridges. As many paint systems have a propensity to fail at the sharp edges of a beam or angle, paint failures appear most frequently on truss-type bridges, which have many more edges than girder bridges. In Massachusetts, paint systems on girder bridges outlast the same systems on truss bridges by three years. In sharp contrast to this failure of paint coatings, galvanized edges tend to build up in thickness, as shown in Figure 1 and, thus, create a complete protective envelope around the steel object.

In November 1983, Roebuck, Morrow, and Neveson (8) offered a paper on the use of various forms of zinc on bridges. The authors make the significant point that metallic films (galvanized, metallized, and inorganic zinc-rich compositions) create both a barrier effect and an electrochemical galvanic effect that prevent undercutting and delamination coating failures. The authors also make the point that with time and inflation the value of a well-maintained bridge actually increases. This value will increase in direct relation to the cost of erecting an identical bridge. To maintain this investment only high-quality protection should be used.

A research program on coatings usually begins with evaluation tests conducted on simple configurations, such as a 4 by 6 in. metal plate. The test of conviction, however, is the one conducted on full-scale components in their service environments. The resulting performance of the components is far more significant than the performance in an artificial environment created to simulate one or more of the atmospheric constituents.

APPLICATIONS OF GALVANIZED STEEL

Nishimura (9) reported that designers, engineers, specifiers, and owners in both government and industry were surveyed to ascertain their interest, knowledge, and convictions regarding coatings on steel in general and hot-dip galvanizing in particular. More than 60 percent of the respondents indicated that they were under-informed about the technical and performance aspects of galvanized systems; and 80 percent felt inadequately prepared to analyze the cost of galvanizing versus the cost of application of conventional coatings.

Nishimura indicated the results of the survey showed that applications based on specific case histories of good performance would aid in evaluating the specification of galvanized steel for new projects. The designers and owners wanted to see where someone in a similar situation had specified galvanized steel many years earlier and today is realizing the benefits of that decision.

Galvanized Bridges

In 1964, Hall (10) pointed out the enormous maintenance problem of the five bridges across San Francisco Bay and the cost of maintaining the several bridges leading to Montreal Island in Quebec. He indicated that a need existed to overcome the deficiencies in bridge painting and suggested that there is a precedence for using hot-dip galvanizing in that the Callender-Hamilton type galvanized bridges have been erected all over the world since 1940. The points he made, besides the one of increased corrosion resistance, are:

FIGURE 1 Galvanized edge with built-up thickness.

- Messy touch-up of bolt heads after erection is eliminated.
- Steel workers prefer working with clean steel.
- The bridge can be opened immediately after erection because touch-up or finish coats are unnecessary.
- The inspection routine both initially and during the life of the bridge can safely be minimized.
- The frequent traffic interruptions owing to touch-up and repainting are essentially eliminated.
- When the time arrives for painting the zinc surface, costly blast operations with all that is implied are unnecessary because only a simple cleaning is required.
- Individual galvanized members should never require replacement.

Hall dealt with the cost of galvanizing (1964 prices in Canada) by stating that as "labor costs continue to rise and as galvanizing prices on large tonnages decrease this initial cost difference may soon close and perhaps even reverse" (10). According to Seelinger (11), such a reversal occurred in 1982 in the southwestern United States.

In 1963 the Quebec Ministry of Transport decided to galvanize Pont Lizotte, a 3-hinged arch structure joining river banks 400 ft apart (10). The bridge contains more than 300 tons of steel, has a clear mid-span of 200 ft and cantilevers 60 ft back from the piers that carry 45-ft suspended box girders. The deck-type truss is composed of rolled wide-flange shapes and some welded H sections. The longest members are the 49-ft chord sections and the largest are the box girders that weigh 4½ tons each and measure 45 ft long with a cross section of about 2 by 3½ ft. Shop connections were welded and field assemblies were joined with 1-in. diameter high-strength bolts. All structural members were galvanized as were other components of the bridge including railings, bolts, and expansion joints. The total cost of the bridge was $320,000. Erected structural steel amounted to $200,000. The difference between the cost for galvanizing and the estimate for painting (a 5-year system) was about $11,000 or about 3 percent of the cost of the bridge. The paint system was not identified in reference 10.

One of the largest Canadian zinc suppliers has monitored the performance of the earliest galvanized bridges erected in Canada, particularly in the province of Quebec. In a review it points out the Pont Lizotte as being the world's first bridge designed with friction-grip connections to be completely galvanized (12). Since then six other bridges were commissioned and erected as listed in Table 1.

Corrosion engineers from the zinc supplier have periodically inspected these bridges. In 1980 they reported that the galvanized coating for the 17-year-old Pont Lizotte was intact and generally distress free (11). The coating had weathered to a gray color only slightly different from that observed at the 1969 inspection. The film thickness still measured 4.2 mils on light sections and up to 7.8 mils on the heaviest members. The Canadian Standards Association specification G164 calls for a minimum 3.4-mil coating. The coating on nuts, gusset plates, hand rails, and other attachments measured 3.5 mils or thicker. Superficial rusting that occurred during transit as a result of impact damage had not advanced to any degree requiring attention after all this time. The corrosion engineers concluded that hot-dip galvanizing has effectively controlled the corrosion of the steelwork of the seven Quebec bridges. They state maintenance costs for the group as a whole would have been con-

siderably higher as repainting would have been required at least once for each of the six newer bridges and several times for Pont Lizotte.

The first hot-dip galvanized bridge in the United States was the Stearns Bayou bridge erected in Ottawa County, Michigan in 1966. Every structural member, fastener, and other steel component was hot-dip galvanized after fabrication. At the time of erection and during the design stage, the county bridge engineer had the benefit of consultation concerning the ongoing research at the University of Illinois on friction-type connections in galvanized steel joints. Brechting (13) revealed the modifications he made to facilitate the galvanizing process. Other modifications incorporated in the initial design to avoid the corrosive effects of deicing salt water drainage included telescoping splash plates in the joints to divert deck drainage away from the beams. Additional information is contained in references 14 and 15.

In 1970, the Indiana Department of Highways initiated an experimental project to compare hot-dip galvanizing and painting for the protection of structural steel (16). One of two bridges on Interstate 69 in Marion County was hot-dip galvanized in accordance with ASTM A 153 and A 123. A small section of the galvanized bridge was painted with the conventional zinc dust-zinc oxide primer. The other bridge was coated in accordance with the Indiana specifications (basic lead silico chromate primer with basic lead or aluminum first and finish coats).

Although there was some warping of structural elements during galvanizing, the project engineer reported no difficulty in the erection in 1973. The 1974 inspection report stated that some brown staining (considered to be evidence of beginning rust) was occurring in the web section of some of the painted beams. The most pronounced stain was noted near the end of the 4th beam. The 1975 report indicated that the web stains had changed little, but some corrosion was observed on the end diaphragms of the painted structure. This is a continuation of that reported the year before. Also observed were localized areas of corrosion along edges of the bottom flanges of the painted beams. The 1976 report indicated a slight extension of the rust staining reported in 1975. No comments were made concerning the galvanized structure other than to note that there had been little change since the previous inspection.

The 1977 report indicated that, on the painted structure, more of the diaphragms developed rust stains and that there was some general increase in rust staining but no increase in severity. As for the galvanized structure, the report stated that there appeared to be little change since the previous inspection. The 1980 report indicated further rusting of painted diaphragms. Rust was progressing also in other areas. The condition of the galvanized structure continued to be satisfactory as did the primer on the zinc surface. The 1983 report is an extension of the 1980 report in that the galvanized structure is satisfactory and the paint staining is continuing.

During the 1960s, Michigan tested several coating systems for bridges, including galvanizing. In 1974 Permoda and Gabel (17) reported that the best performing coating was hot-dip galvanizing with an estimated service life of more than 20 years.

Although protection from corrosion is documented, much of the hot-dip galvanizing practice is found in only a few states (Ohio, Michigan, Indiana, and Iowa) and one Canadian province (Quebec). While hot-dip galvanizing is presumably cost-effective in some other areas as well, examples of its application in other

TABLE 1

DETAILS OF GALVANIZED BRIDGES IN QUEBEC

| Bridge and Location | Commissioned | Dimensions | | Type |
		Length	(Tons Steel)	
Lizotte Rivière-du-Chêne, Déchaillon	1963	400'	(350)	Cantilevered 3-hinged arch
Val-des-Bois Rivière-du-Lièvre, Val-des-Bois	1964	275'	(180)	Conventional truss, single span
Notre-Dame-de-Pontmain Rivière-du-Lièvre, Notre-Dame-de-Pontmain	1964	152'	(180)	Conventional truss, single span
Parrot Rivière-du-Loup, St. Antonin	1965	456'	(500)	3-span conventional truss
St. Wenceslas Rivière Becancour, St. Wenceslas	1968	632'	(525)	Support structure below road surface
Manicouagan Hauterive, Baie Comeau	1969	900'	(1500)	Cross-braced below road deck
Bromptonville Rivière St. François, Bromptonville	1970	275'	(370)	Single span, conventional truss

areas were less frequent, perhaps because of excessive distances between the galvanizing facility and the assembly site or because of other factors. Similarly, there are undoubtedly instances when painting was chosen in preference to hot-dip galvanizing following an economic comparison.

Miscellaneous Steel for Highways

Michigan's experience with bridge railing indicated that protecting this item with paint involved substantial maintenance including repainting on a three-year schedule (18). As sandblasting was not feasible, power and hand brushing were used to prepare the surface. For comparison, before 1940 repainting cost $1.00 per linear foot. After World War II, costs ranged between $3.00 and $4.00 per foot and in a controlled test it reached $4.25 per foot. In fact, 80 percent of the cost was for surface preparation. Cardone (18) estimated it would cost $1,056,000 every three years to repaint 50 miles (264,000 linear feet) of bridge rail at $4.00 a foot.

In 1956, one section of a bridge rail was galvanized. After two years of exposure, no deterioration was visible and the remainder of the railing on the bridge was galvanized. By 1961 the cost for galvanizing was $2.25 per foot plus $3.00 per foot for removal, transportation, and re-erection. The performance of this bridge railing at the time convinced the Highway Department of the quality of service received from galvanized steel. Consequently, galvanizing of bridge railing was adopted as a basic maintenance program. Inspection of this railing in 1973 revealed only minor spot rusting and a 20- to 25-year service life was projected (17).

In 1959, galvanizing was extended to guardrail, which for the two previous years had been painted after introduction as a replacement for galvanized cable. Cardone (18) stated that the initial application costs of painting and hot-dip galvanizing were roughly comparable; because the service life expectancy of galvanizing was four to five times that of paints, substantial savings could be expected if galvanizing were used instead of painting.

In Pottawattamie County, Iowa, bridge guardrails and posts have been dismantled, stripped of old paint and rust, hot-dip galvanized, and reinstalled (19). The rails and posts are taken down on a Monday, shipped 70 miles to a job-shop galvanizer, and replaced on Friday. The bridges being treated range in length from 20 to 300 ft. The cost for reconditioning has averaged $12 per linear foot per side, including galvanizing, labor, hardware, and equipment. There is approximately 2.5 tons of steel per 100 ft of bridge. The minimum coating weight of 2 oz/ft² of surface is expected to result in 20 to 30 years of service.

Galvanizing is used extensively for guardrail, bridge railing, fencing, and other miscellaneous steel. Surprisingly few published reports exist to document the cost-effectiveness of this treatment. Most of the literature on galvanizing as a protective coating analyzes industrial uses in more corrosive environments than would be expected for a bridge. Some of these are presented below.

Wastewater Treatment Plants

The Detroit Wastewater Treatment Plant is one of the country's largest (20). Constructed in the 1930s as a primary treatment plant, it was expanded in the 1960s as a secondary treatment facility. More than 620 linear ft of troughs and baffles fabricated in sections 21 and 23 ft long for 4 250-ft diameter clarifiers were galvanized.

The architect for the project stated that galvanizing "gave maximum protection to the effluent troughs and their brackets,

which are totally and continuously immersed in wastewater" (20). Other items exposed to the same corrosive environment were also galvanized.

The Baltimore Back River Wastewater Treatment Plant was constructed in 1911 as a secondary treatment facility (21). According to the principal engineer, the major structures and components of this mature plant were virtually maintenance-free for the first 30 years of its life, largely because of the extensive use of hot-dip galvanizing.

Conditions in a wastewater plant can be extremely corrosive. The Back River plant deals "with some of the most severely corroding conditions found on the East Coast. . . . Although galvanized steel is used for many applications in the plant, the most frequent is for immersion service. Galvanized weirs have been used in the primary settling tanks in continuous service since 1938. All the brackets and guide rails in the settling ponds have been in excellent condition for 30 years" (21). The gratings at the grit removal facility have lasted for 40 years.

> Much of the structural steel, especially at the water line—the point of greatest attack—is galvanized, as are the scum and flow troughs in the final settling tanks. Underwater structures, guide rails, floor gratings, pit covers, catwalks above tanks—which have highly corrosive atmospheres because of methane gas—are all protected by the zinc coating. Not only is the flow of sewage corrosive, but the atmosphere around each facility is also very destructive. For that reason we have used galvanized material for many of the structural members above ground (21).

Applications of zinc-coated steel exposed to atmospheric corrosion centered around the aeration process. Here, large tubular rotary distributors driven by water pressure must be protected from attack both internally and externally. These galvanized elements have been operated since 1950.

The article concluded, "because of the excellent results at Back River, personnel from treatment plants and consulting engineering firms nationwide have frequently sought information and advice from our staff. We have experimented with many types of coatings and have concluded that the galvanized variety is the most cost-effective" (21).

Refineries

• In 1978, Texaco Canada Limited opened its 1480-acre refinery in Nanticoke, Ontario (22). Some 2700 tons of galvanized structural steel was used, much of it on the process side of the plant, which is more corrosive. The decision to use galvanized steel was based on long experience with a low-cost, long-life, and low-maintenance system. The engineers point out that "while pre-painted steel was a possibility, the high cost of painting at that time and the added expense of implementing a paint maintenance program precluded this option." A breakdown of the 2700 tons of structural steel shows that about 1870 tons can be found among columns, beams, and "I" and "L" frames, while 130 tons were used for platform structures, stairways, and for some 700 ladders. The remaining 700 tons were used for platform steel, handrails, and other structural elements. This commitment to galvanized structural steel was based on the excellent maintenance record of this product in scattered applications at their other refineries as well as on the costly maintenance of the paint systems employed on their structural steel.

Chemical Plants

The Celanese Company in 1956 decided to use galvanized steel in its Deer Park, Texas polyethylene plant (23). The decision to use galvanized steel was based on the excellent 10-year performance of hot-dip galvanized catwalks in another plant. The initial cost estimate for galvanizing the structural steel was equal to that for a three-coat paint system over a wire-brushed surface. A 10- to 15-year service life was anticipated.

Ten years later, in 1966, the plant was jointly inspected by representatives of the Celanese Company and the Zinc Institute. There were no signs of significant deterioration. None of the galvanized structural members required any maintenance. A few rust spots were found on the anchor bolts in the concrete footings and there was an occasional trace of iron-zinc alloy stain but no visible rust on any of the galvanized structural components. Zinc coating thickness averaged 5 to 7 mils with a high of 15 mils on large structural members and a low of 3 mils on small angles.

A more recent inspection after 20 years service in January 1978 showed that thickness measurements on structural columns, stairways, stringers, and beams averaged 5 mils. The galvanized coating on fasteners was gone and some pitting of the steel was evident. The structures, however, were not distressed and the galvanized coating adjacent to the fasteners was not depleted.

The Soltex Corporation is now the owner of the Celanese plant and has completed a new polypropylene plant on the Texas Gulf Coast, an area with extreme atmospheric corrosion problems. On the basis of the 20-year service experience, it was specified that both exterior and interior structural steel be hot-dip galvanized. In view of the successful service results, no confirmatory tests were performed.

ATMOSPHERIC EXPOSURE TESTS OF ZINC

The varied group of applications cited earlier indicated the successful performance of hot-dip galvanized structural steel in rather aggressive atmospheres. The inference from such performance is that a hot-dip galvanized bridge structure should have a long, trouble-free service life in almost any geographical location subject only to the local level of pollution. Toward that end it would be useful to examine the performance of test panels of zinc exposed in a one- and two-year exposure sequence by ASTM Committee G-1 (24). The weight-loss data for the zinc test panels were recalculated by Windross to represent years of service life for a galvanized panel before showing first evidence of rusting (25). The performance data are given in Table 2.

From an engineering and corrosion standpoint the last column in Table 2 represents the performance of a 2.0-oz/ft^2 coating before a visible iron-zinc alloy color is observed. For the industrial locations, such as Waterbury, Pittsburgh, Cleveland, Newark, and Bayonne, the current performance of a hot-dip galvanized structure can be expected to approach the performance shown for such locations as Columbus and Monroeville. This is because, at the time of the test, the full effects of EPA-mandated sulfur reductions in fossil fuels had not yet taken effect, and the installation of scrubbers in power plants and other large-scale fuel users had not been extensive.

TABLE 2

EFFECT OF ZINC COATING THICKNESS AND ATMOSPHERE ON CORROSION

Test Location	Environment	Zinc Corrosion Rate (mils/year)	Years Before Rusting 1.25 oz/sq. ft (2.125 mils)	2.0 oz/sq. ft. (3.4 mils)
Phoenix, Ariz	Rural	.0116	183.2	293.1
Detroit, Mich.	Urban	.0518	41.0	65.6
Morenci, Mich.	Rural	.0473	44.9	71.9
Potter Co., Pa.	Rural	.0491	43.3	69.2
Waterbury, Conn.	Industrial	.1000	21.3	34.0
State College, Pa.	Rural	.0456	46.6	74.6
Durham, N.H.	Rural	.0625	34.0	54.4
Middletown, Ohio	Semi-industrial	.0482	44.1	70.5
Pittsburgh, Pa.	Industrial	.1018	20.9	33.4
Columbus, Ohio	Urban	.0849	25.0	40.1
South Bend, Pa.	Semi-rural	.0697	30.5	48.8
Bethlehem, Pa.	Industrial	.0509	41.7	66.8
Cleveland, Ohio	Industrial	.0108	19.7	31.5
Miraflores, Panama C.Z.	Marine	.0447	47.5	76.1
Limon Bay, Panama, C.Z.	Marine	.1045	20.3	32.5
Galeta Point Beach, C.Z.	Marine	.6075	3.5	5.6
London (Battersea), U.K.	Industrial	.0956	22.2	35.6
London (Stratford), U.K.	Industrial	.2734	7.8	12.4
Monroeville, Pa.	Semi-industrial	.0750	28.3	45.3
Newark, N.J.	Industrial	.1456	14.6	23.4
Bayonne, N.J.	Industrial	.0188	11.3	18.1
East Chicago, Ind.	Industrial	.0705	30.1	48.2
Cape Kennedy, Fla. 1/2 mi. from ocean	Marine	.0447	47.5	76.1
Cape Kennedy, Fla. 60 ft. from ocean, 60 ft. elevation	Marine	.1733	12.3	19.6
Cape Kennedy Fla., 60 ft. from ocean, 30 ft elevation	Marine	.1581	13.4	21.5
Cape Kennedy, Fla. 60 ft. from ground level	Marine	.1635	13.0	20.8
Brazos River, Tex.	Indus-Marine	.0724	29.4	47.0
Kure Beach, N.C. 800 ft. from ocean	Marine	.0795	26.7	42.8
Kure Beach, N.C. 80 ft. from ocean	Marine	.2501	8.5	13.6
Daytona, Beach, Fla.	Marine	.0786	27.0	43.3
Point Reyes, Calif.	Marine	.0598	35.5	56.9

[a]Based on tests conducted by ASTM Committee G-1.

Three important factors should be recognized concerning the mechanism by which a hot-dip galvanized coating acts as a protective film. The first is that in a marine environment the zinc corrodes initially to form a thin chalky film of very low water solubility known as basic zinc chloride. The second is that in all other environments, the initial corrosion product of the zinc forms a mixture best described as a very thin film of basic zinc carbonate. This product confers protection to the zinc film until attacked by the acidic sulfur oxides during periods when the surface is slightly dampened by dew. The third factor is that the service life of a zinc-coated product is related essentially to its thickness. The early work that established this relationship and the factors related to various types of environments are discussed in greater detail in Appendix B.

Some valuable information on relating data obtained from zinc plates to the performance of a galvanized panel has become available from a comprehensive exposure program conducted in the Panama Canal Zone (26). The reduction in thickness of the plates and galvanized panels, as determined by weight-loss studies of 9-in. square panels, shows a close correlation as seen from the data in Table 3.

The data in Tables 2 and 3 indicate that the weight loss of zinc plates is linear with time and also correlates well with the weight loss of galvanized panels. Thus, the performance of a hot-dip galvanized structure in a particular location may be predicted by exposing weighed zinc plates in the location for 1 to 3 years.

TABLE 3

AVERAGE REDUCTION IN THICKNESS OF ZINC PLATES AND GALVANIZED PANELS IN PANAMA CANAL ZONE (mils)

Specimen	Location	1 yr	8 yr	16 yr
Zinc plates	Coastal	0.23	1.05	1.62
	Inland	0.05	0.21	0.54
Galvanized panel	Coastal	0.26	0.91	-
	Inland	0.06	0.21	-

CHAPTER THREE   .

THE HOT-DIP GALVANIZING PROCESS

GALVANIZING PROCEDURES

The galvanizing field encompasses two methods of hot-dip galvanizing: sheet and job shop galvanizing. Sheet is galvanized in steel mills where coils of sheet are processed through several steps at a speed in excess of 300 ft per minute. In contrast, job shop galvanizing handles individual structural components that may require as much as 90 minutes to process.

The hot-dip galvanizing process is conducted in a series of rectangular carbon steel tanks. Most job shop galvanizing operations maintain tanks that range from 42 to 60 ft long, 60 to 72 in. wide, and about 72 in. deep. As the hot-dip galvanizing process is essentially a materials-handling process, tanks generally are arranged parallel to one another for efficiency in operation and ease of transfer of material. Some articles longer than 60 ft may be galvanized by dipping one end at a time.

Incoming fabricated steel is first immersed in a degreasing tank to remove all deposits of oil and grease and permit effective wetting. The fabricated steel is rinsed then immersed in a tank of either dilute sulfuric acid or dilute hydrochloric acid. This pickling operation facilitates the removal of mill scale and rust. The fabricated item is then rinsed and either immersed in a flux tank where it is further cleaned and covered with a film of zinc ammonium chloride or immersed directly into a molten bath of zinc that is covered with several inches of the flux composition. The purpose of the flux is to promote bonding of the zinc.

The galvanizing bath is maintained around 850° F. Fabricated items are immersed in the bath sufficiently long so that agitation and bubbling in the bath ceases, indicating that the item has come to bath temperature and the zinc is reacting with the steel to form the iron-zinc alloy bonds. After the bath has quieted, the fabricated items are removed. The angle and the speed of removal influence whether there will be a relatively thick top coat of zinc or primarily an alloyed coating with a relatively thin layer of zinc. During the removal process, inspection can readily detect areas that have not been wetted or galvanized because zinc will not react with any part of the steel surface that is not perfectly clean. Thus, inspection is immediate and any uncoated areas are obvious. Black spots, lumps, and dross deposits are readily detected at this point and the part can be rejected, stripped, and regalvanized at once. Appendix D contains more detailed information on inspection. The job shop galvanizing process ranges from 30 to 90 minutes from degreasing to loading for shipment, depending on the massiveness of the item. The procedures are routine. The process is simple, involves no complicated operations, and is not labor intensive. So-called poor galvanizing results when, the degreasing bath is weak, the acid bath is weak, or the molten zinc bath contains too much suspended matter. As these baths are easily monitored, there should rarely be instances of poor galvanizing. Damage

to galvanized areas that occurs during handling and erection should be repaired in accordance with ASTM A 780.

Careful attention to design and construction of galvanized items will minimize problems such as distortion, embrittlement, or tensioning high-strength bolted connections (see Appendix D).

EFFECT OF ALUMINUM

The visual appearance and performance of hot-dip galvanized steel structures is controlled by the coating weight or thickness of the deposit of zinc. The zinc film on sheet steel is quite different from that on structural steel. Because the zinc film on sheet steel must be flexible to permit forming, aluminum is added to the molten zinc galvanizing bath to prevent the formation of iron-zinc alloy layers beneath the zinc. In contrast, hot-dip galvanizing of structural steel objects results in the formation of a series of iron-zinc alloy layers topcoated by a film of pure zinc. It is the presence of these alloy layers that confers such properties as long service life and abrasion resistance to hot-dip galvanized structural components. Figure 2 shows a photomicrograph of a hot-dip galvanized film and identifies the alloy layers and their compositions, and shows further the diamond pyramid number (DPN) hardness of each layer, and the base steel. The soft zinc is capable of absorbing impact while the harder alloy layers protect the base steel.

In hot-dip galvanizing aluminum is added to the bath in much smaller quantity not to interfere with alloy formation but to increase the brightness of the galvanized item as it is being withdrawn from the molten bath. Sometimes when a dull product is encountered it may be caused by a lack of aluminum in the bath. (Some additional information is contained in Appendix C.)

EFFECT OF SILICON

Because the continuous casting of steel has become so widespread much steel is being deoxidized (killed and semi-killed) through the use of silicon. There is also an increasing demand by design engineers and specification writers for the high-strength, low-alloy steels, which contain silicon levels in excess of those used for deoxidation. It is a well-established fact that the presence of silicon in steel above the level required for semi-killing is the primary factor that contributes to the excessive reactivity of such steels in the galvanizing bath. The resultant coatings are of concern both to the galvanizer and the consumer, but for different reasons. The coatings are much thicker than specification demands. These thicker coatings tend to be brittle, sometimes less adherent, often lack uniformity in appearance,
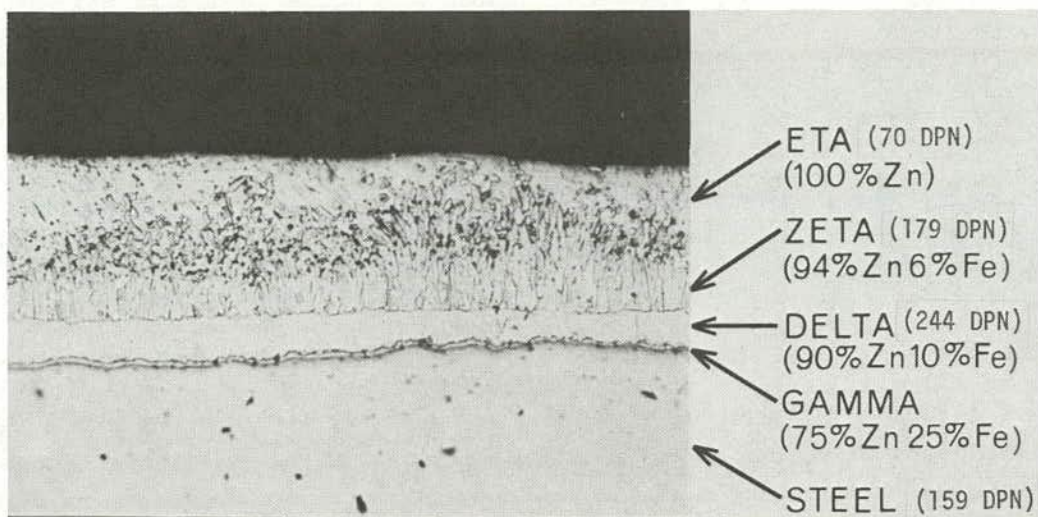
FIGURE 2 Photomicrograph of a section of a typical hot-dip galvanized coating showing serious alloy layers metallurgically bonded to the base steel.

and may be prone to a premature exhibition of a light staining suggesting the product has failed and requires painting. This staining is superficial and does not affect the corrosion resistance of the coating; however, if painting of the stain will be required for aesthetic reasons, this should be considered when performing a cost-effectiveness analysis. The galvanizer often is unaware of the chemical composition of the steel that is to be galvanized

and, thus, is unable to take compensatory steps to overcome the presence of the silicon in the steel.

Because this type of steel often is involved in heavy construction, such as in bridges, transmission towers, light standards, and the like, a knowledge of some of its properties is helpful. As mentioned earlier, the coating tends to be thicker. However, thickness is an asset in extending service life. There is a tendency
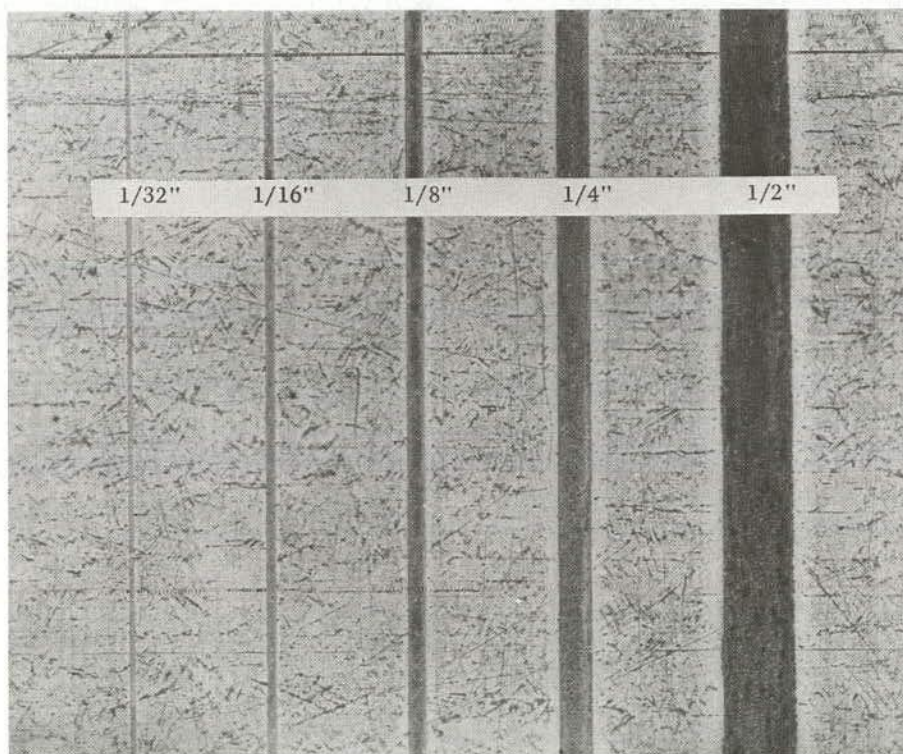
FIGURE 3 Example of cathodic protection exerted by a film of zinc across gaps of exposed steel.

for the silicon-influenced coatings to exhibit a somewhat greyish matte appearance in contrast to the more silvery appearance. The brittleness and adhesive qualities of the coating are more apparent in the thinner applications where the components are subject to vibratory and flexing conditions, as would occur in a sheet-steel application. Girder components and tower-leg angles usually do not experience such conditions. However, care should be exercised to avoid mechanical impact in handling, shipping, and erection.

SACRIFICIAL PROTECTION

Up to this point the discussion has focused on zinc's barrier protection. Zinc also provides sacrificial protection when it has been scratched or gouged leaving the base steel exposed to the atmosphere. An experiment that demonstrates this was reported by Frazier (27). A steel plate was given a one mil-thick coating of zinc. The coating then was scored to the base steel with a series of lines $\frac{1}{32}$, $\frac{1}{16}$, $\frac{1}{18}$, $\frac{1}{4}$, and $\frac{1}{2}$ in. wide and exposed to an industrial environment for 56 months. Visual inspection revealed no red rust in the $\frac{1}{32}$ and $\frac{1}{16}$ in. scored areas, a few red pinpoints in the $\frac{1}{8}$ in. area, a reddish surface smut in the center of the $\frac{1}{4}$ in. area, and some surface rusting in the $\frac{1}{2}$ in. gap. The surface of the panel was darkened by oxidation and soiling; however, along the edges of the scored gaps the coating remained light and clear from the dissolution of the zinc as it sacrificially protected the scored area. The combined width of the clean edges equalled the width of the scored area except at the $\frac{1}{2}$ in. gap. Figure 3 shows the extent of sacrificial protection of steel by a thin coating of zinc, the effect of which increases with increasing thickness of the galvanized coating.

CHAPTER FOUR

ECONOMIC CONSIDERATIONS

Life-cycle costs are an important consideration in choosing among coating alternatives. In the preceding chapters it has been shown that galvanized steel has demonstrated its ability to perform effectively in a variety of environments. This performance must be related to the cost of galvanizing to determine the life-cycle costs.

COST DATA FOR PAINTING AND GALVANIZING

The galvanizing of structural steel is quoted usually on a cost per weight basis ($/ton or $/hundredweight) because galvanizing costs are more a function of handling considerations and the time required to bring the mass of immersed steel up to the galvanizing temperature of 850° F. On the other hand, painting is usually quoted on a cost per area basis ($/ft²) because preparation and painting costs are directly related to the area to be coated.

Seelinger (11, 28) has shown that a three-coat paint system consisting of a commercial shop blast cleaning, an organiz zinc primer, and intermediate and top coats of an epoxy composition costs $1.19 per sq ft (Table 4).

The cost to galvanize a ton of light- and medium-weight structural steel in the Texas Gulf Coast area in 1982 according to Seelinger (11) ranged between $175 and $200/ton. This base cost is increased by an estimated $30/ton for extra handling and touch-up, and by $20/ton for straightening to give a total of $250/ton. Job shop hot-dip galvanizing costs in different parts of the country for the early part of 1982 are shown in Table 5.

Seelinger cannot account for why Texas prices are lower unless it is due to the close proximity of galvanizing shops to the petrochemical plants on the coast. The key point to note is that small items such as handrails require a lot of individual handling when being galvanized, hence the higher cost. In contrast, a massive item requires one or two handlings even while being double-end dipped and, therefore is less expensive to galvanize.

When costs are to be equated it is necessary to know how many square feet of steel are present in a ton of steel. Small angles and hand rails have a high ratio of surface area per ton of steel. In contrast, a girder may average 125 sq ft per ton of steel. Based on the costs found in his survey, Seelinger prepared a graphical representation that relates the cost of painting per square foot to the cost of galvanizing per square foot (Figure 4).

TABLE 4

APPLICATION COSTS OF PAINTS ON GULF COAST

Primer	$/ft²
Shop-based commercial blast cleaning	0.24
Shop-applied inorganic primer - sprayed	0.20
Inorganic Primer cost	0.11
Top Coats	
Epoxy, two coats - field sprayed	0.34
Material costs	0.18
Touchup in field	0.12
Total	1.19

TABLE 5

REGIONAL JOB SHOP GALVANIZING COSTS IN EARLY 1982

Location	Description	Cost ($/ton)
New Jersey Shop	Light steel (up to 17 lbs/ft)	360
	Medium steel (17 to 35 lbs/ft)	260
	Heavy Steel (over 35 lbs/ft)	200
Texas Shop	Light steel (up to 20 lbs/ft)	200
	Medium steel (20 to 40 lbs/ft)	175
	Heavy steel (over 40 lbs/ft)	130
Southeast Shop #1	Handrails	540
	Average mix (light and medium)	215
Southeast Shop #2	Heavy steel	235
Northeast Shop (Pennsylvania)	Medium steel (no touchup, no transportation, no straightening)	220
	(With all of the above)	280

ECONOMIC ANALYSIS

The current method for evaluating any coating system is to determine its dollars per square foot per year of coating life. Such an analysis reveals that the more expensive coating system or surface preparation results in longer service life and lower maintenance costs in the future. Unfortunately, the aforementioned figure does not reflect the decreased flow of funds into maintenance needs. To find a means for acknowledging the savings, one must focus on the time value of money and the cash flow.

It is appropriate at this point to review the economic analysis developed by the St. Joe Minerals Company for the Stearns Bayou Bridge (15). It involved comparing the cost and anticipated service life of the hot-dip galvanizing process to those of a paint system. When the bridge was erected in 1966, the cost to galvanize the 170 tons of steel was $8,750. This was about $150 more than the cost of the proposed painting system (which was not specified), which involved $3,000 for blast cleaning, $2,100 for shop painting, and $3,500 for field painting, totalling $8,600.

The cost of repainting the bridge was conservatively estimated to be equal to the initial cost less the shop painting, or only $6,500. This cost was increased by an equally conservative inflation factor of 5 percent. As Michigan state highway officials indicated that the time intervals between bridge paintings would be extended owing to budgetary constraints, a 20-year interval was projected. Using the 20-year repainting cycle and a 5 percent inflation rate, a repainting cost program was developed:

First repainting after 20 years	$ 17,250
Second repainting after 40 years	$ 45,750
Third repainting after 60 years	$121,400
Fourth repainting after 80 years	$322,150
Total	$506,550

A discounted cash flow analysis shows that the additional $150 investment made for hot-dip galvanizing would yield a return on investment of 27 percent per year by postponing the (negative) cash flows required for repainting. Were the bridge to be repainted on a more frequent cycle, had funds been available, then the return would have been even greater. In 1978 the relationship between painting costs and galvanizing costs had changed little. Thus, it could be assumed that the economic analysis was still valid.

Brace and Porter (29) believe that economists and technologists should collaborate to ensure that the protective systems employed represent those that confer protection with the minimum use of resources (that is, at the lowest economic cost).
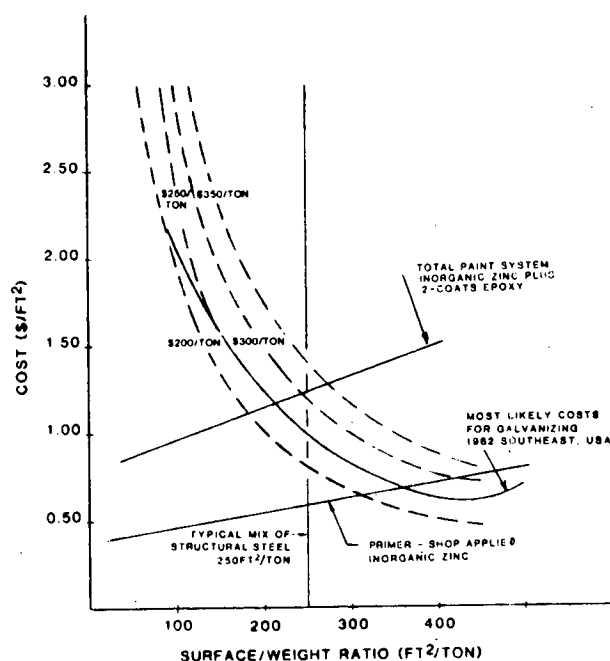

FIGURE 4 Initial costs of painting compared to galvanizing.

The problem facing maintenance engineers is not one of finding a means for protecting a structure, but one of choosing among a large selection of materials and protective treatments of varying degrees of sophisitication and durability. In brief, the basic issue is to decide the best practical form of protection that can be applied at the lowest overall cost, taking into account expected service life. The authors indicate that this is by no means a simple problem as it requires that the principles of economics and accounting be combined with those of corrosion science and engineering. Little or no work up to the present has been done in this area and there is a distinct need to establish basic principles for assessing the true economic cost of alternative protective methods. An example of such an approach was that illustrated earlier in connection with the Stearns Bayou bridge.

The traditional approach has been to take the first cost of a protective system, add to it the cost of several maintenance applications, and divide the total cost by the number of years the operation exists to give an average annual cost. This approach evades a basic economic principle, namely, that money has a time value. A given sum of money in hand today is worth more than that same sum received at some future date. The reason is that this sum can be invested or deposited in the bank and grow in value through the interest gained. For example, a sum invested at 10 percent interest can double in seven years through compounding. This can be expressed as the future value (FV) in the compound interest expression:

$$FV = P(1 + i)^n$$

where

- P = principle
- i = interest rate
- n = number of years

It is important to remember that separating costs into capital and maintenance charges does not change the fact that costs have been incurred. Maintenance costs represent money that can be used profitably for other investments in the private sector and for other uses in the government sector and should be charged the appropriate rate of interest.

Thus, if the cost of galvanizing a structure is assumed to be $10,000 and it is expected to perform without further attention for 25 years, the discounted cost or the value that the money being spent today could have reached if invested at, for example 6 percent would be:

$$FV = \$10,000 (1 + 0.06)^{25}$$
$$= \$42,920$$

Thus, the future value of galvanizing is $42,920.

The alternative to galvanizing could be painting in which the initial cost might be less than the cost of galvanizing, for example, $8,500. It is anticipated that after 9 years and 17 years some degree of coating repair will be necessary and it is estimated to be about $2,000 each time.

The discounted cost then becomes what that money could have earned over the time available for investment at compound interest of 6 percent. It does not take inflation into account.

The general expression that describes the discounted cost can be represented as follows:

$$T = I(1 + r)^n + M_1(1 + r)^{n-p1} + M_2(1 + r)^{n-p2} \ldots etc.$$

where

- T = discounted cost or future value
- I = initial cost to galvanize or paint
- M_1 = cost of maintenance in the year p1
- M_2 = cost of maintenance in the year p2
- r = interest rate or discount rate
- n = numbers of years

Thus, for the specific alternative described above:

$$FV = \$8,500(1 + 0.006)^{25} + \$2,000(1 + 0.06)^{16}$$
$$+ \$2,000(1 + 0.06)^8$$
$$= \$44,733$$

By recognizing the basic economic fact that money spent in maintenance could have been spent for other things, it can be seen that the real economic cost (i.e., the total discounted cost) is quite different from simply adding the initial cost to the cost for maintenance.

The aforementioned procedure can show that application of a protective coating with a higher initial cost but requiring no maintenance may be cheaper than an alternative coating that is less expensive initially but requires repetitious maintenance. The procedure does not consider such costs as traffic disruption, weather, variable skills of the maintenance crew, and disposal of loose paint residues.

The design engineers for the Hood Canal floating bridge in Washington wanted to build a bridge with 70 to 75 years service life (30). Because of the marine environment they selected materials that would give a maximum of corrosion protection with a minimum demand for maintenance. Their review of the literature suggested that they select a high-strength, low-alloy steel and galvanize it. They wanted a thick galvanized coating and were able to achieve that because of the silicon content of the high-strength steel. Because the appearance of the galvanized coating on such a steel is somewhat irregular, for purposes of aesthetics a standard zinc-dust, zinc-oxide primer coat was specified with a topcoat of a gray phenolic composition. They estimated that it would have to be repainted after 20 to 25 years.

The bridge contains three lift spans, each 104 ft long and 75 ft wide. The welded plate girders in each span are 72 in. deep and 22 in. wide; the floor beams are 61 in. deep by 18 in. wide. This results in surface areas of 133 and 118 sq ft per ton, respectively. Some 450 tons of structural steel were used. Only six to eight years of service life was realized from various paint systems previously used in that environment. The designers had considered metallizing but realized that only molten zinc could reach some areas.

The method they chose for their economic appraisal of alternative corrosion control measures is given in the Recommended Practice of the National Association of Corrosion Engineers RP-02-72 (31). The cost data utilized in this illus-

TABLE 6

LIFE-CYCLE COST DETERMINATIONS

Year	Galvanizing + Paint Costs		Paint Cost Only	
	Escalated Cost	Present Worth	Escalated Cost	Present Worth
0 (1983)	680	680	380	380
12	0	0	764	244
24	800	81	1,539	156
36			3,096	100
48	3,279	34	6,230	64
60	0	0	12,535	41
Total	$4,759/ton	$795/ton	$24,545/ton	$985/ton

tration were those negotiated by the Washington DOT with local contractors in the northwest. The contract cost for cleaning, galvanizing, handling, painting, transportation, and overhead and profit for the galvanizer and contractor was $680/ton during the 1982–1983 construction season. It was planned for aesthetic reasons to repaint the bridge after 24 years at an estimated cost of $200/ton with only a wire brushing for surface preparation. The corresponding cost of a three-coat system applied directly to the sandblasted steel substrate was $380/ton with an estimated life of 12 years.

The escalated cost (EC) formula for repainting (which is identical to the compound interest formula) is

$$EC = C(1 + e)^n$$

where:

C = present cost for repainting

e = escalation or inflation rate

n = number of years before repainting

The present worth (PW) can be obtained by inverting the compound interest formula

$$PW = \frac{EC}{(1 + i)^n}$$

where i equals the interest rate.

Lwin (30) selected an inflation rate of 6 percent and an interest rate of 10 percent to make estimates for costs over the 70-year life of the bridge (Table 6). From the sum of the escalated costs/ton one can calculate that for the 450 tons of structural steel it will require $2,141,550 to use the painted galvanized steel and $11,045,250 to utilize the sandblasted and painted structural steel. The result of using the galvanizing system is a potential saving of $9 million.

Another application of the net present worth method is the bridge corrosion cost (BCC) model (2). The model is designed to help an agency choose from several possible protection methods including galvanizing. The model is flexible and allows users to change various parameters based on local experience.

Several options are open to a decision maker, such as one that might cost $X/ton with a repainting period of 10 years, or another that may cost more initially but only requires repainting every 15 years. To compare alternatives, the BCC model uses the net present value method to discount future costs into their present-day equivalent. By this technique one ends up with a single value—the net present value of each alternative. The alternative with the smallest net present value is the optimal solution. In other words, if one can estimate costs for repainting or other corrective measures at 5, 10, and 15 years into the future with appropriate factors for inflation, then one knows how much to lay aside today at some fixed interest rate to reach the required sum at the selected future date.

These examples illustrate a modest advantage for using hot-dip galvanizing under the conditions and assumptions shown. Other examples could be shown where a paint system is cost-effective. Thus, an economic analysis should be done in each instance to determine which coating system is the least costly alternative. This analysis will require a careful evaluation of the expected life of each coating system, as well as consideration of local costs, maintenance frequency, interest rates, and inflation.

CHAPTER FIVE

CONCLUSIONS

Hot-dip galvanized steel has a long, successful record for serving effectively in such familiar applications as farm buildings, refuse containers, and gutters and downspouts, but it has not often been considered seriously by highway engineers for protecting anything larger than guardrails and sign posts.

The atmospheric resistant properties of galvanized steels are not a recent discovery. Controlled exposure tests have been conducted by the American Society for Testing and Materials Committee A-5 since 1926 when specimens of hot-dip galvanized sheets, and later wire and pole line hardware (such as bolts, clamps, angles, and the like), were exposed in numerous locations around the country.

While the performance record for zinc was accumulating, the protective coating field, likewise, was developing a knowledge of how to enhance the performance of paints through improved materials and systematic attention to the preparation of the steel surface. From such efforts the service life of many coating systems has been increased substantially. However, some primer materials—chromates and lead-based derivatives—are health hazards and extreme care must be exercised in their use; solvents that are photochemically sensitive when they evaporate have been eliminated from use, outdoor sandblasting has been severely curtailed as a means of preparing the surface, and the efficient removal of old paint systems from outdoor structural steel has posed some difficult problems.

In contrast to paint, the performance of galvanizing is significantly different with many agencies reporting 20 years or more of maintenance-free service. Moreover, painting systems perform better on galvanized steel than on bare steel because rust cannot form beneath the paint film (2).

An increasing number of writers reporting on the subject of maintenance are qualifying their suggestions and recommendations in terms of life-cycle costs rather than the initial costs of materials. The life cycle of hot-dip galvanized steel can be inferred from its performance in various industrial environments, such as wastewater treatment plants, oil refineries, and petrochemical plants. In each of these, the atmosphere was far more severe and aggressive than that encountered in the average highway setting, yet the hot-dip galvanized steel performed well. Such long-term accomplishments in varied industrial environments, combined with the results of long-term ASTM and other worldwide exposure tests, provide design engineers with sufficient data to make confident projections of service life for hot-dip galvanized steel.

An economic analysis in 1966 for the Stearns Bayou bridge indicated that the slight additional cost of hot-dip galvanizing would be more than offset by the continuing costs of repainting, even assuming a modest 5 percent inflation rate over the 20-year analysis period. A 1978 study showed that this analysis was still valid. A detailed analysis for the Hood Canal bridge in 1982 (using a 6 percent inflation factor and a 10 percent interest rate) showed that, for a service life of 70 years, galvanizing plus a paint coating for aesthetics would be substantially less expensive than a painting system alone.

In some instances, notably in arid climates or in regions where access to suitable hot-dip galvanizing facilities requires transportation to distant baths, painting may be more cost-effective than hot-dip galvanizing.

Thus, an economic analysis that includes both initial costs and future maintenance costs and that uses accounting techniques, such as net present worth, should be used to select the most economic protective coating system.

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APPENDIX A

THE CORROSION PROCESS

For a proper appreciation of the various methods for combating metallic corrosion, it is necessary to have some understanding of the nature of the corrosion process. Because of its complexity, only a superficial description will be given here.

Fundamentally, corrosion is an electrochemical process. It is accompanied and accelerated by the passage of a very small electric current between the corroding metal and any other metal with which it is in electrical contact. Similar currents flow to various locations on the surface of a single metal. To illustrate the process, consider the dry cell in a flashlight—it represents the corrosion concept almost in its entirety. The battery consists of a zinc case and a carbon core. The interior consists of an electrolyte, which is essentially a damp electrically conductive mixture of zinc ammonium chloride. As the zinc dissolves it supplies electrons that go through an exterior circuit to light the flashlight bulb and continue on their path through to the carbon core. When the battery no longer functions, the zinc case is in a state of deterioration. The battery functions because the internal face of the zinc is attacked and begins to dissolve.

The electrochemist and the corrosion engineer identify the two metals in a battery as the anode and the cathode. The anode is the metal that is consumed, or is attacked and deteriorates. It is the dissolving away of the anode that supplies the electrical energy that comes from the battery. The other metal, the one that is unaffected, sometimes described as being protected sacrificially by the anode, is the cathode or the noble metal in the battery. The two metals comprising the battery are the elec-trodes. The electric current originating from the sacrificial metal is visualized as a stream of electrons that moves through the metallic circuit.

A similar electrochemical process causes bridge corrosion and is known as differential aeration cell corrosion. It has been observed that when pairs of copper wires, zinc strips, or iron wires are placed in separate containers filled with salt water and connected to a meter, and the two containers are linked by a porous divider, no current will be detected. When air is bubbled into one container or inert nitrogen gas bubbled into the other to flush out the air, a flow of current is detected and the strip where the air was flushed out assumes the anodic role as it begins to corrode. In other words, where the air level is low the metal electrode becomes vulnerable and assumes the anodic role. Where the air level is high, the metal electrode assumes the cathodic role and is not attacked. The difference in air concentrations is what constitutes the cell.

Differential aeration cells thus are created on bridge girders wherever accumulations of dirt are permitted to occur and remain where they can be repeatedly dampened by rainwater or drainage. As the protective paint coating slowly breaks down, attack of the steel will begin. Thus it is the differential aeration cell problem, which can be repeated in a variety of ways, that is a significant cause of metallic corrosion. All metals, even aluminum, copper, and stainless steel, share this common vulnerability with structural carbon steel.

APPENDIX B

EXPOSURE TESTS FOR GALVANIZING

In 1917, ASTM Committee A-5 on Corrosion of Iron and Steel announced that a Subcommittee II would be organized on "Preservative Metallic Coatings on Metals." In 1925 it published a description of the exposure arrangement of test specimens in five representative locations in the country. Subcommittee VIII on Field Tests of Metallic Coatings laid the ground work by exposing specimens in the spring of 1926 at the five geographical locations: severe industrial (Brunot Island, Pittsburgh, Pennsylvania); moderate industrial (roof of locomotive shops of Pennsylvania Railroad, Altoona, Pennsylvania); foggy marine (Fort Hancock, Sandy Hook, New Jersey); tropical marine (Navy base, Key West, Florida); and rural (Pennsylvania State College, State College, Pennsylvania) (32).

The specimens were corrugated sheets, 10 corrugations per sheet, measuring 30 in. by 26 in. The sheets were cut from a nine-foot length and one portion was exposed facing west, the other facing east, each on a 30° incline from the horizontal. The galvanizing of the test specimens was conducted by five steel firms under the supervision of subcommittee representatives.

The condition of the sheets was determined twice yearly by inspection committees comprising both producers and consumers of commercial galvanized steel products as well as general interest members of the committee. Because of the irregular distribution of coating on a sheet, test specimens, generally described as edge-center-edge, were taken from across the widest dimension of the sheet.

Shortly after the sheet test was underway a hardware test consisting of items commonly used and termed "pole line hardware" was initiated. By 1936, a galvanized wire test, likewise, was installed at eleven geographical sites.

During the course of the numerous inspections a substantial amount of visual data were accumulated. In terms of records, the quantitative data involved reporting the "time to first rust" and the "time to achieve 100 percent rust." It must be appreciated that the iron-zinc alloy layer ranges from a bluish-black to a brown and rust-colored appearence; however, the texture of the surface is not that of a true rust. This is why many farmers' roofs on old buildings appear to be rusted when, in fact, they are merely exhibiting the iron-zinc alloy layer following the disappearance of the thin top layer of pure zinc (See Appendix C).

Relative to the inspection procedure, the various percentages of area rusted were periodically plotted against the number of years of exposure. After about a decade, as a consequence of these systematic accumulations of data, it was noted that the corrosion rate of zinc, or more precisely, of galvanized steel, was very close to being linear in character and, thus, proportional to the thickness of the coating. Such data were an index to the relative corrosiveness of a particular atmosphere and presaged the era of acid rain (Figure B-1).

Figure B-1 shows that the slope of the time:corrosion curves represents the relative corrosivity of the respective locations.

The two industrial sites differ only slightly. The industrial-foggy marine area of Sandy Hook is not very corrosive toward zinc and, of course, the rural location of State College is the least aggressive. To illustrate the results after 28 years of exposure at Key West, 34 years at Altoona, and 50 years at State College, a brief summary of the major factors describing the performance

0.38 to 1.28 oz per sq ft.
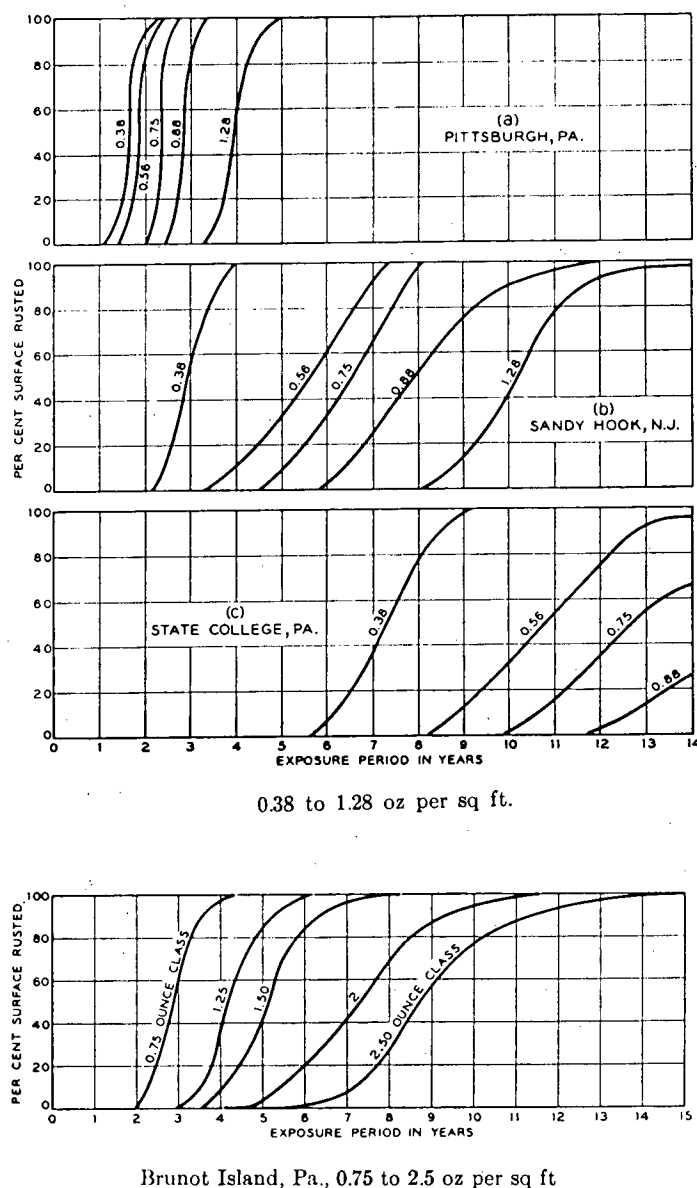

Brunot Island, Pa., 0.75 to 2.5 oz per sq ft

FIGURE B-1 Progressive development of rust on galvanized steel specimens exposed in various environments.

TABLE B-1

SERVICE LIFE OF CORRUGATED GALVANIZED SHEETS AT
REPRESENTATIVE ATMOSPHERIC SITES (Years)

Zinc Coating Thickness (mils)	Location[a]	Spots[b]	First Rust	100% Rust	Perforation
2.12 (1.25 oz/ft^2)	Altoona	-	4.6	11.2	24.5
	State College	-	28.6	-	-
	Key West	20.9	-	-	24.7
1.6 (1 oz/f^2)	Altoona	-	3.8	8.1	2.1
	State College	-	22.5	-	-
	Key West	18.5	-	-	20
0.8 (0.5 oz/ft^2)	Altoona	-	2.4	4.3	13
	State College	-	10	23.5	-
	Key West	11.8	18	-	17.5

[a]Altoona is an industrial environment, State College is rural, and Key West is marine.

[b]At Key West, spots that developed on the surface and that perforated shortly thereafter were caused by salt deposits that accumulated on the bottom face and that were not washed away by rain.

is given in Table B-1 for the behavior of different coating weights of zinc.

The data in Table B-2 show that galvanized steel resists corrosion in a marine or saline environment if the surface deposits are periodically washed away by rain. The salt is moderately aggressive to areas where the rain cannot reach the salt residues. In contrast, immersion studies of zinc and galvanized steel in seawater show a removal rate of zinc equivalent to about one mil per year. Thus, a hot-dip galvanized item with a three-mil film is likely to be stripped of that film in about three to five years.

A relationship was developed between steel and zinc in an exposure test conducted at several elevations at the Kennedy Space Center in Florida. The data in Table B-2 illustrate the results.

The data in Table B-2 show that elevation can be of significance in connection with steel, whereas the basic zinc chloride protective film that characteristically forms on zinc in a marine environment serves to eliminate the aggressive effects of that environment regardless of elevation. Because of the "rip rap" (large boulders), the waves broke into large droplets that fell rapidly. Distance from the ocean aided both the zinc and the steel. Thus the steel-zinc corrosion ratio is controlled more by the vulnerability of steel than the uniform performance of the zinc when exposed to a saline environment.

TABLE B-2

INFLUENCE OF ELEVATION AND DISTANCE FROM THE OCEAN ON THE
PERFORMANCE OF STEEL AND ZINC AT THE KENNEDY SPACE CENTER
IN FLORIDA

	Reduction in Thickness, mils			
	60 yards from the Ocean			1/2 Mile from Ocean
	Ground Level	30 ft High	60 ft High	
Steel	34.8	13	10.3	6.8
Zinc	0.32	0.31	0.35	0.09
Steel/Zinc Ratio	109	42	29	74

APPENDIX C

METALLOGRAPHIC FACTORS IN GALVANIZED STEEL

The best way to become familiar with the nature of the coating that results from the hot-dip galvanizing process is to immerse a steel plate or bar in molten zinc and then cut through the coating and prepare a cross section for examination under the microscope.

Generally, four layers are distinguishable regardless of their relative thickness (Figure C-1 and Table C-1). The layer adjacent to the steel is called gamma and is quite thin. It contains about 21 to 28 percent iron with a melting range from 1238 to 1436° F and corresponds to a composition $Fe_3 Zn_{10}$. It is hard and brittle. The next layer is more substantial, although thin, and is called the delta layer. It contains from 7 to 12 percent iron with a melting range between 986 and 1238° F. At the higher iron level its composition corresponds to $FeZn_7$. The layer is tough and ductile. This layer then shades into another layer that tends to be thicker than the others and is called the zeta layer. Its iron content is about six percent and corresponds to a composition $FeZn_{13}$ with a melting point of 986° F. The crystals are long and columnar and nonsymmetrical, and tend to crush on deformation of the film. The bright outer layer of zinc is soft, tough, and ductile and can withstand fracture upon deformation. The relative hardness of the various alloy layers is shown in Figure C-1.

The following group of photomicrographs illustrates a number of factors that point to the complexity of the galvanized coating. Small differences in composition, temperature, time of immersion in the molten zinc bath, and rate of withdrawal and cooling can effect significant changes to appearance and physical properties. Figures C-2, C-3, and C-4 illustrate the effect of time in

TABLE C-1

PROPERTIES OF ALLOY LAYERS OF A HOT-DIP GALVANIZING COATING

Layer	Composition	Hardness (DPN)	Iron %	Melting Temp. (°F)
ETA	Zn	70	0	850
Zeta	Fe Zn_{13}	179	6	986
Delta	Fe Zn_7	244	7–12	986–1238
Gamma	$Fe_8 Zn_{10}$	–	21–28	1238–1436

the bath on the growth of the delta and zeta layers. As the steel being galvanized must reach the temperature of the bath before chemical reaction can occur, its mass plays a significant role. The control of the alloy layers can be affected on a trial-and-error basis if more than one structural member of the same mass is being galvanized.

The total thickness of a coating, and the amount of alloy layer that forms can be varied by adjusting the galvanizing conditions such as the temperature of the molten zinc, the time of immersion of the steel item, and the speed with which the item is withdrawn from the zinc bath. The relationship existing between these factors was investigated for three temperatures: 815, 851, and 887° F. The immersion times ranged from 30
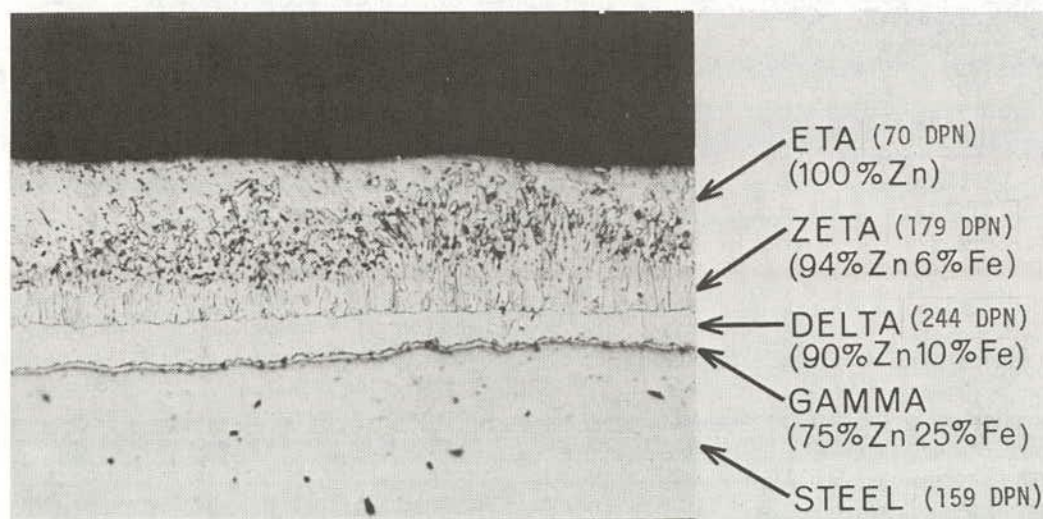

FIGURE C-1 Photomicrograph of a typical hot-dip galvanizing coating showing various alloy layers.
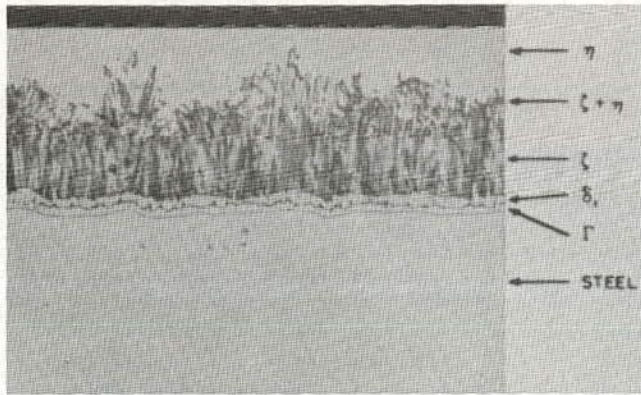
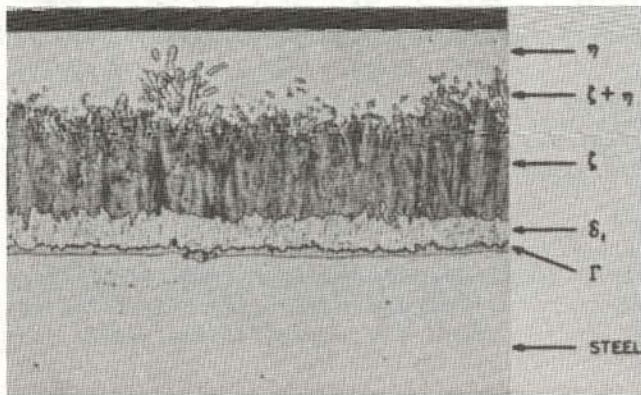FIGURE C-2 Growth of alloy layers after one minute immersion.

FIGURE C-3 Growth of alloy layers after five minutes immersion.
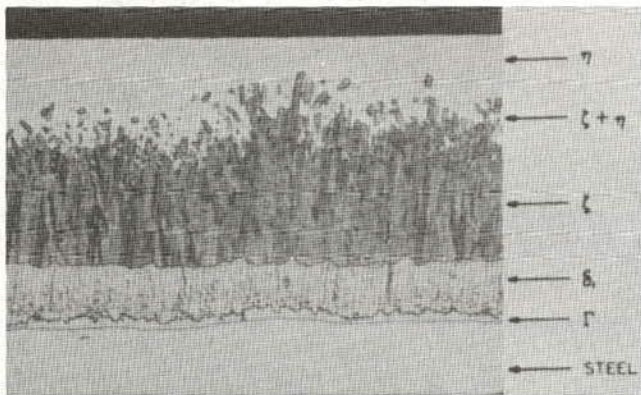
FIGURE C-4 Growth of alloy layers after 10 minutes immersion.

FIGURE C-5 Alloy layer from galvanizing bath without aluminum.
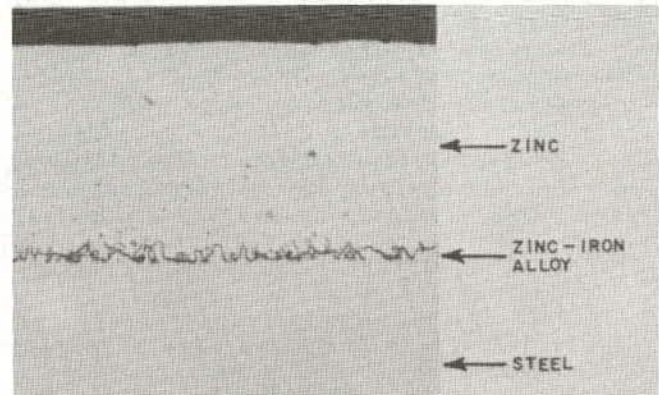
FIGURE C-6 Alloy layer from galvanizing bath with 0.15 percent aluminum.

seconds to 10 minutes. Withdrawal time rates ranged from 2.5 to 50 ft/minute.

From an examination of the data the thickest coating, 8.2 oz/ft² (13.5 mils), was obtained at 887° F following 10 minutes immersion and a withdrawal speed of 50 ft/minute. The thinnest coating, 1.8 oz/ft² (3 mil), was achieved at 815° F at a withdrawal speed of 2.5 ft/minute. Thus increasing the bath temperature, the immersion time, and the withdrawal speed all combine to achieve thick coatings. With this knowledge, the galvanizer has some flexibility in meeting coating-weight specifications.

EFFECT OF ADDITION OF ALUMINUM TO THE ZINC BATH

Aluminum, unlike the other elements, is not normally present in zinc ores but is added purposely to the zinc bath. In continuous sheet galvanizing, aluminum is added to the extent of 0.15 percent to prevent the formation of the iron-zinc alloy layers. This leaves the product in a more ductile condition, which is conducive to forming (Figures C-5 and C-6). For hot-dip galvanizing, aluminum in a concentration between 0.001 and 0.01 percent markedly increases the brightness of the product. It is believed that a thin film of aluminum oxide forms on the surface of the molten zinc replacing the dull zinc oxide film. Generally, the aluminum is added at the exit end of the tank.

APPENDIX D

THE DESIGN, FABRICATION, AND INSPECTION OF GALVANIZED PRODUCTS

MINIMIZING DISTORTION

The temperature of the galvanizing bath is high enough to cause distortion of fabricated assemblies because of release of stresses induced in the steel during the manufacturing process and the fabrication operation. These stresses may be compounded by poor design and by use of parts of unequal thickness or nonsymmetrical sections. To minimize the effects of distortions, attention to the following points will be helpful:

1. Effect designs that can be fully galvanized by a single dip or be in a position to disassemble for galvanizing.
2. Use symmetrical sections in place of angles and channels.
3. Use sections of near equal thickness at joints.
4. Bend members to the largest accepted radii.
5. Preform members accurately to avoid the need to use force or restraint at the joints.
6. Continuously weld joints if possible and avoid uneven thermal stresses.
7. Use the information covered in ASTM A 384, "Recommended Practice for Safeguarding Against Warpage and Distortion During Hot-Dip Galvanizing of Steel Assemblies."

COMPOSITION

A fabricated item that includes component parts of different dimension and minor variations in steel composition, will not exhibit a uniform appearance following immersion in the galvanizing bath. The thinner portions will develop a thicker coating and, possibly, a slightly different coloration because they reach the bath temperature sooner than the thicker portions. It should be noted also that steels with the higher silicon levels may exhibit bright shiny areas adjacent to grey matte areas owing to an uneven silicon distribution. The galvanizer should be informed of the type of steel and the silicon levels.

FATIGUE STRENGTH

Experience and the results of a variety of studies over the past 20 years show that the fatigue strength of the steels most commonly galvanized equals or exceeds that of the same steel before galvanizing. Fatigue strength, of course, is reduced by the presence of notches and weld beads, regardless of the effects of such processes as the heating cycle that galvanizing imposes.

Rapid cooling of hot work may induce microcracking in weld zones and create a possible notch affect. To avoid microcracking, specifications for the galvanizing of welded steel for use in critical applications should require air cooling rather than water quenching after removal from the bath.

WELDED STRUCTURES

Welding of structural steel should be performed before galvanizing because welding destroys the galvanizing and the process creates toxic fumes. The two most important factors of concern to the galvanizer are the cleanliness of the weld area and the metallic composition of the weld. As welding flux residues are inert toward the normal pickling solutions, they must be removed before the galvanizing process through chipping, blasting, or wire brushing. The fabricator is responsible for such cleaning unless the galvanizer agrees to do it. It is desirable that the welding technique selected be one that yields no slag, such as metal inert gas (MIG) or tungsten inert gas (TIG). For heavy weldments, a submerged arc method is recommended. The members of an assembly should be preformed accurately so that it is unnecessary to force, spring, or restrain them during welding. Weld rods that are high in silicon have a propensity for the formation of thick or dark coatings in the weld area. Finally, if the fabricated item is to be pickled in acid, all metal components should be of similar chemical composition or there might be some differential attack owing to the formation of a galvanic cell.

CASTING

Sound stress-free castings can be successfully galvanized provided a few rules are followed. These include the need for a uniform section thickness as much as possible, large fillet radii, and avoidance of sharp corners and deep recesses. Should a fabricated assembly that included cast material be prepared for galvanizing, the entire surface should be blastcleaned to eliminate unequal surface conditions before immersing it in the pickle bath.

SAFETY

Hollow structures with enclosed sections must have provisions for adequate venting during galvanizing. Any moisture present at the galvanizing temperature is converted to superheated steam that expands at explosive velocities and can spatter large quantities of molten zinc outside of the tank. Correct venting also ensures that all interior surfaces are reached by the molten zinc. Internal baffles should be cropped on the bottom to permit free flow of molten zinc. Likewise, strengthening gussets in channels and fabricated columns should be cropped to facilitate drainage (Figures D-1 and D-2).

Narrow gaps between overlapping plates and back-to-back angles and channels should be avoided because pickle acids may penetrate the joint and come out explosively during galvanizing
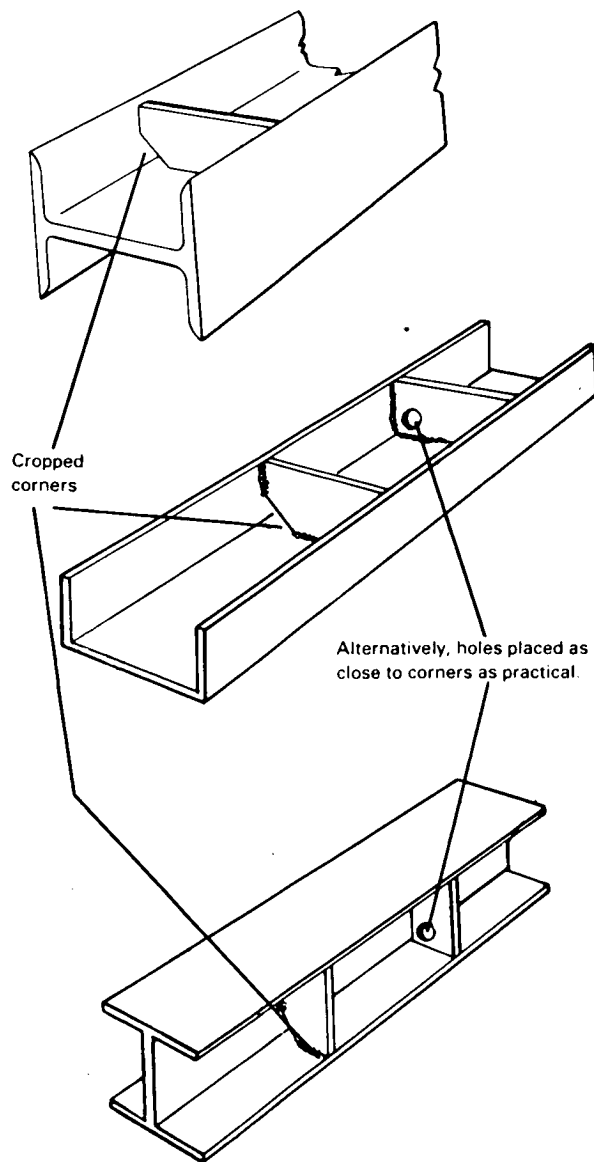
FIGURE D-1 Generously cropped corners provide for free drainage. Where cropping is not possible, holes no less than ½ in. in diameter close to the corners are required.

or may come out after galvanizing and streak the surface with corrosion products of steel. Such areas should be sealed by welding shut. Consultation with the galvanizer before completion of design will avoid a potentially difficult situation.

JOINING TECHNIQUES

Because galvanized members should not be welded, bolting has become the most widely used, versatile, and reliable method for making field connections in structural steel members. Galvanized low-carbon steel bolts have been used for many years for field connections of galvanized steel members. Design application has followed conventional considerations based on allowable stresses in tension, shear, and bearing. The major

advantages of bolting over welding and hot riveting are the following:

1. Economy, speed and ease of erection.
2. Fewer and less highly skilled operators.
3. No pre-heating of high-strength low-alloy steels.
4. No weld cracking and induced internal stresses.
5. Relative simplicity in inspection.
6. Ease in making alterations and additions.
7. Reliability in service.

The last 30 to 35 years have seen the development of high-strength bolts, the application of these to "friction type" connections, and, more recently, the use of these with galvanized coatings; however A 490 bolts are not galvanized. The introduction of galvanized high-strength bolting has brought improved economy and efficiency to the fabrication of galvanized steel structures by permitting the use of:

1. smaller size bolts of higher strength, and
2. the need for fewer bolts and bolt holes, resulting in:
   a. lower fabrication costs for members, and
   b. faster erection and economy in labor.

In 1964, the International Lead Zinc Research Organization sponsored the beginning of an extensive program at the University of Illinois to evaluate for structural uses the behavior of hot-dip galvanized bolts and joints assembled with such bolts (33).

There are two main design methods used in high-strength bolting: 1) friction-type joints and 2) bearing-type joints. The principle of the friction-type joint, shown in Figure D-3, is that in clamping members tightly together shear load is transmitted from one member to another by means of friction between the contacting surfaces. Development and availability of high-strength bolts has permitted the design of bolted joints in which very high bolt tension produces high friction forces across mating surfaces. The friction force is controlled by the tension of pre-load developed in the bolt in tightening and the coefficient of friction on the mating surfaces.
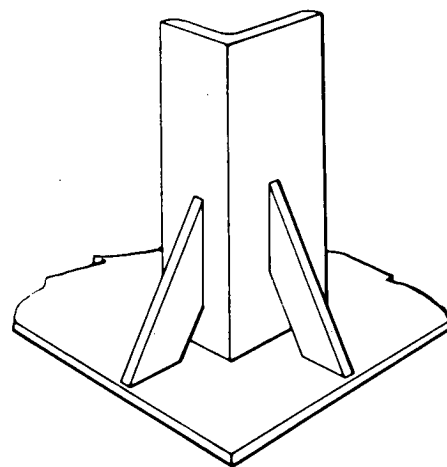

FIGURE D-2 Stiffener plates should be cropped or bar stiffeners should be used.
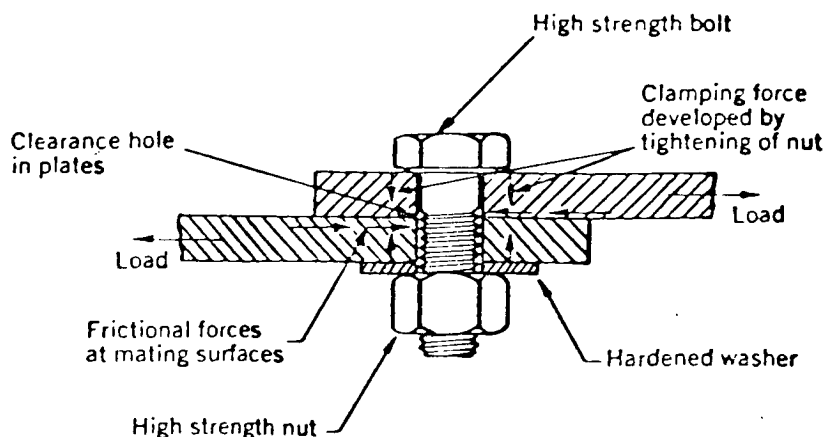
FIGURE D-3 Friction joint with a hexagon-head high-strength bolt in a clearance hole.

The principle of the high-strength bearing-type joint is the same as in low- and medium-strength bolted joints where loads between members are carried by bolts in shear and bearing. The advantage of high-strength bolts used in bearing-type applications is that higher loads can be carried with fewer bolts.

Munse (33) conducted research on joining galvanized structural members with galvanized bolts. To justify the use of galvanized high-strength bolts it must be possible to install them to the desired levels of bolt tension with relatively simple bolt control and with little or no change in standard technique. Two acceptable methods of installation are "turn of the nut," usually a half turn from the snug tight condition, and "torque," in which torque is applied to a predetermined level using a calibrated wrench. The friction forces between the nut and the bolt threads must be low enough to prevent torsional failure of the bolt shank and to ensure high bolt tension.

With "as galvanized" assemblies there is a wide scatter in induced tension at any torque level. Hence, torque cannot be used as a reliable method for gauging the required bolt tension.
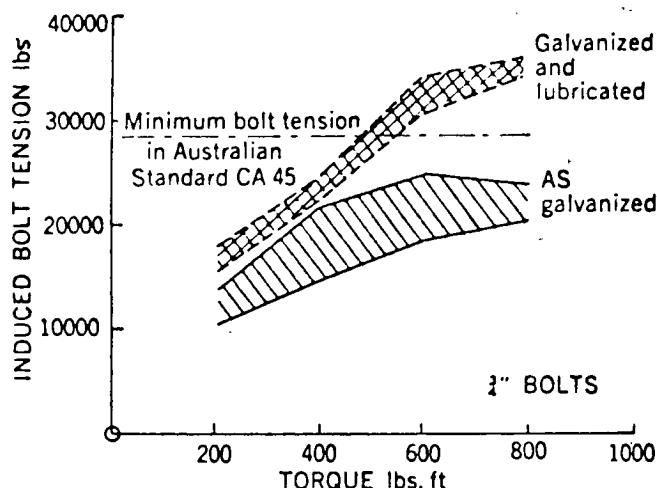
Similarly, galvanized bolts developed only ¾ to one turn of the nut to failure compared to 1½ to 2½ turns of the nut to failure for an ungalvanized bolt. Munse has shown that suitable lubrication reduced the variability and enabled tightening of the galvanized bolt in excess of the minimum tension without danger of bolt fracture as seen in Figure D-4. The lubricants evaluated included a cutting oil, Molykote G (molybdenum disulfide type), graphite, a cutting wax, and beeswax. The beeswax proved most effective.

To develop suitable design specifications for friction type connections in bolted galvanized structures, methods to increase the low frictional resistance of zinc surfaces were explored. The slip factor or coefficient of friction Munse found for a number of conditions is shown in Table D-1.

It is quite apparent from this work that an as-delivered mill-scale-coated surface has a slip factor of 0.32, for purposes of calculation. Rusting and blast cleaning increases the factor, as anticipated. Paints, in general, reduce the factor, as would be expected. The inorganic zinc-rich finishes are rough and, of course, the metallized or flamesprayed coatings are even rougher in texture. Note how the zinc can be given a rough texture by blasting despite its relative softness. It should be appreciated that the iron-zinc alloy layers beneath are quite a bit harder than the free zinc.

Munse also showed that light wire brushing or a light brush-over and blasting will also suffice for increasing the coefficient of friction as noted in Table D-2.

The favorable results summarized in Figure D-4 for pretreated galvanized steel became the basis for a change in specification by the Research Council on Riveted and Bolted Structural joints of the Engineering Foundation and the American Association of State Highway and Transportation Officials. The revised specification reads, "Contact surfaces within friction type joints shall be free of oil, paint, lacquer, or rust inhibitor except that hot dip galvanizing will be permitted provided that contact surfaces are scored by wire brushing or blasting after galvanizing and prior to assembly. The wire brushing treatment shall be a light application that removes relatively little of the zinc coating. That blasting treatment shall be a light brush-off which will produce a dull, gray appearance."

This significant acknowledgment of the effectiveness of galvanized bolting systems provided support for its increasing use

FIGURE D-4 Relation between torque and induced tension for galvanized high-strength bolts and for galvanized and lubricated high-strength steel.

TABLE D-1

COEFFICIENT OF FRICTION—SLIP FACTOR FOR VARIOUS SURFACE FINISHERS AND COATINGS

Surface Treatment	No. of Tests	Slip Factor		
		Mean	Max.	Min.
Plain Steel				
Mill Scale	352	0.32	0.60	0.17
Rusted	15	0.43	0.55	0.41
Flame cleaned	88	0.48	0.75	0.31
Blast cleaned	183	0.57	0.81	0.32
Coated Steel				
Red lead paint	6	0.07	-	0.05
Rust preventive paint	3	0.11	-	0.07
Hot-dip galvanized	95	0.19	0.36	0.08
Lacquer-varnish	17	0.24	0.30	0.10
Blast cleaned vinyl wash primer	24	0.28	0.34	0.22
Galvanized and grit blasted	12	0.49	0.55	0.42
Grit blasted and inorganic zinc rich paint	48	0.51	0.65	0.38
Grit blasted and zinc sprayed	42	0.65	0.99	0.42

by design engineers. To advance the utility of this concept, the effects of dynamic loading were evaluated in fatigue machines employing four-bolt galvanized joint specimens. When the data were compared to those obtained with similar ungalvanized steel specimens, the fatigue results were comparable. In addition, when tested considerably above the allowable design stress where the frictional resistance of the connections was exceeded, the joint "locked up" after a few cycles caused by the cold welding of the zinc surfaces.

It is useful at this point to summarize some of the significant results of Munse's work as verified in Australian practice and reported by Ritchie (34, 35). The questions Munse was asked to seek answers to were: 1) Does a galvanized bolt maintain its clamping-force in the structure? 2) Will the galvanized connections provide sufficient frictional resistance to carry their loads properly? and 3) Will the galvanizing treatment reduce the fatigue resistance of the structural joints?

From the foregoing data, it appears that he has satisfactorily answered those questions. However, it remained for Ritchie to state in his summary review of Munse's work that "Australia has the highest per capita zinc consumption in the world, largely due to the wide use of hot dip galvanized steel in various forms. It is not surprising, therefore, that wide use has been made of galvanized high strength hexagon head bolts, and also galva-

TABLE D-2

EFFECT OF SURFACE TREATMENT OF GALVANIZED SURFACE ON SLIP FACTOR

Surface Treatment	No. of Tests	Slip Factor		
		Mean	Max.	Min.
As received	15	0.14	0.18	0.11
Weathered	3	0.20	0.26	0.15
Wire brushed	4	0.31	0.33	0.27
Sand blasted	2	0.31	0.34	0.28

nized high strength bearing or interference body bolts. These have been used in both galvanized and also in zinc-sprayed and inorganic zinc-rich coated structures" (34, 35). His illustrations included some rather massive structures; for example, a 320 ft high A-frame carrying galvanizing suspension cables for the 675-ft span deck structure in which galvanized high-strength bolts were used for all of the field connections, both in the deck and in the A-frame. A large grain elevator, a large wheat storage silo, and an iron ore tunnel using galvanized corrugated steel plate employing special design high-strength bolts were illustrated as examples of such applications of galvanized bolts.

EMBRITTLEMENT

It is relatively rare for steel to be in an embrittled condition following galvanizing. Of the several types of embrittlement that can occur only strain-aging is aggravated by galvanizing. The condition is caused by cold working of certain steels followed by aging at temperatures less than 1100° F or by warm working the steel below this temperature. Cold working, such as punching holes, shearing, and bending before galvanizing, may lead to embrittlement of susceptible steels. If it is possible to specify the steel-making process before ordering, the product coming from the basic oxygen process is to be preferred followed by that produced by the open-hearth process. Hydrogen embrittlement is associated with immersion in acid pickle solutions; however, any absorbed hydrogen is rapidly expelled at the galvanizing bath temperature. Certain steels that have been cold worked or stressed can absorb hydrogen and initiate cracks before entry into the molten zinc. Galvanizing is not permitted on A 490 high-strength bolts.

Suggestions for Minimizing Embrittlement

If possible, use a steel with a low susceptibility to strain age embrittlement. Where cold working is necessary the limitations

that should be observed are carefully described in ASTM A 143, "Recommended Practice for Safeguarding Against Embrittlement of Hot-Dip Galvanized Structural Steel Products and Procedure for Detecting Embrittlement." The following points are made by the American Hot Dip Galvanizer's Association:

1. For steels having a carbon content of 0.1–0.25 percent, a bending radius of three times the section thickness (3t) should be maintained if the material is fabricated cold.

2. Drill rather than punch holes in material thicker than ½ in. or, if holes are punched, they should be punched undersize and reamed an additional ⅛ in.

3. Avoid cold shearing plates that will be subject to heavy loads. Flame cutting or sawing is preferred.

4. Where 3t cold bending cannot be performed, fabricate hot or stress relieve at 1100° F, one hour per inch of section thickness following cold fabrication.

5. Select steels having a carbon content below 0.25 percent.

6. Select steels having a low transition temperature.

The Association suggests further that a sample quantity of the fabricated product be submitted to the galvanizer for coating and then impact tested to determine whether any loss of ductility has occurred during galvanizing.

TABLE D-3

VISUAL INSPECTION GUIDE

CONDITION	CAUSES	GROUNDS FOR REJECTION?
Bare spots	Paint, grease or oil residues. Scale or rust residues. Residual welding slag. Rolling defects in basis steel. Embedded sand in castings. Overdrying of preflux. Excess aluminum in bath. Articles in contact during galvanizing.	Yes, except where bare spots are small and suitable for patching.
General Roughness	Analysis or original surface condition of steel. Overpickling. Uneven cold working. High galvanizing temperature and/or long immersion time.	No, except by prior agreement.
Dross Protrusions	Entrapped dross particles.	No, unless dross contamination is heavy.
Blisters	Surface defects in steel. Absorbed hydrogen.	No. Not if due to steel composition.
Lumpiness and Runs	Withdrawal speed too high. "Cold" galvanizing bath. Delayed run-off from seams, joints, bolt holes, etc. Articles in contact during withdrawal.	Only on basis of prior agreement.
Flux Inclusions	Stale flux burnt on during dipping. Surface residues on steel. Flux picked up from top of bath.	Yes. Yes. Yes, unless removed.
Ash Inclusions	Ash burnt on during dipping. Ash picked up from top of bath.	Yes, if in gross lumps.
Dull Gray Coating or Mottled Appearance	Steel composition (high silicon, phosphorus or carbon) or severe cold work. Slow cooling after galvanizing.	Not if due to steel composition or condition, or limited to occasional areas.
Rust Stains	"Weeping" of acid, etc., from seams and folds. Storage on or near rusty material.	No. No.
Wet Storage Stain ("White Rust")	Confinement of close-packed articles under damp conditions. Packing of articles while damp.	No, unless present prior to first shipment. Customer to exercise caution during transportation and storage.

INSPECTION OF GALVANIZED COATINGS

A guide to visual inspection of hot-dip galvanized coatings is given in Table D-3.

The nondestructive instruments commonly used for determining coating thickness are based on the principle of magnetic attraction. The two simplest types are called pull-off gauges and magnetic balance gauges. The pull-off gauge looks like a thick pencil. It has a hemispherically shaped magnetic tip with a vertical scale. To make a reading the gauge is placed in a vertical position and then slowly and steadily drawn upwards until the magnet breaks away from the item. The scale is continuously read until the point of break away. Accuracy is ± 15 percent.

The magnetic balance gauge involves a rotating dial to which a spring is attached from the magnet that is placed on the galvanized surface. By slowly rotating the dial and noting the point at which attraction has been broken, a reading can be made. The scales generally are calibrated in microns and/or mils. Accuracy with this type of gauge is ± 10 percent. There is a magnetic reluctance type gauge that involves a horseshoe magnet with its two poles exposed for contact with the galvanized surface. Between the arms of the horseshoe is a small bar magnet counterbalanced by a coil spring and connected to a pointer that moves across a calibrated scale.

A recent development in the field of magnetic gauges is an instrument (PosiTector 2000) that is the size of a package of cigarettes and has a digital readout. The contact point is a ruby-tipped probe and as soon as it is set down a reading in mils can be made. Unlike the other two gauges, the operator is free from manual manipulations. Readings are made instantaneously and calibrations are easily made with shim plates from the National Bureau of Standards.

APPENDIX E

RELEVANT STANDARDS OF THE AMERICAN SOCIETY FOR TESTING AND MATERIALS

A 90   Test Method for Weight of Coating on Zinc-Coated (Galvanized) Iron or Steel Articles

A 123   Specification for Zinc (Hot-Galvanized) Coatings on Products Fabricated from Rolled, Pressed, and Forged Steel Shapes, Plates, Bars, and Strip

A 143   Recommended Practice for Safeguarding against Embrittlement of Hot-Dip Galvanized Structural Steel Products and Procedure for Detecting Embrittlement

A 153   Specification for Zinc Coating (Hot-Dip) on Iron and Steel Hardware

A 325   Specification for High-Strength Bolts for Structural Steel Joints

A 384   Recommended Practice for Safeguarding against Warpage and Distortion During Hot-Dip Galvanizing of Steel Assemblies

A 385   Practice for Providing High-Quality Zinc Coatings (Hot-Dip)

A 386   Specification for Zinc Coating (Hot-Dip) on Assembled Steel Products

A 394   Specification for Galvanized Steel Transmission Tower Bolts and Nuts

A 563   Specification for Carbon and Alloy Steel Nuts

A 780   Practice for Repair of Damaged Hot-Dip Galvanized Coatings

E 376   Recommended Practice for Measuring Coating Thickness by Magnetic-Field or Eddy-Current (Electromagnetic) Test Methods

F 436   Specification for Hardened Steel Washers

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