

Part II. Deterioration and Methods of Preserving Metals

by John G. Waite, AIA



Contents

Foreword	1	Decorative Cast Iron	56
Part I: A Historical Survey of Metals	3	Stairs and Elevators	56
Chapter 1. Introduction	5	Lintels and Grilles	62
Chapter 2. Lead	8	Verandas and Balconies	64
Roofing and Related Items	8	Railings, Fences, and Cresting	64
Lead-coated Metals	9	Street Furniture and Lighting	64
Window Cames	10	Fountains and Statues	66
Sculpture	11	Tombs	72
Paint	11	Rolled Sheet Iron and Steel	72
Chapter 3. Tin	12	Steels	74
Pure Tin	12	Structural Steel	74
Tinplate	12	Stainless Steel	79
Tinplate Roofing and Related Items	12	Copper-Bearing Steels	79
Decorative Uses	13	Chapter 8. Aluminum	84
Chapter 4. Zinc	15	Part II: Deterioration and Methods of	
Pure Zinc Roofing and Related Items	15	Preserving Metals	89
Zinc-coated Metals	15	Chapter 9. Preservation of Architectural Metals	90
Decorative Uses	15	Chapter 10. Causes of Metal Deterioration and Failure	92
Paint	21	Corrosion	92
Chapter 5. Copper and Copper Alloys	22	Uniform Attack	92
Copper	22	Pitting	92
Roofing and Related Items	23	Selective Attack	92
Decorative Uses	24	Stress Corrosion Cracking	92
Bronze	27	Corrosion Erosion	92
Brass	31	Galvanic Corrosion	92
Chapter 6. Nickel and Nickel Alloys	35	Oxygen Concentration Cell	93
Nickel Silver	35	Atmospheric Corrosion	93
Monel Metal	39	Corrosive Agents	93
Chapter 7. Iron and Iron Alloys	42	Mechanical Breakdown	93
Wrought Iron	42	Abrasion	93
Decorative Wrought Iron	42	Fatigue	93
Structural Wrought Iron	44	Creep	95
Cast Iron	50	Fire	95
Structural Cast Iron	50	Overloading	95
Columns	50	Weathering	95
Building Fronts	51	Connection Failure	95
Domes and Cupolas	56	Chapter 11. General Preservation Methods	97
Lightcourts and Skylights	56	Introduction	97

Proper Design.....	98	Chapter 16. Nickel and Nickel Alloys;	
Control of the Environment.....	98	Preservation and Repair.....	128
Dehumidification.....	98	Identification.....	128
Cathodic Protection.....	98	Nickel.....	128
Corrosion Inhibitors.....	98	Nickel Silver.....	128
Protection with Applied Coatings.....	98	Monel Metal.....	128
Cleaning.....	99	Causes of Deterioration.....	128
Mechanical Repairs.....	99	Methods of Preservation and Repair.....	128
Patching.....	99	Chapter 17. Iron and Iron Alloys;	
Splicing.....	99	Preservation and Repair.....	130
Reinforcing.....	100	Identification.....	130
Duplication and Replacement.....	100	Iron.....	130
Chapter 12. Lead; Preservation and Repair.....	101	Wrought Iron.....	130
Identification.....	101	Cast Iron.....	130
Causes of Deterioration.....	101	Steel.....	130
Methods of Preservation and Repair.....	102	Galvanized Steel.....	130
Chapter 13. Tin; Preservation and Repair.....	104	Stainless Steel.....	130
Identification.....	104	Causes of Deterioration.....	131
Causes of Deterioration.....	104	Iron and Steel.....	131
Methods of Preservation and Repair.....	104	Cast Iron.....	131
Priming and Painting.....	105	Wrought Iron.....	131
Replacement.....	105	Steel.....	131
Chapter 14. Zinc; Preservation and Repair.....	111	Galvanized Iron and Steel.....	131
Identification.....	111	Stainless Steel.....	131
Causes of Deterioration.....	111	Copper-Bearing Steel.....	135
Methods of Preservation and Repair.....	113	Methods of Preservation and Repair.....	135
Chapter 15. Copper and Copper Alloys;		Cleaning and Coatings.....	135
Preservation and Repair.....	118	Paint Coatings.....	136
Identification.....	118	Plating and Glazes.....	140
Copper.....	118	Repairs.....	140
Bronze.....	118	Replacement.....	142
Brass.....	118	Substitute Materials.....	142
Causes of Deterioration.....	118	Stainless Steel.....	147
Copper.....	118	Chapter 18. Aluminum; Preservation and Repair.....	149
Bronze and Brass.....	119	Identification.....	149
Methods of Preservation and Repair.....	125	Causes of Deterioration.....	150
Copper.....	125	Methods of Preservation and Repair.....	151
Bronze and Brass.....	125	Notes.....	154
		Selected Bibliography.....	157

Chapter 9: Preservation of Architectural Metals

The metals used most commonly in historic American building construction have been lead, tin, zinc, copper, bronze, brass, iron, steel, and to a lesser extent nickel alloys, stainless steel, and aluminum. While they have been employed in a variety of ways, these metals have been used primarily for structural systems, sheathing, roofing, siding, and decorative elements. The first part of this report provided a pictorial survey and historical description of these metals and their architectural uses. This part will discuss the deterioration, preservation, repair, and maintenance of metal building components.¹

Like other building materials, metals can deteriorate over time or be damaged and require conservation or replacement to continue to serve their intended functions. The problems of size and weight or the integration of these metals into the structure of a building can complicate conservation attempts.

Before steps can be taken to analyze or treat deterioration, it is necessary to know which metal is involved. Determining the metallic composition of an architectural component may not be easy, especially if it is inaccessible or encrusted with paint. If possible, the original architect's specifications and any correspondence relating to the structure should be checked for any references to foundries, catalogs, or stores where building materials might have been purchased. If these resources prove fruitless, a preservation consultant or historical architect may be able to help.

When deterioration has set in, prompt action to halt or correct the damage is essential. But first, the exact cause of the problem must be found. If water, oxidation, *galvanic action* (destructive corrosion between two dissimilar metals), or a host of other conditions continue to exist in a building system, it may be that no amount of corrective action will be sufficient to save it. These problems must be accurately diagnosed before any restoration or rehabilitation is undertaken. For example, many buildings in the past were constructed with unfortunate combinations of dissimilar metals, which resulted in destructive reactions. Builders then did not always know enough about the properties of various metals and the potential for reactions with each other and with other materials such as certain types of wood, masonry, and coatings. Once the causes of deterioration have been identified and the damage repaired, a regular maintenance program is needed to prevent recurrence. Records of the structural investigations and all changes, including additions and subtractions from the building, should

be kept. When records are kept, later problems with materials or remedial measures will be easier to detect and inappropriate treatments easier to avoid.

After a general discussion of metal deterioration, this part of the report will discuss methods of stabilizing metal components that are currently available and will recommend steps toward their preservation and maintenance. The metals most widely used in historic buildings will be discussed for specific properties, deterioration characteristics, and preservation and repair techniques.

Metals are, in general, those inorganic substances that have luster and hardness, can conduct heat and electricity, are opaque, and possess certain mechanical properties, the most valuable of which is the ability to resist deformation. All metals² have crystalline structures and are somewhat malleable and ductile; that is, they can be shaped by hammering or rolled into thin sheets and drawn into wire. Metals have tenacity, resist separation of individual particles, and are fusible; that is, they become liquid when heated at a high temperature. Metals also have high specific gravity or relative weight.

In chemistry, a *metal* is defined as an element that yields positively charged ions in aqueous solutions of its salts. Another definition is that a metal is a lender of electrons; that is, a metal loses electrons during a chemical reaction. Different types of metals have different chemical properties and consequently react in various ways with elements of the environment.

The preservation architect must be knowledgeable about these physical and chemical properties and their relationship to the agents of deterioration in the building's environment in order to choose proper stabilization or restoration techniques. If the properties of the metal are not fully understood, an inappropriate treatment that, in the long run, may cause more deterioration than it corrects, might be selected. (table 1).

In order to be used successfully for architectural purposes, the metals selected must maintain their functional integrity over a long period of time and must also be aesthetically acceptable. The long-term performance of metal architectural elements depends upon the metals' intrinsic physical and chemical properties, the climates to which they are exposed, and the specific design details that determine their relationship and proximity to other metallic and nonmetallic building components. Properly selected, installed, and maintained, metal architectural elements are among the most durable and per-

manent building materials. However, metal elements that are not properly suited for the chosen function or are not properly cared for can be very fragile and short lived.

Table I.

Metal	Symbol	Atomic Number	Atomic Weight	Relative Density	Melting Point Degrees C	Specific Heat	Heat Expansion Per °C	Heat Cond'y % of Cu	Elect. Cond'y % of Cu	Coef. of Elect. Res. Per °C	Modulus of Elast'y psi
Lead	Pb	82	207.1	11.38	327	0.031	.000029	9.	7.8	.0041	800,000
		50	118.7	7.28	231.8	0.054	.000020	16.	15.		6,000,000
Zinc	Zn	30	65.37	7.14	420	0.094	.000029	29.	28.2	.0040	13,700,000
Copper	Cu	29	63.5	8.89	1083	0.093	.000.17	100.	100.	.0040	16,000,000
Phosphor Bronze				8.66		0.104	.000018		36.	.0039	16,000,000
Brass				8.46	900	0.088	.000020	28.	28.	.0015	13,800,000
Nickel	Ni	28	58.6	8.85	1440	0.130	.000013	15.5	16.	.0041	30,000,000
Nickel Silver				8.75	1110	0.095	.000018	7.6	5.2	.0003	17,000,000
Monel Metal				8.80	1315	0.127	.000014	6.6	4.	.0019	26,000,000
Iron	Fe	26	55.8	7.7	1535	0.110	.000013	15.	15.	.0062	25,000,000
Cast Iron				7.2	1000-1200		.000010	10-12	2-12		12-27,000,000
Steel				7.9	1400		.000013	6-12	3-15		30,000,000
18/8 Cr/Ni Iron (stainless steel)				7.9	1400	0.118	.000017	3.6	2.8		28,600,000
Aluminum	Al	13	27	2.7	660	0.218	.000024	52.	56-59	.0042	10,000,000

Table I. Properties of Metals Used in Building Construction.

The information in this table is of special interest to preservationists because it includes alloys commonly used in construction. The metals and alloys in this table are listed in the same order as they appear in this report. This order was devised to avoid repetition, that is, the discussion of elements would precede the discussion of bronze and brass. The relative density has no units because it is a ratio and expresses the relative weight of equal volumes of metals to the weight of the same volume of a standard. The melting point is of interest because it has a bearing on the ease or difficulty of casting, soldering, brazing, and welding. Historically, copper has been used as a standard for comparing the properties of heat conductance and coefficients of electrical resistance because of its excellent ability to conduct heat and its extensive use in electrical wiring. Other tables use silver or hydrogen as a standard, but these are not used in construction and are more difficult to relate to for people in the construction industry. The modulus of elasticity is a measure of the rigidity of a metal, that is, its ability to resist deformation until the elastic limit (point at which the metal will not spring back to its original position after the load or weight has been removed; therefore, permanent deformation) of the metal has been reached. (Adapted from *Practical Design in Monel Metal*, (p. 10, published in 1935 by International Nickel Company.)

Chapter 10: Causes of Metal Deterioration and Failure

In scientific terms, *deterioration* is generally defined as a decrease in ability of the material to fulfill the function for which it was intended.³ It usually refers to the breakdown of a material because of natural causes, although deterioration can also be either directly or indirectly caused by man. Although deterioration usually implies a chemical change, under some conditions, the change can be physical.

Corrosion

Corrosion, in one form or another, is the major cause of the deterioration of architectural metals. Often called oxidation, it is the chemical reaction of a metal with oxygen or other substances. Metals are constantly undergoing change. With exposure to the atmosphere, heat, moisture, pressure, and other agents, they tend to revert from a pure state, such as iron and copper (elements), to their natural ores, such as iron oxide and copper sulfide (compounds). The deterioration of metal architectural elements is a complex process because the types and degree of corrosion are affected by minor variations in environment, contact with other metals and materials, and the composition of the metal itself.⁴

Upon exposure to the atmosphere, almost all new or newly cleaned metals become coated with a thin complex film, which is a result of the reaction of the metal with oxygen in the air. This film may modify the properties of the metal and make it less susceptible to further corrosion. As the film thickens, it may tend to insulate the metal from moist air or other corrosive agents. The inherent nature of the metal to resist corrosion and the nature of the film determines to what degree the corrosion of the metal is controlled. With some metals such as aluminum and copper, the oxide coating can form a protective membrane which restricts the passage of metal ions out of it or oxygen into it and through it. With other metals, such as iron, the oxide does not form a protective film, but rather promotes the continued corrosion of the metal.

Architectural metals are attacked by corrosion in several ways, including the following:⁵

Uniform Attack is where the metal corrodes evenly when exposed to corrosive agents.

Pitting is the localized corrosive attack on the metal (see figure 180 and 181).

Selective Attack can occur where a metal or alloy is not homogeneous and certain areas are attacked more than others.

Stress Corrosion Cracking can occur where stresses were induced into the metal in the pulling or bending process of metalworking and the metal was later subjected to a corrosive environment. For example, wrought brass can crack if small quantities of ammonia are introduced into the environment; stainless steels can crack in chloride-containing environments; and carbon steels in nitrate, cyanide, or strong caustic solutions.⁶

Erosion occurs when the corrosion-resistant film or oxide or layers of protective corrosion product is removed by abrasion, exposing fresh metal to the corrosive agents.

Galvanic Corrosion is an electrochemical action that occurs between two different metals in electrical contact in the presence of a common electrolyte forming an electrical couple (where there is a flow of electrons). Positive ions can travel through an electrolyte such as ionized water (which must be present). A galvanic action will occur only (1) when there are two dissimilar metals having a difference in a potential, (greater and lesser degree of nobility), (2) when the two dissimilar metals are in electrical contact so there can be a flow of electrons, and (3) when there is an electrolyte so that ions can move from one metal to the other (figure 116). In some cases, the electrolyte may be moisture or condensation on the surfaces of the metals. If any of the three conditions are not present, then galvanic action will not take place.⁷

Table II is a galvanic series from the ASTM Standard Guide G82-83 (Development and Use of Galvanic Series Predicting Galvanic Corrosion Performance).⁸ It is based on actual potential readings in sea water, a standard corrosive environment used to test many metals. Although few architectural metals are found in contact with sea water, this table is still useful because the positions on the list would change little if the metals were subjected to other corrosive environments such as urban pollution.

The severity of galvanic corrosion is also a function of area size: if the more noble metal is much larger than the baser metal, the deterioration of the baser metal will be more rapid and severe; if the more noble metal is much smaller than the baser metal, the deterioration of the baser metal will be much less significant. For example, if

two copper sheets fastened together with iron rivets are placed in a corrosive environment, the iron rivets will deteriorate rapidly. On the other hand, if two iron sheets fastened together with copper rivets are placed in the same corrosive atmosphere for an equal period of time, the iron plates will only show a slight amount of deterioration and the copper rivets will be unaffected.⁹

Oxygen Concentration (Galvanic) Cell is an electrolytic cell set up where oxygen is trapped between two metals such as between tin and steel on a sheet of tinplate, or between a metal and a nonmetal, such as between a metal and a gasket or between a metal gutter and tree leaves.

Atmospheric Corrosion is an electrochemical reaction resulting from a film of moisture on the surface of the metal which serves as an electrolyte. The film contains gases absorbed by the water. Here the potential difference is between two points on the same metallic surface. This type of corrosion is the most common form of corrosion to which architectural metals are exposed. The rate of atmospheric corrosion generally increases with the humidity levels. Once a critical humidity level is reached, corrosion proceeds rapidly. Generally, an increase in temperature also increases the rate of corrosion.

Industrial atmospheres contain (along with oxygen, water, and carbon dioxide) other corrosive agents including soot, fly ash, and sulfur compounds produced by the combustion of sulfur-containing fuels, especially coal. Common sulfur compounds include hydrogen sulfide (H_2S), sulfur dioxide (SO_2), sulfur trioxide (SO_3), and particles of ammonium sulfate $[(NH_4)_2SO_4]$ ¹⁰ or salt ($NaCl$) near the sea coast.

Sea water is especially corrosive. Marine atmospheres and sea water contain several corrosive agents including chlorides and other salt particles which can be deposited on the surface of the metal (figure 182). These corrosive agents can affect metals as far as 60 to 70 miles from the sea (depending on weather patterns). Chloride ions are also found in some de-icing salts and in some forms of industrial pollutants. Metals immersed in water are also subject to corrosion by dissolved solids and gases, especially oxygen.

Soils also contain a number of metal-corroding agents including acids, alkalis, dissolved salts, water, oxygen, and sometimes anaerobic sulfate-reducing bacteria.

Corrosive agents other than oxygen and sulfur compounds which attack architectural metals include salts, especially halides such as fluorides, chlorides, bromides, and iodides, and organic compounds such as bird droppings. These agents are found in many substances, such as scum, mud, and marine plants as well as sea water and fresh water.

Mechanical Breakdown

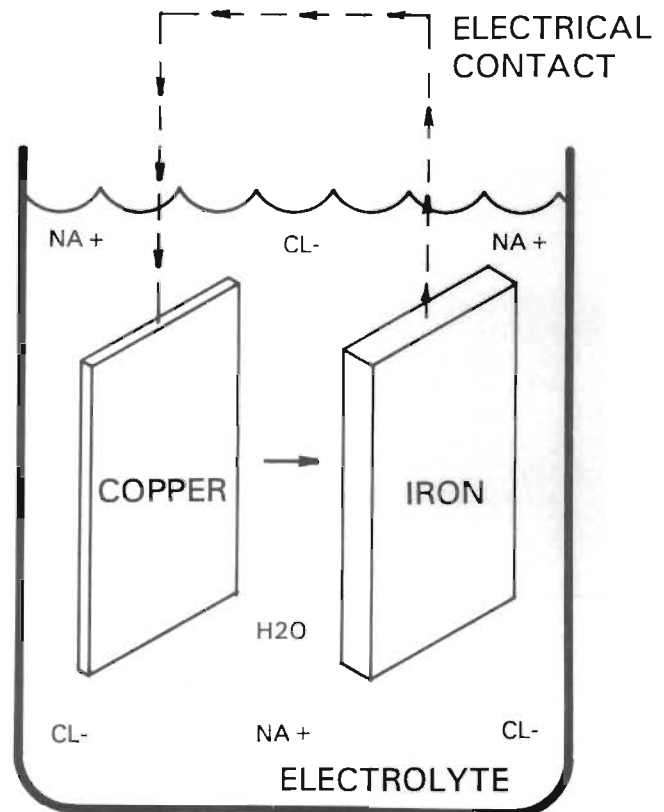
Metal architectural elements can also fail from purely physical causes such as abrasion, or a combination of physical and chemical attack, such as weathering and stress corrosion cracking.

Abrasion is the erosion of the metal (figure 149) caused by the impact of dirt, dust, sand grit, sleet, rain, and hail, or by rubbing with another architectural or human element. Abrasives can also encourage corrosion by remov-

ing the protective corrosion deposits from the metal surface. Abrasion is an especially critical problem with metal flashings and valleys used on slate roofs. As the slate deteriorates, particles break off and are washed down the valleys, causing erosion. Other examples of abrasion are when the patina, push plates and rail on bronze and brass doors (figure 117), chrome plating on railings, and brass thresholds are worn by pedestrians.

Fatigue is failure of a metal by the repeated application of cyclic stresses below the elastic limit—the greatest stress a material can withstand without permanent deformation after removal of the load. It results from a gradual or progressive fracture of the crystals. It has been estimated that approximately 90% of the structural failures of metal railroad bridges are fatigue failures which develop late in the life of the structure.¹¹ One of the major causes of the failure of copper roofs is fatigue

MECHANISM OF COPPER / IRON GALVANIC CORROSION



ARROWS INDICATE ELECTRON FLOW PATH

Figure 116. Galvanic Corrosion. A galvanic action occurs between the copper and iron with the water serving as the electrolyte. (Texas Instruments)

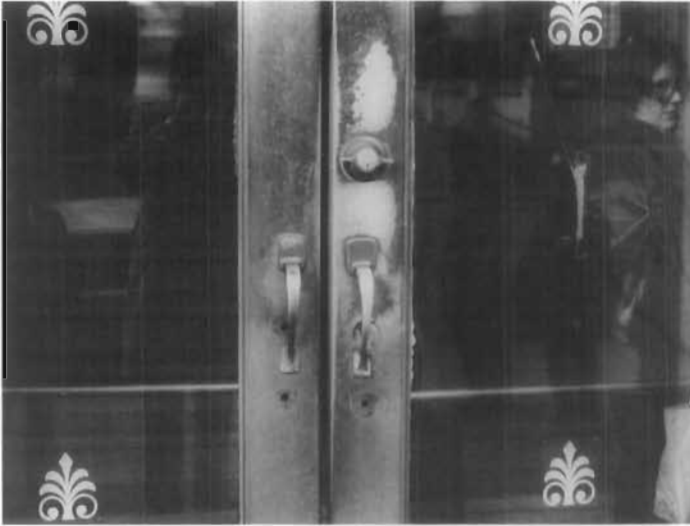


Figure 117. Human Abrasion. At the Old Post Office in Baltimore, Maryland, the bronze and glass doors show the abrasive effect of human hands on the natural patina combined with a residue of dirt and oil (from skin, which contains a minute amount of acid). This wear with accompanying superficial discoloration is only a minor problem. Over the years, these doors have received inadequate maintenance and inappropriate changes (to the hardware) and repairs. Such doors should be thoroughly cleaned to the bare metal; the holes plugged, ground down, and polished; and new chemical artificial bronze patina applied and protected by a lacquer with a corrosion inhibitor and/or with periodic applications of wax or oil (see section on bronze Chapter 15). (David W. Look)

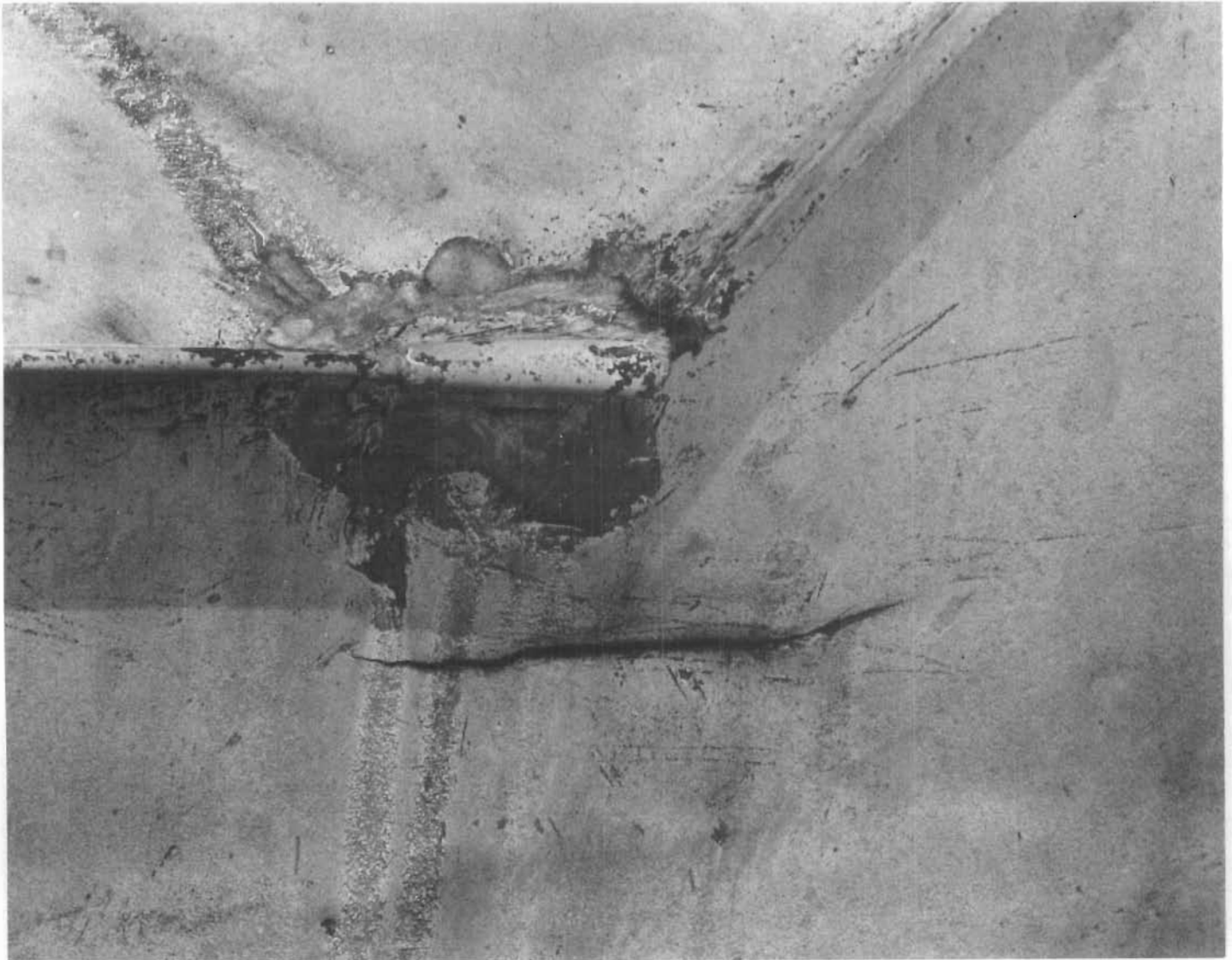


Figure 118. Fatigue Failure. This is an example of fatigue cracking of the copper roof of the Senate House, Kingston, New York. Repeated expansion and contraction due to daily and seasonal temperature changes has caused this sheet-copper roof to crack. Note cracking both at the joint and on the planar surface. (John C. Waite)

cracking caused by lack of provisions to accommodate thermal expansion and contraction (figure 118).

Creep is the continuous flow or plastic deformation of soft metals under sustained stressing, sometimes under relatively high temperatures. It tends to distort the metal, causing thin areas that may fail by rupture. Creep is characterized by inter-crystalline fracture and a lack of strain hardening. The stressing may be related to thermal expansion and contraction and the weight of the



Figure 119. Creep. Deterioration of milled sheet lead roof on a 19th century canal warehouse and office at Nantwich Basin of the Shropshire Union Canal at Nantwich, Cheshire, England. The failure has been caused by creep and the expansion and contraction of the lead. (John G. Waite)

metal. The problem of creep is often associated with sheet lead roofing (figure 119), lead statuary, and pure zinc.

Fire can cause unprotected metal (iron and steel) framing members to become plastic and fail rapidly (figure 120). Lead roofs have melted during fires, and sheet metal decoration can buckle from heat and fall off buildings when its anchorage is lost. Structural iron or steel that has survived a fire without deformation is usually safe to reuse, but any questionable member should be load tested.

Overloading is the stressing of a metal member beyond its yield point so that permanent deformation, fracturing, or failure occurs. The member can fail through the application of static loads, dynamic loads, thermal stresses (figure 121), and settlement stresses either singly or in combination. "Buckling" is a form of permanent deformation from overloading which is usually caused by excessive weight but can also be caused by thermal stresses. Members can also be overloaded if their support is removed and loads are redistributed to other members which can become overstressed and deformed (figure 122).

Weathering

A metal architectural element subjected to the weather is exposed to various chemical and physical agents at one

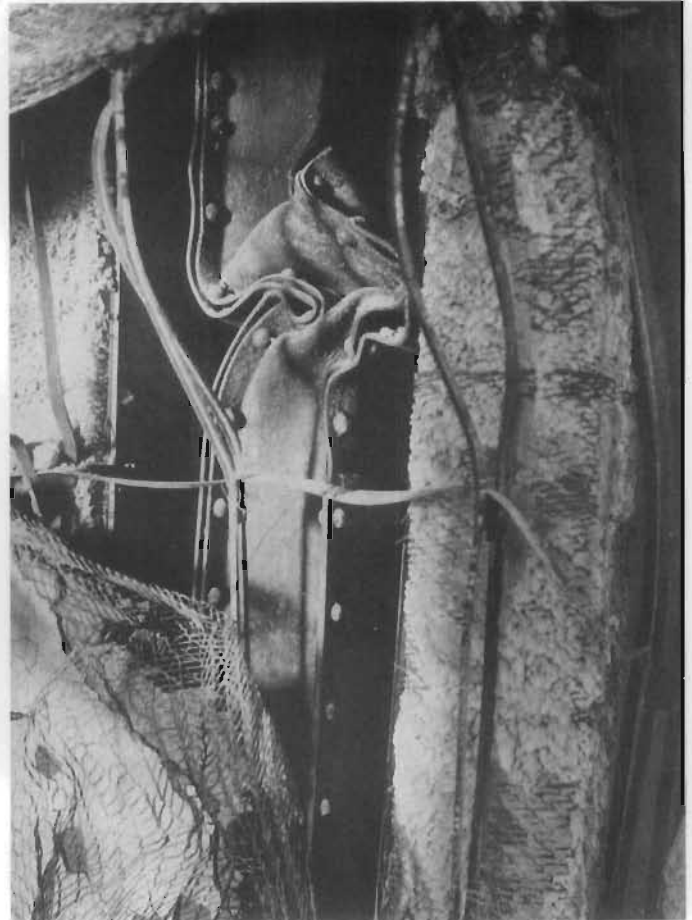


Figure 120. Column Buckling from Fire. In 1906 San Francisco was shaken by a severe earthquake, followed by fires that raged out of control for hours. In the Fairmont Hotel, the metal lath and plaster that covered the columns was probably damaged by the earthquake and was not sufficient to protect the steel from the intense heat. Portions of this building settled down approximately 7 feet from their original position because 37 columns buckled from the heat in this manner. (From *Trial by the Fire at San Francisco: The Evidence of the Camera, 1906*, Library of Congress.)

time. The result is a kind of synergism where the total effect is greater than the sum of the individual effects.¹² For example, the rate of corrosion accelerates with increases of temperature, humidity, and surface deposits of salts, dirt, and pollution.

Connection Failure

The failure of the connections of metal architectural elements, especially structural members, can also be caused by a combination of physical and/or chemical agents. The most common type of connections used for metal structural elements of historic buildings include bolting, riveting, pinning, and welding. These connections can fail through the overloading, fatiguing, or corrosion of the connectors (figure 123). Common examples of this type of failure include the corrosion, usually by the galvanic effects, of nails, bolt heads, rivets, and areas covered by fastening plates. The effective cross-sectional area of the connectors is often reduced by corrosion, making the connectors more susceptible to stress failure.

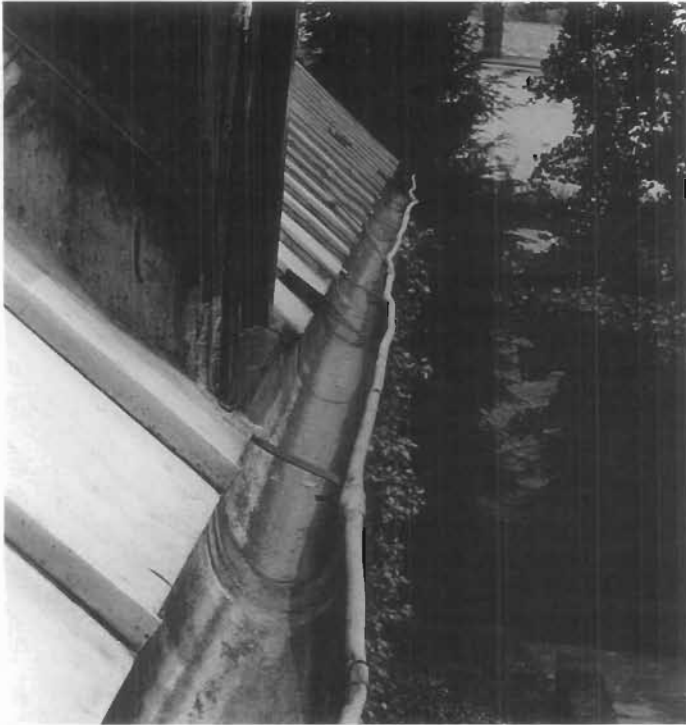


Figure 121. Overloading. The copper gutter on the Senate House, Kingston, New York, installed in the 1920s, has been distorted by ice and snow; the seams between gutter sections have opened. The problems were compounded by the lack of stiffness of the gutter and the absence of adequate provisions for expansion and contraction. The steel retaining straps are deteriorating because of an electrolytic reaction (galvanic corrosion) with the copper (the more noble metal). (John G. Waite)



Figure 123. Anchorage Failure. The nails holding down this section of embossed galvanized sheet-iron roofing have deteriorated and the wind has lifted up the corner of the sheet, allowing water to leak through the roof sheathing. Other sections (not shown in the photo) had flapped in the wind until the sheet metal cracked with fatigue failure and tore loose. In 1977 this roof at St. Edward's University in Austin, Texas, was cleaned and supplemented with reproduction "shingles" where needed. (St. Edward's University)

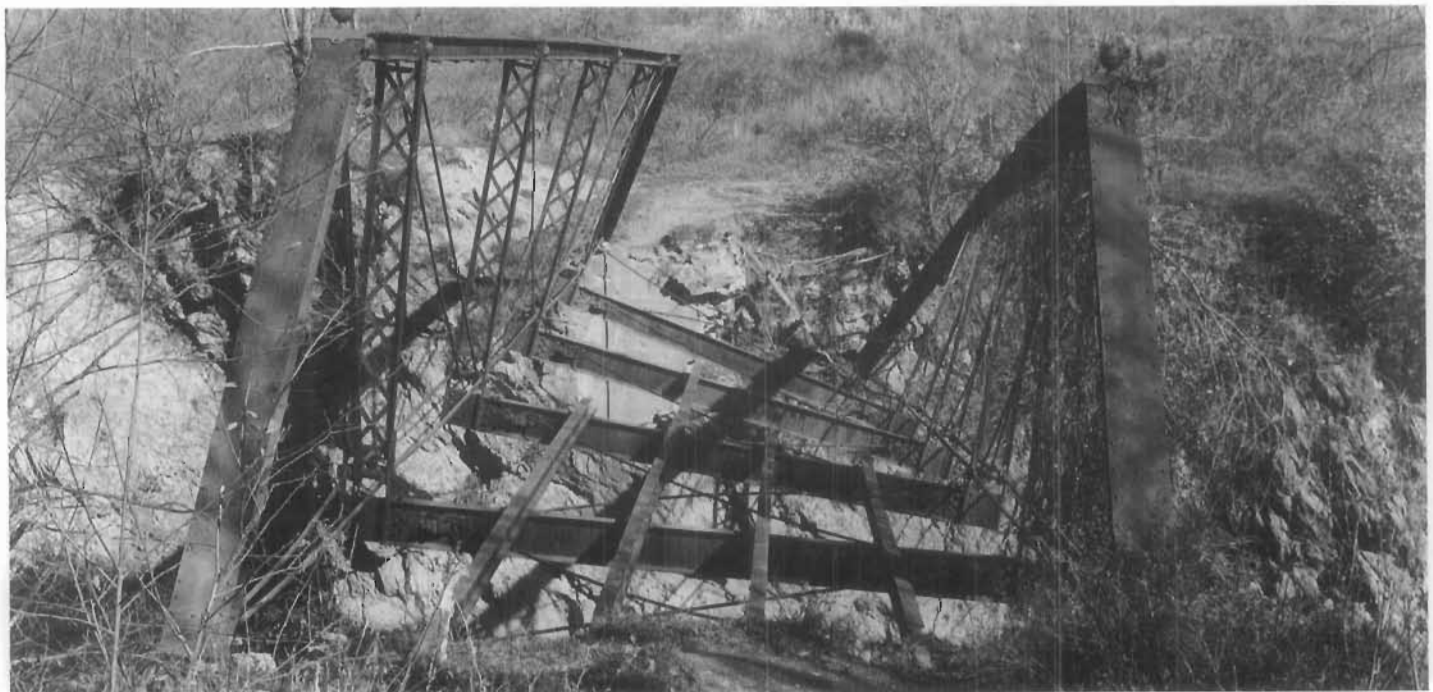


Figure 122. Structural Failure. This 19th-century wrought-iron truss bridge at Brunswick, New York, partially collapsed because the cut-stone abutment supporting it washed away. Once the support was removed, the bridge twisted. (John G. Waite)

Chapter 11: General Preservation Methods

Introduction

Unfortunately, much of the technology that has been developed by the museum conservator for treating small metal artifacts in a carefully controlled laboratory environment is not always transferable to the preservation of architectural metals. When dealing with historic buildings, the architect is often confronted with deteriorated metal elements used either as structural members or as weather protection, such as roof coverings, flashings, and wall cladding. When these elements deteriorate or actually fail, it is not practical to treat them as museum objects under laboratory conditions because of their size or position. These elements are integral parts of buildings and, therefore, cannot be easily removed and replaced. Also, laboratory treatments may not replace lost material; thus, the components would be too weak to use.

The big difference between the treatment of museum objects and architectural components is that once a museum object is cleaned and treated, it is returned to a controlled environment and is never used. The opposite is true of metal architectural components. Once they are treated *in situ*, they remain in their original environment and must function as originally intended. For example, if a roof fails it is not just the roofing material itself that is affected (figure 124). The structure and fabric of the rest of the building as well as the contents of the building can also be damaged. Therefore, it is not surprising to find that architectural metals that have failed are usually removed and replaced with new material.



Figure 124. Successive Failure. If a metal architectural element such as a tinplate roof fails, more than just the tinplate may be destroyed. (a) Deterioration is evident in the original framing and roof sheathing of the Schuyler Mansion entrance wing in Albany, New York. The entrance wing was added to the building about 1817 and reroofed with tinplate sheets during the 19th century. The tinplate gutter liners eventually deteriorated and were replaced with copper during the 1930s. However, the tinplate roof remained and electrolysis occurred along the roof perimeter where the copper and tinplate were in contact. (b) Consequently, the tinplate was completely corroded away (as seen here) when the deteriorated roofing was removed. This resulted in major damage to the sheathing, framing, and masonry walls of the entrance. (John G. Waite)

A practical reason for this approach is cost. The preservation architect normally deals with construction trades which, although skilled in conventional building techniques, have neither the training, experience, nor facility with scientific techniques for conserving historic building materials *in situ*. It is often less expensive to replace the deteriorated metal than to experiment with its preservation, which even if successful, may add only a few years to its life expectancy. If the replacement method is adopted and the original material is significant, it should either be left in place and covered or carefully removed and its location documented; the component (or at least a portion of it) should then be retained as a historic object.

A number of methods have been developed to inhibit the start of corrosion in metals as well as to control corrosion once it has begun. These methods, which will be discussed individually, include the following:¹³ proper installation of the metal elements; control of the environment by the use of inhibitors; dehumidification; cathodic and galvanic protection; the use of metallic, ceramic, and organic coatings; and various options for replacement.

Maintenance is the key to the long-term preservation of metal architectural elements. It is far more desirable to retain genuine old building material through continuous maintenance than to replace it with even the highest quality of modern reproduction material. Professional conservation advice should be sought concerning the most effective preservation techniques, especially those relating to the application of paint as a preservative. In the case of metal structural systems, periodic structural inspections should be made using modern, nondestructive methods of examination to detect the first signs of failure.¹⁴

Proper Design

Much more is known about metals today than when they were first used in construction. In preserving and restoring historic buildings with metal components, proper design may be used to eliminate the cause of deterioration or reduce its effect. A number of factors must be considered, including the following: avoidance of physical or electrolytic contact between dissimilar metals; the selection of new metals that are compatible with the existing metals; the selection of suitable corrosion-resistant materials, when possible; provisions for the removal and prevention of trapped water; and the control of metallurgical factors such as heat-treatment, especially for stress-relief where needed. Proper design should also take into account provisions for expansion and contraction to reduce internal thermal stresses in the metals caused by sun and shade. When working with historic buildings, it is often necessary to balance historical accuracy with sound modern construction practices. Compromises may have to be made to insure that the techniques used do the least damage to the historical, aesthetic, and structural integrity of the building.

Proper design may also include the over-sizing of architectural components that could be attacked by corrosion. A structure with oversized components will still have the structural capacity necessary to fulfill its func-

tion even though corrosion may occur, reducing the cross-sectional area. For sheet metals, extra thickness or the use of sacrificial components may be desirable in certain areas, such as flashing in valleys or other area where abrasive erosion may be anticipated.

Control of the Environment

Control of the environment generally is not possible for the preservation of architectural metals because it usually requires placing an air-tight envelope around the components being treated. However, some techniques to limit the destructive effects of the environment are currently in use. The following are brief descriptions of some of these:¹⁵

Dehumidification is the process of controlling the amount of moisture in the air surrounding a metal element so that water will not condense and dissolve the salts or acids on the surface to form an electrolyte. This is achievable with interior air-conditioned spaces, because air conditioning dehumidifies and filters as it cools. Metal components in air-conditioned spaces corrode less rapidly than metals in noncontrolled environments. (Caution should be exercised when dehumidifying a building because of the effect it may have on the building envelope.)

Cathodic Protection provides an electromotive force which counters the normal flow of current where corrosion is occurring. Such a system is used on ships or steel bridges in sea water where low voltage impressed current is supplied to the objects, effectively reducing corrosion. Both the impressed current anode and the structure to be protected must be in the electrolyte. A similar mechanism is used when a sacrificial metal is coated on a metal architectural component, such as iron galvanized with zinc. Since the zinc is more active than the iron, the zinc will corrode sacrificially and the iron will be cathodically protected.

Corrosion-Inhibitor is any substance which when added in small amounts to a corrosive environment, effectively decreases the corrosion rate of the metal or alloy; examples are zinc chromate and red-lead paints.

Protection with Applied Coatings

Architectural metals can be protected by the factory application of coatings of other metals and ceramic materials, and the factory or field application of organic substances (paints). Metal coatings can be factory applied in the following ways to protect and isolate them from corrosive mediums: electrodeposition (plating); metal spraying; deposition from a vapor phase; dipping into molten metal; adhesive-metal powder techniques; metallic paints; and metallurgical bonding through rolling.¹⁶ Metallic coatings commonly used in construction include galvanizing (zinc), sherardizing (zinc), aluminizing, terno (tin-lead), hot-dip tin, and lead coatings (dipped and rolled).¹⁷ A more noble metal coating will accelerate corrosion of exposed areas of base metals.

Metal structural elements can be protected from fire damage by the installation of insulative masonry cladding, such as brick, clay tile, or concrete. There are also compounds (paints) which intumesce (expand) during a

fire to add thermal insulation to steel that has been coated with them thus providing some fire resistance.

The deterioration of metal architectural elements caused by abrasion can be slowed by painting the metallic surface. For example, as a slate roof deteriorates, minute particles of slate break off and slide down the copper valley, eroding the valley until it is worn through. Painting the copper will prolong the useful life of the valley by providing a renewable surface that protects the copper beneath. Ultimately, however, replacement of the damaged member may be necessary.

In the case of human wear and tear, lacquer, wax, and oil have been applied to brass and bronze to resist corrosion and provide a renewable surface. Replaceable plastic guards may be installed over the metal to prevent wear in high pedestrian traffic areas.

The practice of protecting architectural metals with organic coatings (paints) is very common. Generally the success of the coating depends upon surface preparation, type of primer and finish coating, and the method of application. Paints reduce corrosion by permitting only a sluggish movement of ions through the paint film lying between the metal and corrosive environment. Expanded discussions on paint are contained in the sections on individual metals.

Cleaning methods in preparation for painting can be divided into three categories—chemical, thermal, and mechanical. Chemical methods include acid pickling and phosphate dipping. Since the use of acid may predispose the metal toward subsequent corrosion, it is especially important to remove all traces of the acid thoroughly from the metal elements after treatment. When working with acids, care must also be taken to protect workers and materials, such as glass, masonry and landscape elements, which surround the metal component.

The thermal method involves heating a corroded surface with oxyacetylene burners which crack off the corrosion products, or change their chemical nature and cause them to powder away.

Mechanical methods include various uses of abrasive materials or abrasive tools and equipment, such as scraping, sanding, wire brushing, glass bead peening, or wet or dry grit blasting. For large-scale, very hard metal building components (such as cast iron), dry grit blasting may be preferable because it is more thorough, relatively easy, and therefore, more economical. Unlike wire brushing, dry grit blasting, commonly called sandblasting, does not introduce the risk of subsequent corrosion caused by putting another type of metal in contact with one being cleaned. A common technique, that should be avoided, is the use of a wire brush or steel wool on non-ferrous metals, which may cause galvanic corrosion or abrasion of the softer metal by the steel. (For further information on sandblasting iron and steel, see section entitled, *Iron and Iron Alloys*, in Chapter 12.)

Another more delicate method of cleaning some of the harder metals is glass-bead blasting or peening. (See discussion of abrasive cleaning of bronze and brass in the chapters on copper.)

Most metals used structurally and/or decoratively on historic buildings, with the exception of iron and bronze

(and some brasses), generally should not be cleaned mechanically because they are quite soft and or thin and pliable, and would be deformed, or their finish would be abraded by such a process. It is usually preferable to clean these softer metals (such as lead and zinc), sheet metals (such as sheet copper), and plated metals (such as tinfoil, terneplate, chromeplate, and galvanized iron and steel) with a chemical or thermal method. Stainless steel and aluminum that were originally given a sandblasted finish may usually be cleaned by sandblasting, but if they originally had a high polish, they should not be sandblasted.

Once the surface of the metal has been cleaned of all corrosion products (standards exist to determine the degree of cleaning), a primer coat consisting of a liquid vehicle and a corrosion-resisting pigment is applied. The primer should be applied as soon as possible after cleaning. When the primer is thoroughly dry, the finish coats, which generally consist of lacquers, varnishes (resins in solvent), enamels (pigmented varnishes), or special coatings, are applied. (For more detailed information, see discussions on each metal.)

Other organic coatings include catalyzed or conversion coatings which consist of an "epon" that may be modified with other resins such as vinyls, alkyds, polyesters, et cetera; polyfluorinated ethylenes (Teflon); synthetic rubber; neoprene; rubber based on organic polysulfide (Thiokol); bituminous materials; and high-temperature organic paints formulated from silicone resins, ceramic-type pigments, and inert fillers.

Mechanical Repairs

Metal architectural elements that have deteriorated or failed because of corrosion or physical breakdown, especially fatigue or overloading, can sometimes be repaired by patching, splicing, or reinforcing.

Patching requires mending, covering, or filling a deteriorated area with another piece of material. Depending on the type of metal and its location, the patch can be applied by soldering or by using mechanical connections, such as rivets. For example, a copper cornice with localized deterioration or damage may be patched with sheet copper which has been folded or pressed to match the design of the section of the cornice being patched. Often patching refers to the repair of nonstructural architectural elements. To prevent galvanic corrosion, the patch material should be a very close match to the original material or it should be insulated from the original metal with nonporous insulation.

Splicing refers to the repair of an architectural element, usually structural, by the replacement of the deteriorated section with new material. For example, a deteriorated or damaged section of the web or flange of a steel beam or column may be cut out and a plate of an appropriate thickness welded in its place. Needless to say, all loads must be temporarily supported and the frame braced when structural members are repaired by splicing. The new material is connected to the existing construction in a manner that permits the connection to transfer the loads so that the repaired composite element acts as an integral unit.

Reinforcing is the repair of a damaged or deteriorated element by supplementing it with new metal material. For example, a damaged vertical truss member of a bridge may be straightened and reinforced with plates bolted to the member where it was formerly bent. The new metal does not replace the deteriorated element but is added to it so the old material can still serve its intended purpose while carrying only a *proportion* of the total load.

Duplication and Replacement

When metal architectural components are beyond repair or when the repairs are only marginally useful in extending the functional life of the member, replacement of the deteriorated element with reproduction material is often the only practical solution. If the metal has deteriorated to a point where it has actually failed, duplication and replacement is the only course of action. Architectural components that have been removed for a long time, such as parts of cast-iron storefronts, can be replaced by

new cast-iron members which are reproductions of the original (figures 169-174).

Where deteriorated metal components, such as sheet roofing, are visually important to the building, they should be replaced with materials that duplicate the appearance of the old by matching the original material in composition, size, and configuration of details. However, if a metal building component is seldom seen from normal viewing angles, it may be acceptable to use a substitute material that does not match the original.

Where historic metal structural elements have deteriorated slightly, the elements may not have to be replaced, but can be preserved by changing the use of the building and/or reducing the live loading. This is often done by posting signs to limit the number of people and/or weight of the contents. However, if deterioration continues, some type of remedial treatment will be necessary. Where the deterioration is severe, structural architectural elements can be replaced with new members in most instances if the existing loading can be temporarily supported.

Identification

Blue-gray in color, lead is a malleable, ductile, and heavy metal—the heaviest of the common metals. It is not magnetic, has no load-bearing capacity because it has little tensile or compressive strength, and is so soft it can be scratched with a fingernail. Lead is easily recovered from scrap materials for recycling, is relatively impenetrable to radiation, and is toxic to humans and animals.¹⁹ Lead combined with tin to form a protective coating on sheet iron or steel is known as terneplate (see Tin, Chapter 13). The weight and high cost of sheet lead and the development of more versatile metals have meant its near abandonment as a common building material. However, lead is currently used widely for radiation shielding and as a protective coating on sheet copper for roofing, rain gutters, and downspouts.

Causes of Deterioration

Lead is stable and does not react with most common chemicals: therefore, it is highly resistant to corrosion. When exposed to air, it forms a protective patina that may be a thin, whitish film of basic lead carbonate, or a thick, darker coat of lead sulfate, both of which usually resist further corrosion. Hence, lead does not need to be painted. The resistance of the lead towards a particular corrosive agent depends on the solubility of the coating formed during the initial attack: if the coating is soluble to corrosive elements in solution, corrosion will continue, while an insoluble coating will resist further attack.

When lead is exposed to alkalis, such as lime and cement mortar, a reddish lead oxide results. Reaction with carbon dioxide and organic acids, such as those present in damp wood, form a whitish basic carbonate or lead formate coating, both of which permit further corrosion of the lead.²⁰ But, this corrosion is very slow and could take decades to severely damage most lead building materials.

Lead is highly resistant to corrosion by atmospheric pollution. Sulfur fumes common in urban areas react with lead to form a sulfate layer, which protects the lead from further attack.²¹ Lead resists corrosion by many acids including chromic, sulfuric, sulfurous, and phosphoric; however, it is corroded by hydrochloric, hydrofluoric, acetic, formic, and nitric acids.²² Acetic acids are present in fumes given off by breweries, pickle factories,

and saw mills.²³ Ants and other insects contain formic acid, and certain beetles and squirrels have been known to eat through lead.

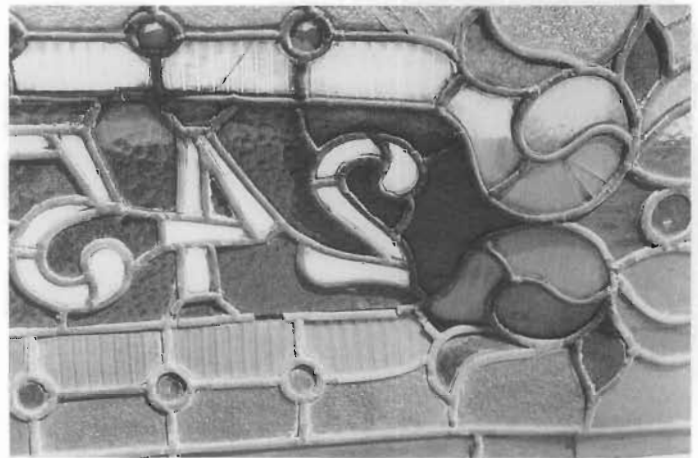


Figure 125. Lead Came Damage. *One of the most common uses of lead is the comes in stained glass windows, transoms, and skylights (see figure 8). Although lead comes are sometimes damaged by corrosion, especially where rain or condensation might collect at the bottom border came (a very slow process), they usually are damaged by creep and fatigue. The weight of the lead and glass in the entrance transom pictured above has caused the comes to creep, resulting in a noticeable sag and outward bulge. This transom did not have iron support bars found on many stained glass windows. The bars (sometimes called saddle bars) were usually set into the frame and attached to the lead comes with copper wires. Transoms are adversely affected by the vibrations of slammed doors and the outward force of compressed air in a vestibule. To complicate things further, the difference in the expansion and contraction coefficients of the lead comes and lead-tin solder has resulted in fatigue cracking, usually at joints. (H. Weber Wilson)*

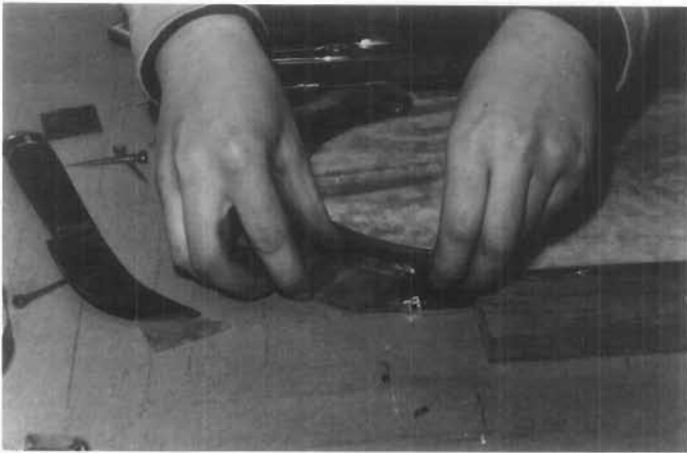


Figure 126. Lead Came Replacement. (a) On the table is a tracing of the original pattern of the lead comes of a late 19th-century stained glass window from the Pilgrim Congregation Church, Cambridge, Massachusetts. Because of the severe deterioration of the original lead comes, it was necessary to replace them with new comes that matched the original configuration. (b) This is a detail of the fitting of the new comes around the original glass. (Cummins Studios)

Care should be taken to protect lead elements from contact with oak building members, as tannic and other acids in the wood attack the metal. Acids produced by other woods such as elm and cedar also attack lead.

Lead flashings and gutters are attacked by acid-charged washings from lichen growing on roofing slate. These washings can score the lead and eventually form grooves and holes. Lead is also attacked by carbon dioxide dissolved in ground water (a situation possible with lead used for damp-proof coursing); however, lead is stable in water containing calcium sulfate, calcium carbonate, or silicic acid.²⁴ Lead resists corrosion by sea water, salt solutions, neutral solutions, and many types of soils.²⁵

Although lead is resistant to most types of corrosion, it can fail because of mechanical breakdown. Lead, like copper and other soft metals, is subject to damage by erosion and abrasion. Lead roof flashings and valleys are especially vulnerable to abrasion from dirt particles, sleet, hail, and rain.

Because lead has a relatively high coefficient of thermal expansion (three times that of steel), it is subject to buckling and fatigue cracking caused by daily and seasonal temperature changes. Creep (figure 119) is damaging to lead roofs, especially where the sheets are of an excessive size, improperly attached, and/or the pitch of the roof is steep.

Fatigue is accelerated by irregularities in the roof sheathing. It is also accelerated by the use of bituminous or asphaltic building paper that can adhere to the metal preventing free movement that can result in buckling. A smooth and even sheathing surface minimizes fatigue, but promotes creep by helping to provide freer thermal movement. As the lead becomes more fatigued, it becomes more brittle until it can eventually fail. Although creep and fatigue are independent deterioration processes, they are commonly found together and one may accelerate the other.

Electrolysis is not often a problem with lead because the protective patina acts as an electrolyte insulator. Normally copper, zinc, and iron (if painted) can be used in contact with lead. For example, copper nails are traditionally used with lead sheets without galvanic corrosion and lead is frequently used to waterproof ironwork where it is fitted into stone²⁶ (figure 127).

Historically, lead used for roofing was cast on sand beds or casting tables approximately 6 feet by 10 feet²⁷ and was considerably thicker than the milled sheets of lead that are frequently used today. Although less expensive than traditional cast lead, milled lead has certain disadvantages. The rolling of lead rearranges its crystalline structure and may cause discontinuities in the form of laminations or folds which can increase its susceptibility to deterioration. Also, it will not match the appearance and texture of cast lead, which was almost invariably used on American buildings of the late eighteenth and early nineteenth centuries.

Methods of Preservation and Repair

The decision to repair or to replace a lead roof may not be easy. Generally, a lead roof should be repaired unless the lead is excessively brittle and/or has failed through

creep or corrosion over a wide area. If the deterioration is localized (from either cracking or corrosion for instance), the damaged section can be removed and a new section inserted by "burning" (localized melting in a hydrogen flame) or welding. Solder should never be used to repair lead because it has a different coefficient of expansion from lead and will eventually break away. Extreme caution is advised when burning or using any method that is a fire hazard. Lead burning should not be carried out *in situ* on a historic building. When lead burning is needed, the section of lead should be removed from the building and the burning carried out in a remote location, which can be made secure. The extensive damage to Uppark, a National Trust property in England in 1989, caused by lead burning on the roof, has resulted in new guidelines for the protection of historic buildings undergoing lead roof restoration. These guidelines were followed during the recent lead roof restoration work at The Octagon in Washington, D.C. and Monticello in Charlottesville, Virginia, where lead burning was only permitted on a remote scaffolding tower, separated from the building and construction scaffolding by a fire-proof barrier.

If creep has occurred but the sheet has not cracked, it is sometimes possible to drive the lead back into place. A steeply pitched lead roof is usually more difficult to repair than a flat roof because the creep is more serious and will tend to recur. With steep roofs, it may be necessary to replace the roof with hardened lead—a lead-antimony-tin alloy, which is more resistant to creep and fatigue.

Where the lead is partially deteriorated from erosion, abrasion, or corrosion, a protective coating of paint, or sacrificial layer of copper could be attached in localized areas.²⁸ These would prolong the life of the lead, but at best, are only temporary repairs. However, mastics or asphaltic or bituminous roofing compounds should not be used because they adversely react with the lead.

Existing lead roofing can be taken up and relaid if repairs to the understructure are necessary. However, if much of the lead is deteriorated, it is desirable to melt and recast the old lead into new sheets. Before the lead is melted down, any solder or other nonlead patches must be removed.

Where historic lead elements are missing, new cast lead should be installed based on surviving evidence of the original. Often fragments of the old roofing are found beneath the roof sheathing boards and within the cornice construction. This evidence can be studied to determine the character and extent of the original work, which can be replicated using new cast-lead sheets.

When the new lead sheets are laid, rosin building paper should be used between the lead and the sheathing to permit thermal movement. When new lead roofs are installed, provisions should be made for adequate expansion joints. Under no circumstances should lead sheets more than 9 feet in length or 24 square feet in area be used. Generally, the thinner the sheet of lead, the smaller the sheet should be. Traditionally, cast roofing lead was code-numbered 6, 7, or 8, weighing approximately 6, 7, and 8 pounds per square foot respectively.

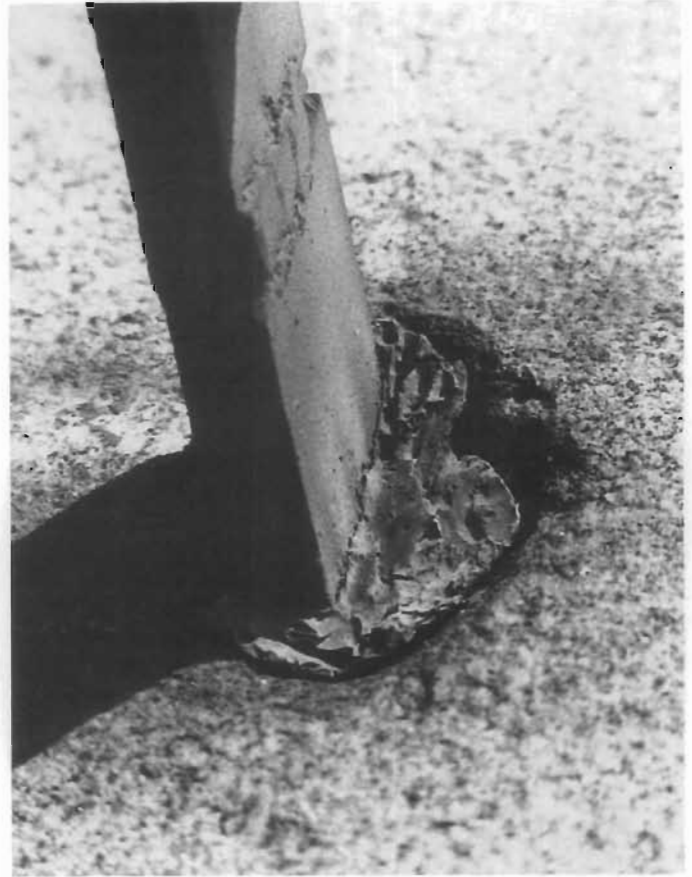


Figure 127. Lead Packing. *At the U.S. Treasury Building in Washington, D.C., the iron fence is supported by stone posts. The iron rails are fitted into pockets in the stone. Water seeped into the pockets and the iron rusted, causing it to expand. Rust, plus freezing and thawing action, caused the stone to spall. To remedy the situation, the iron fences were removed; the ends of the rails were cleaned of rust and repainted; and the fence was re-erected with lead packing. This lead is soft enough to accommodate thermal expansion and contraction of the iron. It also waterproofs the ends of the bars. (John Myers)*

Sometimes it is necessary to clean lead. If repairs are to be made to lead and if it is desirable to remove the crust from a small lead object because the crust contains agents that accelerate corrosion, then the object can be soaked in Versene powder (tetrasodium salt of ethylenediaminetetra-acetic acid), Versene acid, and water.²⁹ The process cleans and stabilizes the object, providing all the crust is removed and the atmosphere to which the newly cleaned metal is exposed is free from acetic and formic acids.

Identification

Pure tin is soft, ductile, malleable, bluish-white in color, nonmagnetic, and fairly resistant to corrosion.³⁰

By far the most common use of tin in buildings is as a protective coating on iron or steel plates. The plates are called "tinplate" or "bright tin" if the coating is pure tin and "terneplate" or "leaded tin" if it is a mixture of lead (75-90%) and tin (10-25%). Both types of material are commonly called just "tin" or "tinplate." Tinplate and terneplate were most commonly used in sheets 10 inches by 14 inches or in multiples thereof (14 inches by 20 inches, 20 inches by 28 inches, and so forth) for roofing and wall cladding.

Cases of Deterioration

When pure tin is heated at low temperatures for long periods of time, it deteriorates by disintegrating and crumbling to a nonmetallic gray powder.³¹ Called "tin pest" or "tin plague," this type of deterioration is usually not a problem with tinplate sheets used for architectural purposes.

Tin by itself is mechanically weak and is, therefore, used for coating stronger base materials. The tin and terneplatings on iron sheets are stable coatings that resist corrosion caused by oxygen, moisture, sulfur dioxide, and hydrogen sulfide, when properly protected.³²

When exposed to the atmosphere, tin readily develops a thin film of stannic oxide, which helps resist corrosion. Although pure tin is mildly corroded by exposure to acids, marine atmospheres, and certain alkalis, tinplate roofing is generally very durable as long as the tin or terne coating maintains its integrity. Once the plating has been broken and the iron or steel is exposed to oxygen, the deterioration begins and is accelerated by the galvanic action between the tin and iron. The more active tin acts as a cathode to the iron. This protects the iron from corrosion but accelerates the deterioration of the tin, exposing more of the iron to be corroded. Tin and terneplate roofing and flashing will deteriorate when in contact with copper, for instance, in gutters. Also they can be corroded by asphaltic and bituminous roofing compounds and building paper (figures 128 and 129a), as well as by paints containing acids, bitumen, asphalt, or aluminum. Tinplate roofing can corrode on the underside from water vapor condensation if the tin is not protected by a coating of paint and/or a nonacidic vapor barrier (figure 129b).



Figure 128. Deterioration of Tinplate by Asphalt Coating. The tinplate flashing of the roof hatch has been corroded away (between the corner and the vent) by the action of the asphalt coating and water. (John G. Waite)

Methods of Preservation and Repair

Techniques for repair range from small localized patches to wholesale material replacement. If a joint in tinplate roofing opens up, or a nail head pops up and punctures the tinplate, it should be repaired by cleaning and resoldering using a solder of 50% pig lead and 50% block tin applied with a rosin flux (figures 131a and b).

Tinplate sheets should be fastened using only tinplate cleats and galvanized iron or steel nails. Copper alloy cleats and nails should not be used because of the potential for galvanic corrosion.

It is not normally practical to replating a deteriorated sheet of tinplate under field conditions. However, at Lindenwald (Martin Van Buren National Historic Site), the terneplate roof installed during the 1848 renovation under the direction of architect Richard Upjohn was cleaned and the coating was repaired *in situ* (figures 133a and 133b). Rust, paint, and asphalt coatings were removed by low-pressure abrasive cleaning using walnut shells. Where the original terne coating had failed, small areas of the iron sheets were recoated with a tin-lead mixture applied with a specially designed soldering "copper." (Historically, a small soldering tool is called a soldering "iron" and a large soldering tool is a soldering "copper.") After this partial recoating, the entire roof was painted.

Priming and Painting are mandatory, and for optimum protection, both sides (not just the exposed face) of the new tin or terneplate roofing should be shopcoated with one coat and preferably two coats of an appropriate primer, such as a linseed oil iron oxide primer. Although seldom done, it is a good idea to apply a coat of compatible, high-gloss oil-base finish paint prior to installation as an added measure of protection, especially for the bottom side.

A finish coat should be applied immediately after installation, followed by another in two weeks. Finish coat paint used on tin roofs should employ only “metallic brown” (another name for iron oxide), “Venetian red” (ferric oxide, calcium carbonate, and ferrous sulfate),³³ or red iron oxide (ferric oxide) pigments. Although red lead pigments were used in the past and are very effective protection in the prime coat, they are in now seldom used because it has been found that they can constitute a serious health hazard. They have largely been replaced by alkyd-based iron oxide primers. Graphite and asphaltic base paints should not be used on tinplate or terneplate because they can encourage corrosion.

Replacement of tinplate or terneplate sheets which have rusted through may be the only practical preservation solution. Damaged sections should be removed and replaced with new materials of similar composition, configuration, and construction (figures 132a, 132b and 132c). Materials other than tinplate or terneplate should not be used to patch tinplate because galvanic corrosion will occur. However, if all of the tinplate roofing or siding must be replaced, it may be desirable to replace the old tinplate or terneplate with units of terne-coated stainless steel or lead-coated copper (figure 134) because these materials are more durable and easier to maintain than tinplate. Although both are more expensive than terne-coated steel in initial cost, they last longer and cost less to maintain if not painted. Either of these materials, if used in visible areas, should match the size, configuration, and construction details of the original roof, and should be painted to match the original color. Although lead-coated copper has been used successfully as a replacement material for tin and terneplate (figure 135), recently terne-coated stainless steel has proven to be a better replacement for tinplate.

If the lead-coated copper is not applied using appropriate methods, its appearance will not duplicate that of a tinplate roof. Many sheet metal workers have a tendency to apply solder freely to the joints over the surface of the lead-coated copper which results in a rough seam that may be an inch or more in width. This contrasts greatly with historic tinplate seams where often no solder was visible on the surface of the metal. Also, 16-ounce lead-coated copper, the thinnest, readily available gauge, is considerably thicker than historic tinplate, resulting in bends that are not as crisp or sharp. Improperly manufactured lead-coated copper may also promote galvanic corrosion, leading to deterioration of exposing the copper base.³⁴

Historically, seams of tinplate roofs were often not soldered. Instead they either were installed dry, as was the case with the tin roofs designed by Thomas Jefferson (figure 136), or the seams were filled with white lead

paste. Today, white lead paste is difficult to obtain and constitutes a health hazard. Consequently, modern caulking compounds are used to fill the joints.



a

Figure 129. Corrosion Failure of Terneplate Roofing. *Hyde Hall, built between 1817 and 1833, near Cooperstown, New York, was roofed with flat-seam terneplate. (a) The plates have deteriorated because of a lack of proper maintenance. Unfortunately, the exposed (top) surface of the terneplate was painted with asphalt coating, which accelerated the corrosion of the roofing. (b) The terneplate also corroded from the underside. When installed, the terneplate was not painted on the underside as it should have been. Condensation formed on the unprotected bottom side of the metal roof and could not evaporate, an ideal situation for corrosion. (John G. Waite)*



b



Figure 130. Modern Solder Joint on a Terneplate Roof. Solder was used to make watertight joints at the edges of terneplates on flat-seam roofs. Nineteenth-century soldered joints were almost invisible, that is, the solder was confined to the seam. These wide-soldered joints are on the Old Pension Building in Washington, D.C. The problems with wide-soldered joints are: (1) they facilitate galvanic corrosion because they provide a wider surface area with which the plates can react, and (2) they tend to fail because of the different coefficients of expansion and contraction of the solder and the terneplate. The black spots to the right of the solder are asphalt or a bituminous roof patching compound, which may cause deterioration of the terneplate and should be removed. (David W. Look)

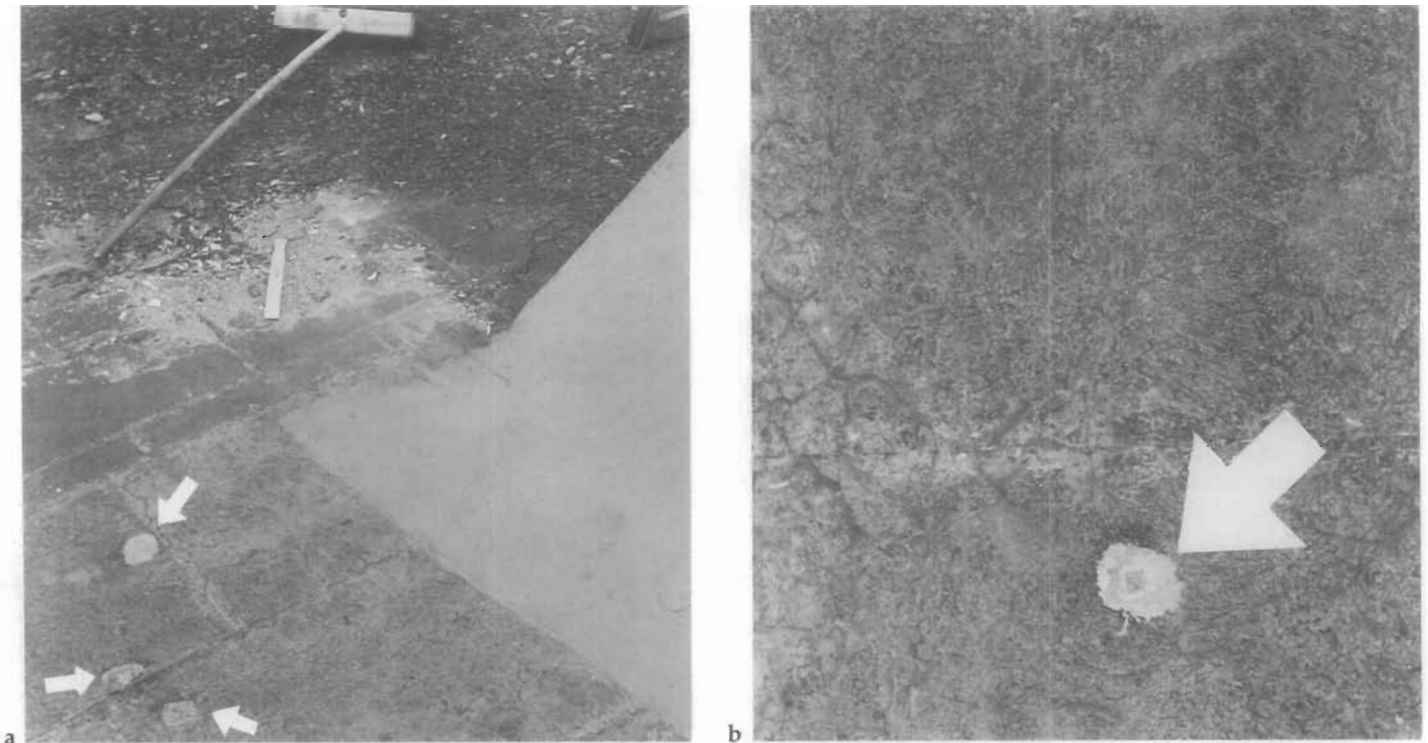


Figure 131. Salvaging a Flat Seam Terneplate Roof. (a) The roof of the Henry E. Bradford House Carriage Barn (c. 1860s) in Bennington, Vermont, had been covered with an asphalt coating (background) which obscured the true cause of the leaking roof. Once the asphalt coating was scraped from the surface (foreground left), it was noticed that the nails in the sheathing had "popped up" (light spots) and had cut through the terneplate. (b) After the asphalt coating had been scraped away and the nail holes repaired with solder (left foreground), the roof was then painted with red-lead primer (right foreground). The primed roofing was given two finish coats of iron oxide paint. (John G. Waite)



Figure 132. Repair and Replacement of Terneplate Roofing.

(a) The ends of the original terneplate battens covers at Lindenwald were badly corroded and could not be replated. (b) The unsalvageable sections were cut out and replaced with terne-coated stainless steel soldered in place. (c) The deteriorated terneplate valley was replaced with sheets of terne-coated stainless steel; the terne coating allowed the valley to be soldered to the original roofing plates. Although terne-coated stainless steel was a good choice, in theory, it proved to be a difficult material to work with in the field. (Correctly, the availability of thinner gauges and a more malleable stainless steel have improved the workability of this material.) (d) The original terneplate had rusted through completely in some areas, requiring reroofing. New sheets of terne-coated stainless steel, duplicating the pattern of the original terneplate, are being laid over rosin paper.

(John G. Waite)

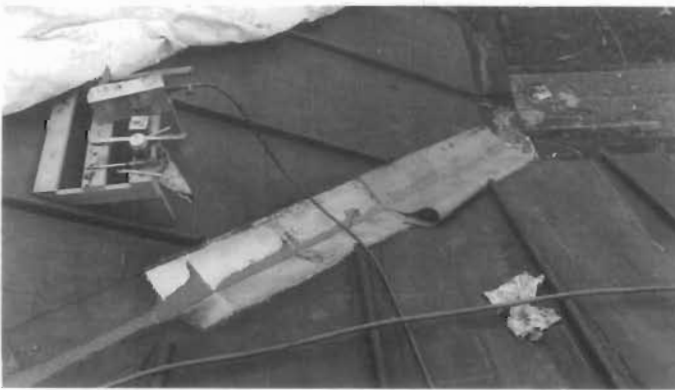




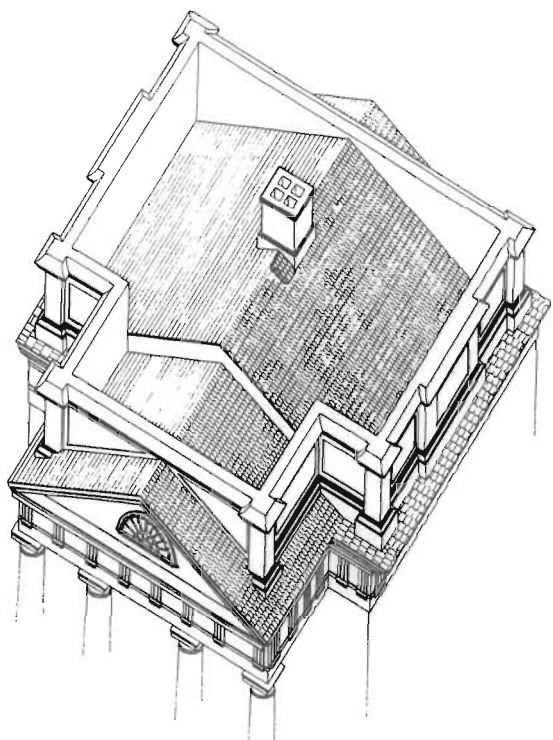
Figure 133. Abrasive Cleaning of Terneplate Roof and Replating. (a) Sections of the original terneplate roof at Lindenwald (Martin Van Buren National Historic Site) in Columbia County, New York, designed by architect Richard Upjohn in 1848, were cleaned with a low-pressure blasting of crushed walnut shells to remove accumulated paint and rust before replating with a lead/tin alloy. (b) The new terneplating was applied in localized areas (only where the original terne had been damaged by falling slates or removed because the sheet iron underneath had corroded). The new terneplating was applied where the bare iron was exposed using a soldering "copper" (a large soldering tool) fabricated for the project. After cleaning and replating, the restored roof was painted. (John G. Waite)



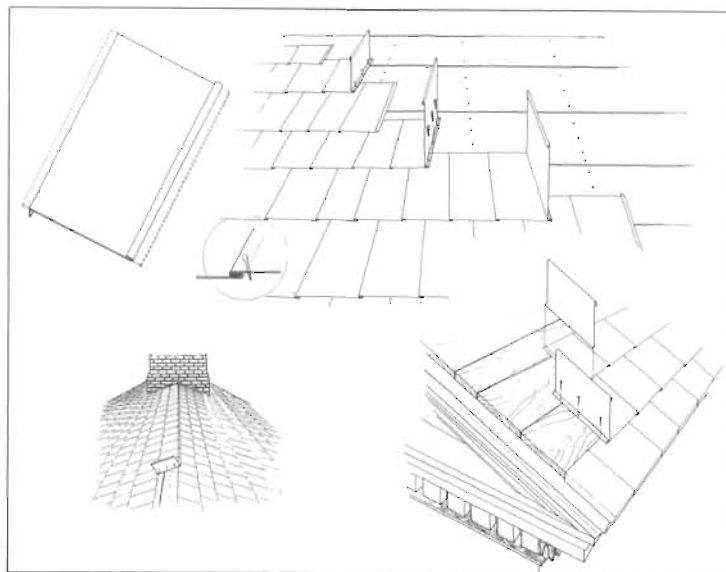
Figure 134. Replacing Flashing and Gutters. Workmen replaced the deteriorated terneplate flashing and gutters at Olana, built between 1870 and 1874 near Hudson, New York, for the noted artist Frederic E. Church. The polychromed slate roof was restored to the original pattern, and lead-coated copper was substituted for the original terneplate flashing and gutters because of ease of maintenance - it does not require painting, unless there is a need to match the terneplate in color. The original terneplate was painted. (John G. Waite)



Figure 135. Complete Substitution of Lead-Coated Copper Roofing for Terneplate Roofing. The 1864 wing addition of Lyndhurst, Tarrytown, New York, originally had a terneplate roof. In an attempt to find a more permanent roofing material, a lead-coated copper roof was substituted for the terneplate, duplicating the pattern and sheet sizes of the original roof. In such substitutions, details may have to be redesigned because of differences in expansion and contraction rates and differences in workability of the material. The color of lead-coated copper is not the same as terneplate because terneplate roofing was never left unpainted. Therefore, lead-coated copper roofing substituted for terneplate should also be painted if it seen from normal viewing angles (usually from street level). (John G. Waite)



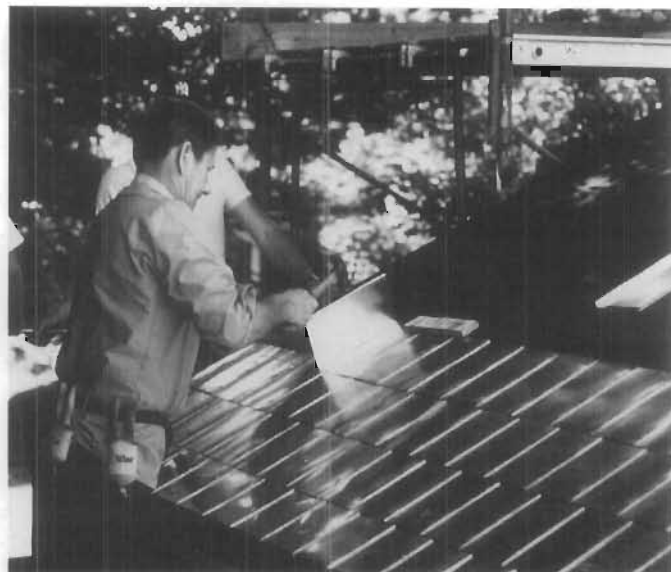
a. Pavilion X roof (Mesick•Cohen•Waite Architects)



b. Installation techniques (Mesick•Cohen•Waite Architects)



c. Original tinplate roof beneath slate (John G. Waite)



d. New roofing (Clay S. Palazzo)

Figure 136. Replacement of a Thomas Jefferson Tinplate Roof on Pavilion X. Most of the pavilions constructed between 1817 and 1826 at the University of Virginia originally had tinplate roofs applied with a unique system which did not use soldered seams (a). Consisting of thinly rolled wrought-iron sheets dipped in tin, the edge of each plate was fitted into the fold of the adjacent plate, folded over, and nailed to the wood roof sheathing. It was a very simple system that only required basic carpentry skills to install (b).

In 1985, during investigations of leaks in the roof of Pavilion X, the entire original Jefferson tinplate roof was found intact beneath a later slate roof (c). The original tinplate roof was preserved in situ and encapsulated by new plywood sheets. A new roof, identical in detailing, was applied over the plywood and a neoprene sheet membrane (d). Using 6 $\frac{3}{4}$ by 10 inch sheets of stainless steel with a terne coating, the roof exactly duplicates the appearance of the original. Terne coated stainless steel was used because tinplated wrought-iron sheets are no longer available.

Thomas Jefferson installed similar roofs on Monticello and Poplar Forest.

Chapter 14: Zinc, Preservation and Repair

Identification

Zinc is a medium-hard, bluish-white metal characterized by its brittleness and low strength. It is also subject to creep.³⁵ Historically, zinc has been widely used for architectural purposes, both in its pure form and as an alloy with other metals, and as a protective coating for iron and steel architectural components using the processes of galvanizing and sherardizing (see definitions). Pure zinc architectural elements are often mistaken for tin-plated or galvanized sheet iron; however, zinc is easily identified because it is softer than iron and is non-magnetic. Zinc can be hot rolled, formed, extruded, spun, punched, cast, machined, riveted, soldered, and welded.³⁶ It is not ductile at normal temperatures.

As in the past, zinc is still widely used as a protective coating for iron and steel. A major advantage of zinc coating on iron is that if the zinc is worn away or broken and the iron is exposed to the atmosphere, galvanic corrosion of the baser zinc occurs, protecting the more noble iron.³⁷ The following are the most common methods for applying protective coatings of zinc to iron and steel.³⁸

Hot-Dip Galvanizing is the immersion of iron or steel in molten zinc, after the surface of the iron has been properly cleaned. This process gives a relatively thick coating of zinc that freezes into a crystalline surface pattern known as spangles. During the hot-dip process, a multiple-layered structure of iron-zinc alloys is formed between the inner surface of the zinc coating and the iron. These middle layers tend to be hard and brittle and may peel or flake if the iron element is bent.

Electro galvanizing is the immersion of iron or steel in an electrolyte, a solution of zinc sulfate or cyanide. Electrolytic action deposits a coating of pure zinc on the surface of the iron. The thickness of the coating can be accurately controlled using this process. However, the thick coatings provided by the hot-dip galvanizing process are not usually possible with this method.

Sherardizing is the placing of a thoroughly cleaned iron or steel element in an air-free enclosure where it is surrounded by metallic zinc dust. The architectural element is then heated and a thin, zinc alloy coating is produced which conforms to the surface configuration of the element. This process is usually limited to relatively small objects.

Metallic Spraying is the application of a fine spray of molten zinc to a clean iron or steel element. The coating can then be heated and fused with the surface of the iron to produce an alloy. The coating is less brittle than those produced by some of the other processes and will not peel or flake on bending. However, the coating is more porous than those produced by the other processes and becomes impermeable with time as products of corrosion fill in the pores.

Another, less effective form of zinc coating is the use of paints containing zinc dust pigments. These can be applied *in situ*.

Causes of Deterioration

Zinc is not resistant to acids or strong alkalis and is particularly vulnerable to corrosion by sulfur acids produced by the hydrogen sulfide and sulfur dioxide pollution in urban atmospheres. Zinc is also attacked by acids found in redwood, cedar, oak, and sweet chestnut, and can be corroded by plasters and cements, especially Portland cements containing chlorides and sulfates.³⁹ Condensation on the underside of zinc plates and ponded water on the exterior surface of zinc architectural ornament can also corrode (figure 137). Zinc also deteriorates on contact with acidic rainwater run-off from roofs with wood shingles, moss, or lichen.

Although zinc develops a carbonate on its surface by exposure to the atmosphere and by the action of rainwater, the film is not dense or adherent enough to protect the zinc from continued attack.⁴⁰ The carbonate becomes brittle and crusty and eventually splits, exposing fresh zinc for corrosion. Thermal movement of the zinc is also damaging to the carbonate film. In industrial atmospheres, the zinc carbonate film is broken down by the same acids that attack zinc. These acids convert the carbonate to zinc sulfate, which is water soluble and washes away with rainwater,⁴¹ often staining adjacent building elements (figures 130 and 143).

Zinc has a relatively high coefficient of thermal expansion and is therefore vulnerable to fatigue failure. Because zinc is relatively soft, it is also vulnerable to abrasion damage (figure 139), especially in roof valley areas where it can be worn paper-thin.

Although zinc is not damaged by electrical contact with lead, galvanized iron and steel, tin, or aluminum, it is damaged by galvanic corrosion when it comes in electrical contact with copper and pure iron in a common electrolyte (figure 138).



Figure 137. Deterioration of Zinc. At the 1874 Cohoes Music Hall, Cohoes, New York, the original zinc window lintels and belt course were cleaned by sandblasting, resulting in pitting and corrosion of the metallic surface. Note the whitish corrosion products caused by the abrasive cleaning and subsequent exposure to the weather. The lintels had been painted originally but were left bare after the cleaning. Zinc and galvanized sheet iron should always be primed and painted with paints especially formulated for zinc. (John G. Waite)



Figure 138. Zinc Deterioration and Staining. On the First Presbyterian Church in Alexandria, Virginia, the engaged columns, arch molding, corner blocks, and the sill molding are fabricated of cast zinc and galvanized sheet iron (the windows and frames are wood). The paint has deteriorated, leaving the surface of the metal bare in some places. The zinc or zinc coating on iron has oxidized. Notice the whitish corrosion stain on the brick from the zinc carbonate coating which continues to wash over the surface of the bare metal and then down over the bricks. The metalwork should be scraped down to remove all loose zinc carbonate. Joints should be caulked and/or resoldered, and repainted with a zinc chromate primer. (Baird M. Smith)

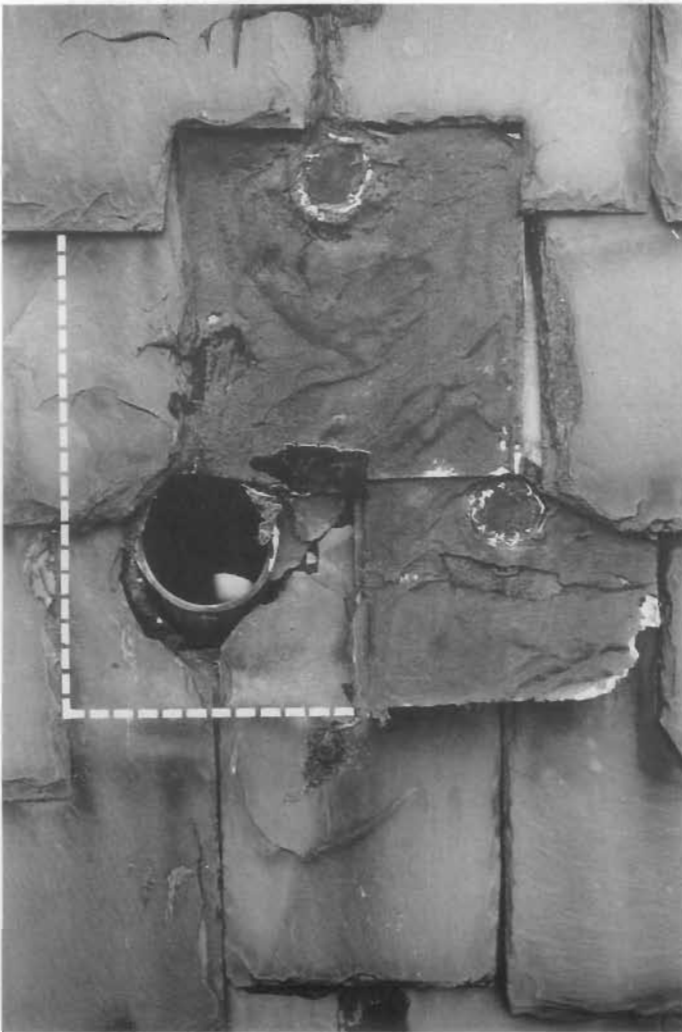


Figure 139. Zinc Corrosion, Erosion, and Inappropriate Repairs. In construction of the Nott Memorial at Union College in Schenectady, New York, during the 1870s, architect Edward Tuckerman Potter used “illuminators” in the ornamental slate roof. These were slate-sized zinc plates with a small colored-glass disc 1 3/4 inches in diameter inserted in the center. Barely discernible from the outside, they transformed the vaulted dome within a “heaven” of red, yellow, purple, orange, and green stars. Shown here is a cluster of three illuminators, each consisting of a zinc plate with a small colored-glass insert and the connecting tube through the metal deck and plaster to the interior. The zinc was inaccessible and not kept painted. Small fragments of slate broke off and tumbled down with gravity. The wind and rain eroded the layer of corrosion from the zinc surface. The left plate is missing (see dotted line), showing the connecting tube. The corner of the lower right plate is missing because it became brittle and fractured off. Unfortunately, modern roofing cement applied over the zinc plates is accelerating the deterioration. (John I. Mesick, *The Nott Memorial: A Historic Structure Report Schenectady, New York: Union College, 1973. p. 65*)

Flaking and peeling of the zinc coating is a problem with old, hot-dipped galvanized iron sheets. Because of the galvanizing techniques, a thick, brittle coating of zinc was formed. This coating can peel and flake when the iron sheet is deformed—that is, folded and stamped—after the coating has been applied, exposing the iron sheet to corrosion.

Galvanized sheets and sheets of pure zinc are also attacked by a type of corrosion known as “white stain” or “white rust.”⁴² Closely stacked sheets stored either in a warehouse or unprotected outdoors will be attacked if dampness and extreme temperatures occur. With the absence of oxygen and carbon dioxide between the sheets, the protective layer of zinc hydroxide is formed with resultant loss of metallic zinc. The corrosion then appears as a voluminous white powder. Perforation of the galvanized or zinc sheets can occur rapidly, causing significant damage.

Methods of Preservation and Repair

It is difficult to carry out piecemeal *in situ* repairs to zinc roofs or architectural elements, except under unusual circumstances. Where repairs can be made, solder with a composition of 50% tin and 50% lead or 60% tin and 40% lead (antimony free) is used. A hydrochloric acid flux should be used, but it should be remembered that the flux can dissolve zinc. The excess flux must be rinsed immediately after soldering. Where the zinc is badly eroded, the only practical solution may be to replace the damaged section with a new material.

When used with redwood, cedar, oak, or sweet chestnut, galvanized steel or iron should be protected from the acids in the wood by a bituminous paint applied to the exposed surfaces. Even though galvanized iron and steel can be painted, preliminary surface treatments may be necessary. The metallic surface should be allowed to weather before painting (usually about six months); however, it should not weather until rust appears. The surface is then wiped with a clean cloth and mineral spirits, not hydrochloric acid, muriatic acid, or vinegar (as recommended by some old paint references), and painted with a specially formulated primer for galvanized iron, followed by two finish coats of a compatible oil-based paint.

If an old galvanized roof has begun to rust, it should be treated with zinc oxide and flaky aluminum prime coats followed by a finish coat containing flaky aluminum and flaky micaceous iron-ore pigments. Rusting may also be arrested by the application of a zinc-rich paint after the rust has substantially been removed.⁴³

In some cases, galvanized sheet metal elements can be removed and repaired in the shop, rather than in the field (figure 141 and 142). Preassembly of large cornices may be cost effective (figure 143).

Where the galvanized coating has been scraped or worn away, it may be necessary to recoat the sheet with zinc. The surface of the iron must be thoroughly cleaned, and one of the galvanizing processes discussed previously must be used. This must be done under controlled conditions in a shop and not *in situ*. Sometimes corrosion is not too severe and the surface can be cleaned and painted in place to prolong the life of the

member. All corrosion, rust, and loose paint must be removed before painting. In other cases it may be necessary to reproduce severely deteriorated or lost elements (figure 144). In some situations, often for economic reasons, reinforced polyester, commonly known as fiberglass, has been used for reproduction of missing cornices and other sheet metal details (figure 179).

Direct contact of galvanized iron or steel with plaster and cement must also be avoided. If contact is unavoi-

able, the galvanized material should be painted as described in this section, so that it is isolated from the alkaline material.

Proper design and installation is very important with galvanized iron or steel roofing and flashing. Special care should be taken to insure that the roof has adequate expansion joints to accommodate thermal expansion and contraction and adequate anchorage to guard against wind damage (figure 123).

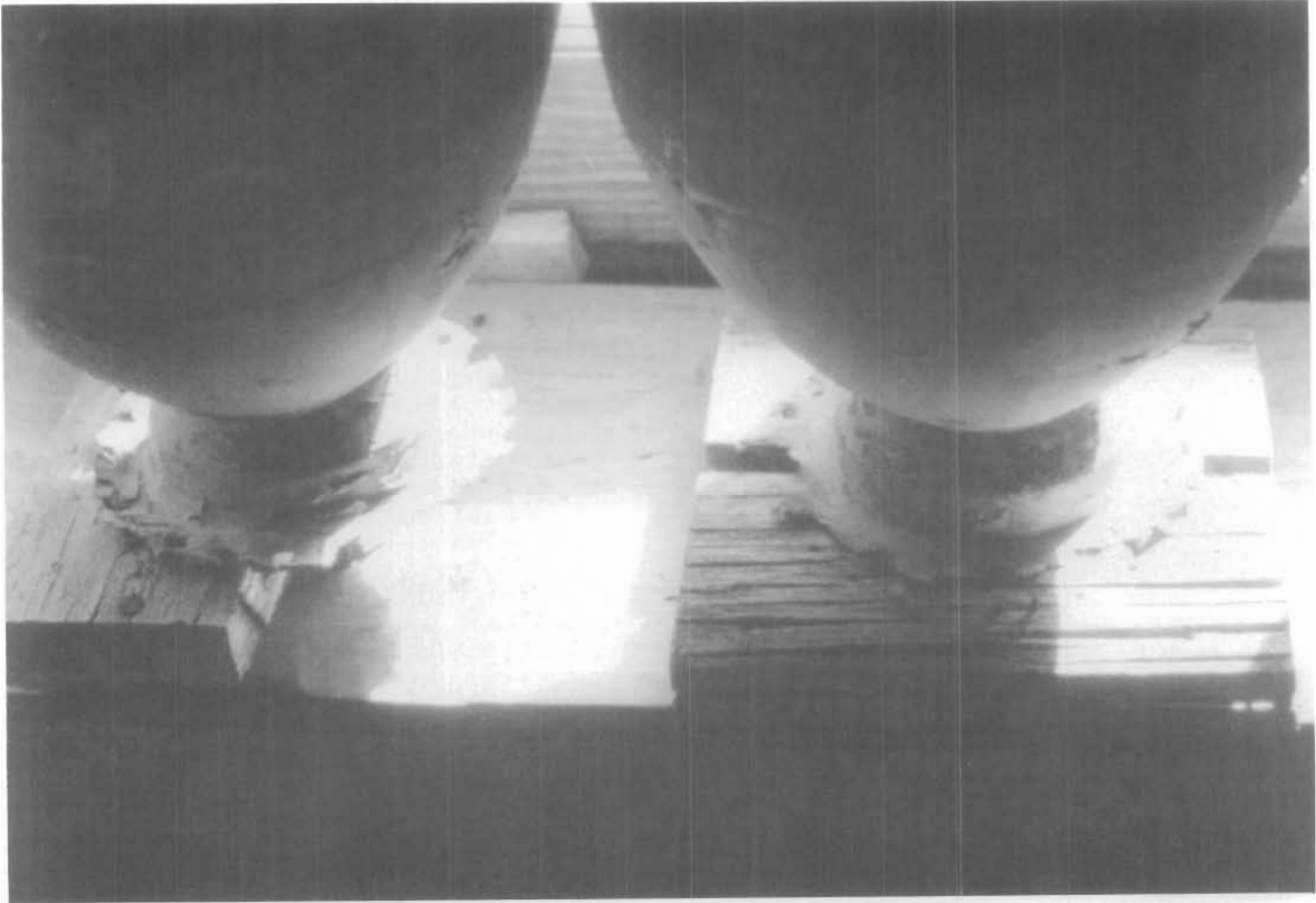


Figure 140. Galvanic Deterioration. Bases of zinc vases from the roof balustrade of Lorenzo, Casenovia, New York, have deteriorated because of the electrolytic action between the zinc and the machine-cut iron nails used to fasten the vases to the balustrade. The zinc was sacrificed in favor of the iron because the iron is more noble than the zinc. (Douglas Clinton)



a



b

Figure 141. Repair of Galvanized Sheet Metal Capitals. (a) Fabricated for the 1890 Bullard-Hart House, Columbus, Georgia, these Corinthian capitals were originally assembled from many pieces of pressed sheet metal, which were soldered together to form the acanthus leaves. (b) The capitals were in salvageable condition and were taken to a sheet-metal shop where they were cleaned. Loose pieces were resoldered and caulked; missing pieces were replaced with new stamped pieces; and the completed capitals were repainted. The deteriorated wooden column shafts were repaired and repainted. The restored capitals were refitted onto the shafts and the entire columns were then returned to their original positions. (Thomas Taylor)



a

Figure 142. Restoration of Galvanized Sheet Iron and Cast-Zinc Cornice. *This is the upper third of a wooden bay window on a Second Empire brick rowhouse in the Logan Circle Historic District of Washington, D.C. (a) From the window down, the bay is wood and glass. The roof of the bay had leaked for years and the wooden roof rafter and projecting supports for the cornice had rotted. The bay window was carefully disassembled and rebuilt replacing all deteriorated lumber. The surviving pieces of galvanized sheet-iron and cast-zinc cornice were taken to a sheet-metal shop. The pieces that were repairable were cleaned; missing portions of brackets on the right were replicated of galvanized sheet iron using the originals as a model. (b) On the opposite side of the bay, all of the brackets and modillions are repaired originals but all of the flat and molded sections are new 26-gauge galvanized steel. The 65-year-old sheet-metal worker on this job said that the only two major advances in metal cornices in his lifetime are the use of pop rivets for fasteners (used also in leatherwork) and the use of autobody putty to patch holes, mold small missing details, and waterproof joints. The putty dries hard and can be sanded. (David W. Look)*



b

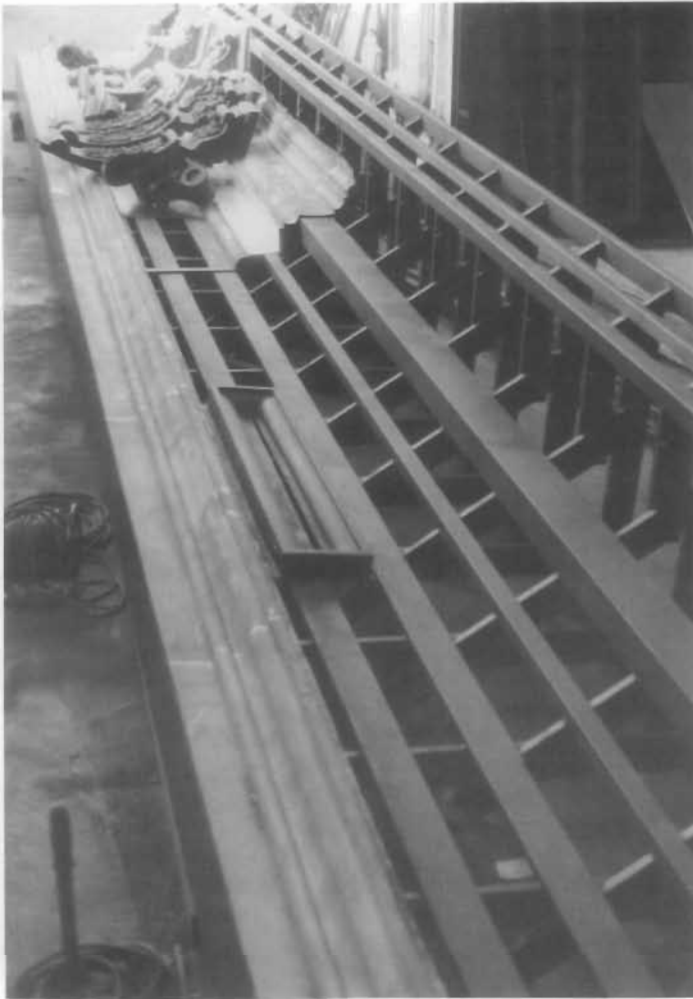


Figure 143. Preassembling Cornice. As illustrated in figure 142, most sheet-metal cornices were supported by wooden support members projecting out from the facade of the building either as an extension of the roof framing or as a cantilever from a parapet wall. In either case, these wooden support members are often found to be rotten and have to be replaced. For large cornices high above the street level, it may be economically unfeasible to use scaffolding for in situ repairs and reconstruction unless the scaffolding is also needed for other work. The entire galvanized sheet-iron cornice of the ZCMI Store in Salt Lake City, Utah, was preassembled on the ground with repaired original parts and some new pieces onto a new support system fabricated on small steel angles. Fifty-foot sections of the preassembled cornice were then hoisted to the top of the facade and bolted onto the building without the need for scaffolding. (Steven T. Baird)

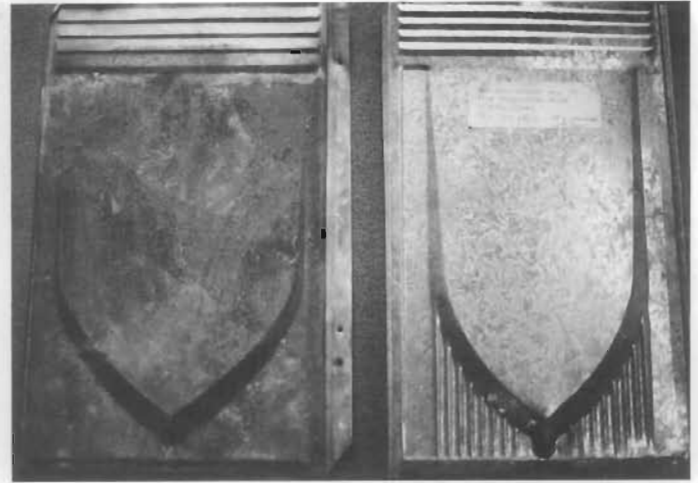


Figure 144. Reproduction of Galvanized Sheet-Iron Shingles. Wind and hail had damaged many of the sheet-iron shingles at St. Edward's University in Austin, Texas (see Figure 122). Mass production of replicas was economically feasible. A die was made with the pattern of the original shingle and new galvanized sheet-steel shingles were stamped. The new, unpainted shingle (right, notice spangled appearance) is a reproduction of the other shingle (left). These shingles are from the private collection of Charles E. Fisher, III. (John Myers)

Chapter 15: Copper and Copper Alloys; Preservation and Repair

Identification

Copper, one of the most corrosion-resistant architectural metals, is ductile, malleable, nonmagnetic, high in electrical and thermal conductivity (second only to silver), and is easily soldered, welded, or brazed. It can be cast, drawn, extruded, hot and cold worked, spun, hammered, or punched.⁴⁴ Copper is initially a bright reddish-brown in color, but when exposed to the atmosphere, it acquires a protective patina that turns from brown to black to green over a period that may extend for decades, depending on environmental conditions. The patina is actually a thin, tough layer of corrosion that usually prevents deeper and deeper layers of corrosion (such as rust, which can totally consume iron); therefore, even though copper corrodes, it is corrosion-resistant.

Bronze and Brass are copper alloys that can be combinations (mixtures not compounds) of many elements. "True" bronze is composed of approximately 90% copper and 10% tin⁴⁵ and is a rich pink metal seldom seen without an artificial brown patina or a natural green patina. True bronze is particularly suited for casting because of its fluidity in a molten state, its density (not porous), and its ability to retain an impression of even the most intricate mold.

Bronze can also be rolled, extruded, and forged; and in most forms, it is resistant to the wear or abrasion of heavy use. Most bronzes used for architectural purposes today are not true bronzes but rather alloys of copper with silicon, manganese, aluminum, zinc, and other elements—with or without tin. Any copper alloy that contains zinc is termed brass. However, some alloys have both tin and zinc; therefore, there is sometimes little to distinguish between some bronzes and brasses.

To complicate this further, some copper alloys that are definitely brasses are marketed as bronzes. The three types of so-called bronzes most used for architectural purposes are "statuary bronze," "architectural bronze," and "commercial bronze." Of these, only statuary bronze is close in composition to a true bronze, since it is composed of approximately 97% copper, 2% tin, and 1% zinc. Architectural bronze is really a leaded brass composed of 57% copper, 40% zinc, and 3% lead; and commercial bronze is a brass composed of 90% copper and 10% zinc.

Brass is an alloy of copper and zinc with small quantities of other elements. The composition of brass may

vary from 95% copper and 5% zinc to 55% copper and 45% zinc.⁴⁶

Brass varies from deep golden-brown to lemon-yellow to silvery-white depending on the amount of surface tarnish (oxidation) and the amount of zinc in the copper mix: 10% zinc for bronze color; 15% zinc for golden color; 20% to 38% zinc for yellow; and above 45% for silvery-white.⁴⁷ The color of brasses can also be artificially changed with chemical patinas, especially to achieve a brown statuary bronze color. Brasses are not as hard as steels, but are superior to them in workability and resistance to corrosion.

In modern times, brasses are classified according to color (red, yellow), to zinc content (high, low), to metallographic constituents (Alpha, Beta), and to other metals present such as lead and arsenic.⁴⁸ Common brasses include:

Alpha brasses (95% copper and 5% zinc) have a wide range of colors; are ductile and can be cold worked without annealing and hot worked; are corrosion resistant; and have fair electrical and thermal conductivity.

Beta brasses (55-65% copper and 45-35% zinc) have comparatively high tensile strength and hardness, fairly low melting points, and relatively poor corrosion resistance and electrical conductivity. Beta brasses are easily hot worked and may be cold worked without annealing, within limits. Their color range varies and becomes less red as the copper content is reduced. At 58% copper, the color matches that of commercial bronze, and the manufacture by hot extrusion of complicated shapes, which are used with sheets of commercial bronze, is permitted.

Leaded brasses are Alpha and Beta brasses to which lead is added to increase machinability or fluidity during the casting process. Leaded brasses are easily hot worked and may be cold worked within limits; however, they are not as strong, hard, or corrosion resistant as Alpha and Beta brasses.

Causes of Deterioration

Copper is highly resistant to corrosion caused by the atmosphere or salt water. It combines with hydrogen sulfide and oxygen or sulfur dioxide to form a protective copper carbonate or copper sulfate patina⁴⁹ which resists further corrosion and generally does not change further in appearance. However, copper is attacked by alkalis, ammonia, and various sulfur compounds that can combine with water to form sulfuric acid. Some bituminous

roofing cements, containing sulfur compounds, will attack copper, as will sulfate-reducing bacteria, which act as a catalyst for corrosion. Copper is also corroded by rainwater that has become acidic through contact with moss, lichen, algae, or wood shingles.

Copper is not very active galvanically and therefore is not usually subject to galvanic corrosion unless in contact with more noble metals, such as gold, and, under the right conditions, some stainless steels. However, if an electrolyte is present, the copper will act as a cathode and corrode other, more active, metals such as iron or steel (figure 145 and 146).

Sheet copper roofing is vulnerable to mechanical breakdown of the individual metal units caused by insufficient provisions for thermal expansion and contraction (figure 121), inadequate sheet thickness, excessively large sheet size, improper fastenings, insufficient substructure, and erosion caused by particle abrasion or the velocity effect of aerated water. Excessive thermal stressing causes the copper and its protective patina to become friable; eventually the metal may fatigue, resulting in bulges and cracks. Once fatigue cracks or splits occur, the roof or sheathing has failed as a weather-tight membrane (figure 147a).

The failure of copper members can be accelerated by a number of factors. The use of rough and noncontinuous sheathing boards (figure 147b) or the use of bituminous or asphaltic building papers and patching compounds can damage a copper roof (figure 148). Any architectural element can fail from using the wrong temper or gauge of copper or by using fastenings that restrict free movement.

Because of its softness, copper is easily eroded by abrasive agents (figure 150). This is an especially acute problem in roof flashing or valley areas where the copper can be worn so thin that it fails. It is also vulnerable to impact damage such as hail, and to fatigue and "inelastic deformation" as the result of wind damage (figure 146).

Bronze and Brass, like copper, are corroded by exposure to moisture, acidity caused by polluted air or newly-cut wood, chlorides, acetates, and ammonia.⁵⁰ Excrement from birds or other animals is acidic and can also damage bronze, brass, or copper (figure 151).

Bronze and brass oxidize to form a patina that first turns brown, then, black, in color. This coating, consisting of copper sulfide, blackens further with an intermingling of dirt, soot, and dust.⁵¹ This copper sulfide can oxidize to green-blue copper sulfate if the coating is regularly washed with urban rainwater. Some of the sulfate will dissolve and form a green stain on stone or wood beneath the bronze or brass elements.

Salt used to melt snow in the winter can be splashed up on doors, leaving unsightly corrosion, which is also damaging to the bronze (figure 152). Improper cleaning of doors is also frequently a problem (figure 153). Although "bronze disease" is a problem with bronze artifacts that were once buried in the earth, it is seldom a problem with outdoor bronze sculpture or architectural elements.⁵²

A kind of corrosion peculiar to brass or bronze with a composition of more than 15% zinc is dezincification.⁵³ This occurs where acids and other strongly conducting

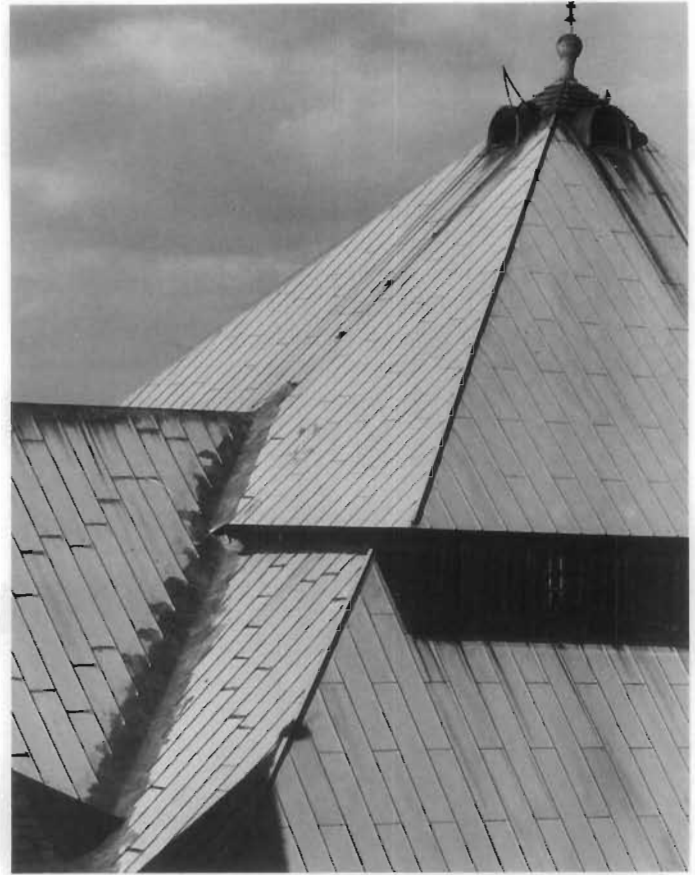


Figure 145. Galvanic Deterioration. An electrolytic reaction between the copper roof and the cast-iron roof finial and monitor window frames on the former Temple Beth Emeth, Albany, New York, built in 1887, is causing extensive deterioration of the iron. The corrosion products are staining and streaking the copper. Another area where deterioration is occurring is the valley, which has been coated with an aluminumized asphalt roofing compound. Electrolysis is occurring between the copper and aluminum (causing the less noble aluminum to corrode) and between the aluminum and cast iron of the monitor window frames (causing the less noble aluminum to corrode). (John G. Waite)

solutions are present. The copper-zinc alloy is dissolved; the copper is redeposited electrochemically; and the zinc either remains in solution or its compounds form a scale. Dezincification may leave the metal pitted, porous, and/or weak depending on the extent and severity of the corrosion.

For many years, the natural corrosion patina on outdoor bronzes, which varies in color from green to black, was thought to provide protection against further corrosion. However, this is not always true. It depends upon (1) how the patina is formed and (2) whether it is soluble in its localized environment. If the patina is formed uniformly and adheres tightly to the surface of the bronze, forming an impervious coating, the patina usually will protect the metal from further corrosion. For various reasons, some corrosion products are porous and allow cor-

rosion to continue deeper and deeper. Factors that probably influence how the patina is formed are wind patterns, rain, surface dirt and soot, industrial pollution, bird droppings, and so forth. In addition, if the patina is soluble in rain contaminated with dissolved chemicals, the patina will offer little protection. When the patina washes away, fresh metal is exposed; it corrodes, is dissolved, and washes away again. If this cycle is repeated many times, a significant loss of material can result. To complicate matters, the porosity and solubility of the patina may vary from spot to spot on one piece of bronze.

Severe pitting and obvious loss of material from corrosion are good indications that the patina is not protective. There are no simple tests to confirm this condition. A bronze conservator should be retained to diagnose the situation and prescribe a conservation treatment.

Bronze is a very durable material. It has always been expensive, which has usually limited its use to well-maintained, monumental buildings, such as banks. However, occasionally bronze architectural elements are vandalized or damaged, as when an automobile damages a street lamp (figure 154) or when graffiti covers a bronze door.

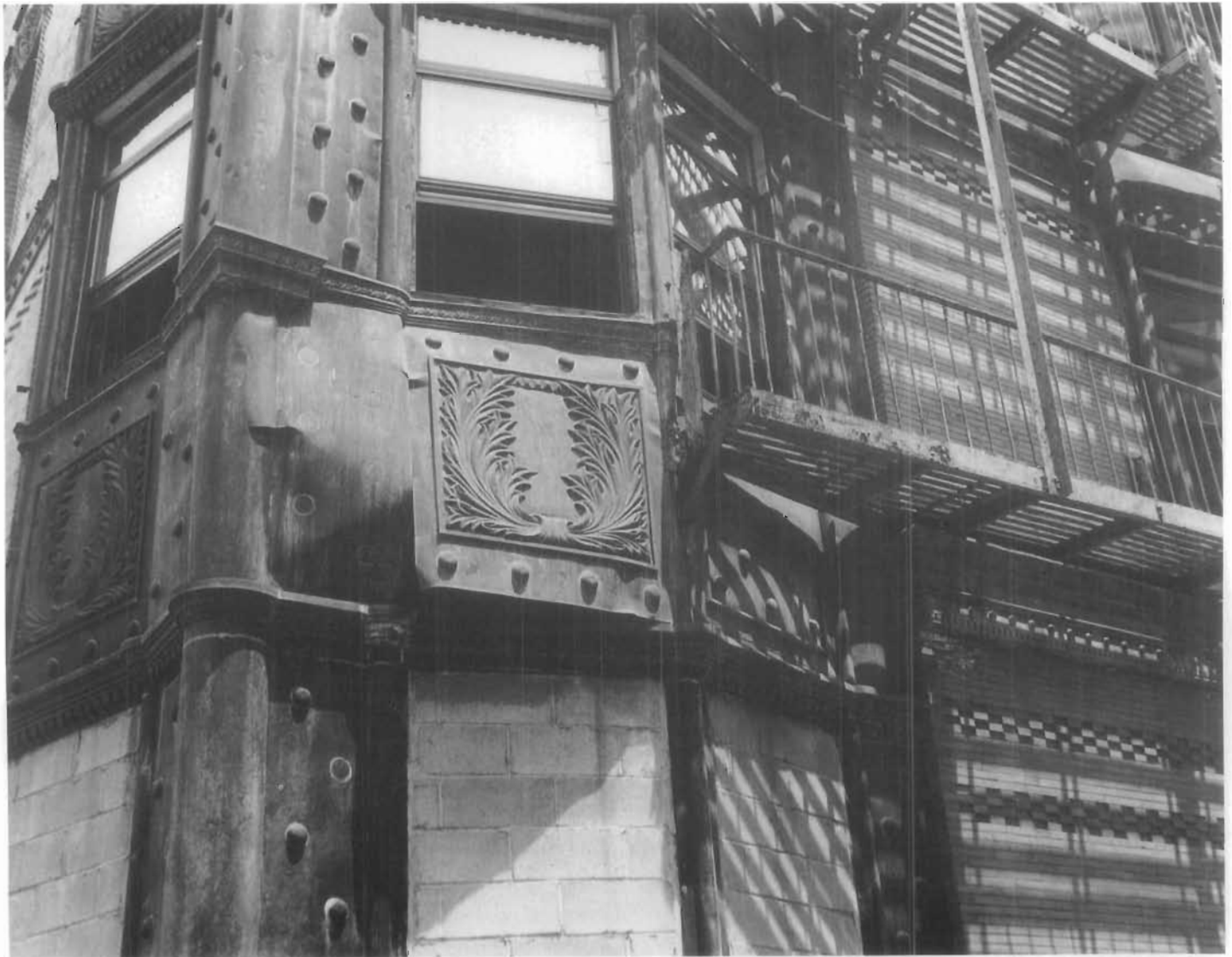


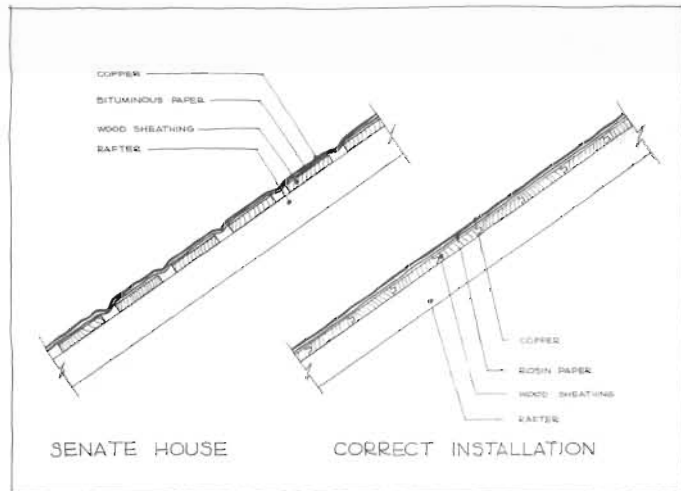
Figure 146. Loose and Damaged Copper Cladding and Deteriorated Steel Fire Escapes. *The corner bay of the Hotel Margaret (1889) in Brooklyn Heights, New York, was clad in ornamental panels of pressed sheet copper. Anchors have deteriorated and the wind has lifted the corners. Galvanic action between the noble copper and the baser steel (in the fire escape) has caused the steel to deteriorate.* (David W. Look)



Figure 147. Fatigue Failure. Fatigue failure occurred on the copper roof installed during the 1920s on the Senate House in Kingston, New York. (a) Failure was caused by cyclical expansion and contraction of the copper without adequate provisions for it. Additionally, the copper sheet was too thin and not rigid enough to resist buckling and sagging between the too-widely-spaced roof sheathing. The use of bituminous roofing paper between the copper and sheathing also contributed to the failure; when the paper was heated by the sun, it adhered to the copper, further restricting its movement (see figure 117). (b) The drawing shows the actual roof installation and the correct procedure, which allows for expansion and contraction. (John G. Waite)



Figure 148. Inappropriate Patching Compounds. Corrosion of a copper roof ridge on the Dakota Apartments (1884), New York City, was caused by the use of an asphalt roofing compound for temporary patches over nailheads and joints between ridge sections. (John G. Waite)



b



Figure 149. Resistance to Corrosion. Little damage had occurred to the copper at The Statue of Liberty. Galvanic corrosion, however, occurred where saline rainwater provided the electrolyte between the copper and the iron armature, resulting in considerable loss in the cross-section of the armature. (Robert Baboian)



Figure 150. Erosion of Copper. *This eaves detail of the 1920s copper roof on the Senate House State Historic Site in Kingston, New York, illustrates erosion of the copper at the edge of the roof caused by continued exposure to rain and snow, which scoured the roof as it flowed to the gutter. Fatigue failure has also occurred at the base of the standing seam, resulting in a tearing of the copper. This failure was caused by the lack of provision for expansion and contraction, as well as the use of bituminous roofing felts, which restricted the movement of the copper. (John G. Waite)*



Figure 151. Bird Droppings. *The 1914 bronze memorial to the writing of the "Star Spangled Banner," which is located in a niche on the porch of the Baltimore City Hall, is a favorite roost for birds. Bird droppings contain acids which are harmful to bronze and should be removed periodically. (David W. Look)*

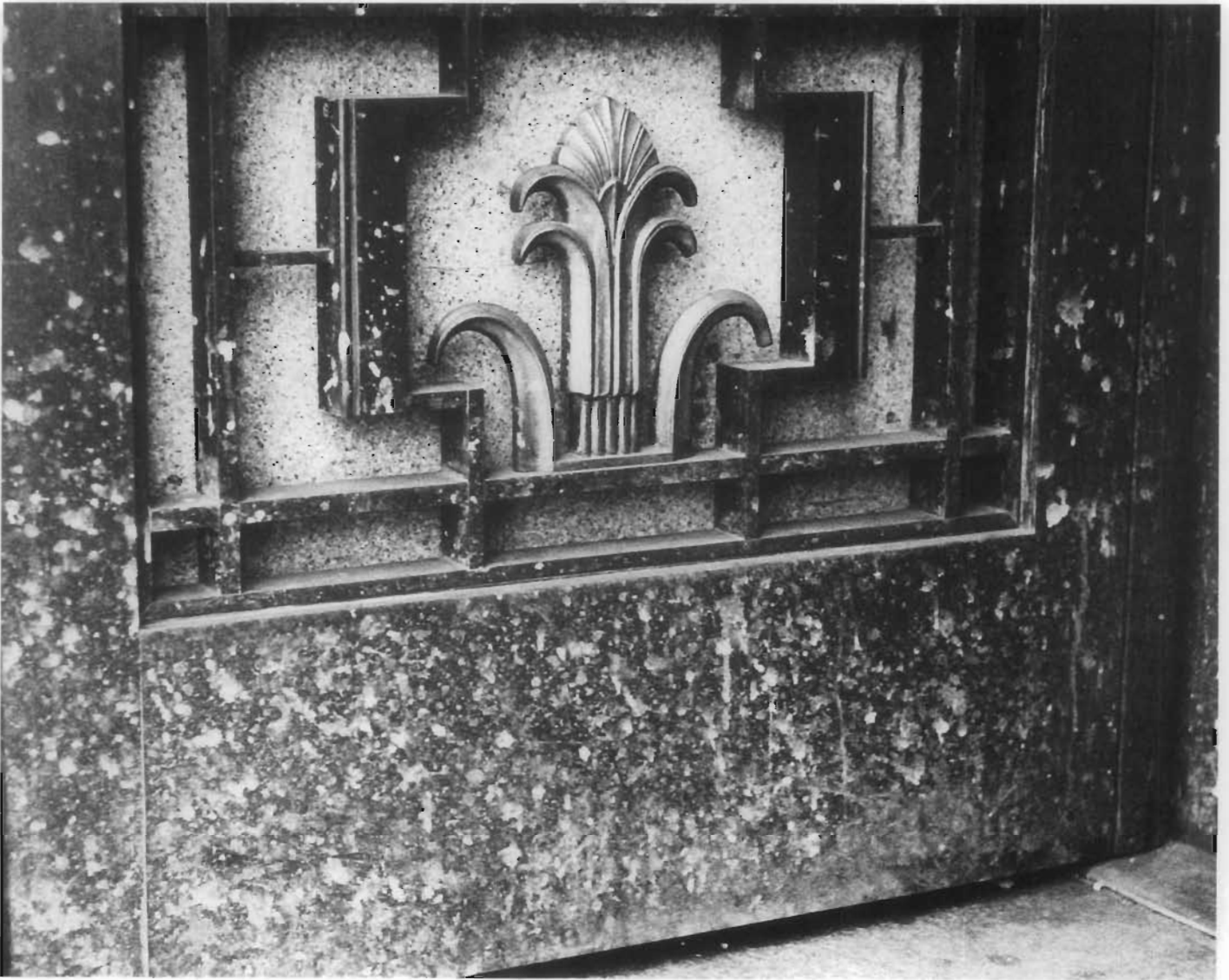


Figure 152. Snow Salt Damage. *On the Circuit Court of Appeals Building in Washington, D.C., the lower extremities of the exterior-bronze gates are discolored and unsightly from repeated splashing of snow-removal salt. As long as the salt remains on the gates, the bronze will continue to deteriorate and its surface may even become pitted. (David W. Look)*



Figure 153. Improper Cleaning of Bronze. *The bronze doors on the Pennsylvania Avenue side of the National Archives in Washington, D.C., were cleaned improperly. They now vary in color from a golden bronze to green to copper orange and brassy yellow. Some of the original artificial patina applied at the foundry has been removed, leaving a blotchy appearance. Part of the corrosion from the deicing salt remains, and the doors have a streaked, unattractive appearance. At this point, the only feasible treatment would be to clean the doors thoroughly (down to the bright metal), by mild chemicals or soft abrasive cleaning. A new artificial patina could be applied to return the doors to their original appearance. To protect against future damage, the doors should be given a barrier coating of wax which will need to be renewed periodically. The maintenance staff should be notified not to use salt near the doors and not to clean or polish the doors other than washing them down once a year with a nonionic detergent. When washed, the doors should be thoroughly rinsed with distilled water and wiped dry with a clean cloth to prevent water spots and streaks. (David W. Look)*

Methods of Preservation and Repair

Copper is very durable and seldom needs maintenance but it can be painted to prevent erosion. It can be difficult to obtain a good bond between the copper and paint because grease and oil are rolled into the surface pores of the copper during manufacturing. Traditionally, lead-based paints were often used in the first or prime coat to obtain a good paint bond to the metal. The following instructions for cleaning and for obtaining a good paint bond are given in a 1956 edition of Kidder-Parker.⁵⁴

1. The surface must be thoroughly cleaned and roughened using a solution of 4 ounces copper sulfate to ½-gallon lukewarm water with ⅛-ounce nitric acid.
2. The first coat of paint is to consist of 15 pounds red lead to 1-gallon raw linseed oil, with not more than ½-pint oil dryer.
3. The final two coats of paint are to consist of 15 pounds white lead to 1-gallon raw linseed oil and not more than 5% oil dryer and color pigments. (Alkyd resin paints specially formulated for copper

use with the appropriate primer are now usually substituted for the lead-base paint, but alkyd resin paints do not provide as good protection against erosion and the metal must be repainted more often.)

However, red and white lead paint are now considered to be health hazards. For this reason, high-performance coating systems, such as epoxy primer and urethane finish coats, are now used in place of the traditional red lead and linseed oil paint. The water runoff from roofs with copper valleys painted with lead-based paint is just as harmful, if ingested, as water from lead or lead-coated copper roofs. In fact, it is not recommended that water from any roof be consumed by people or animals.

There are some cases where a natural or unpatinated copper color is desirable; hence, a clear coating, is used. After the copper elements are completely cleaned of flux, dirt, and oxide by a recommended process of abrasion, they can be protected by a lacquer or Incralac coating. Incralac contains an acrylic resin, a chelating agent (Benzotriazole), and a leveling agent in toluene or butyl acetate. The application of three separate coats should build up an optimal protective coating of more than 0.001 inches in thickness on the surface.⁵⁵ If lacquer or Incralac is used to coat copper, the copper will retain its original color for a number of years; the natural protective patina will not form, except where the coating is broken or worn away. In addition to lacquer, wax coatings may also be used to protect the copper.

When copper architectural elements deteriorate, they should be examined by a specialist to determine if they can be salvaged. If this is not possible, the damaged element should be replaced with new copper of the same weight, configuration, and temper or hardness. Fatigue damage should never be repaired using soldered patches or soft solder (a lead-tin alloy) to fill stress cracks; this solder has a different coefficient of expansion than the copper and will eventually break away. Solder is inherently a weak alloy and should be used only to create watertight joints, not where tensile or compressive strength is needed. However, it does provide some strength in connecting sheets of copper in "weights" less than 20 ounces.⁵⁶ To connect thicker sheets, over 20 ounces, copper rivets must be used. All solder used for copper, either for repair or new installations, should be composed of 50% pig lead and 50% block tin and should be applied using a noncorrosive rosin flux.⁵⁷ Copper can be welded if the sheets are of sufficient thickness.

Where new sheets of copper are used to repair an existing copper architectural component, the maximum length of the sheets should be 8 feet. Adequate provisions should be made for thermal expansion and contraction within the repaired area and all fastenings should utilize copper cleats held with either copper nails or brass screws. Copper roofing sheet should be separated from the wooden sheathing by rosin building paper to allow free movement of the sheets (figure 147b).

Bronze or Brass can be repaired in a variety of ways. If a bronze or brass object is dented, it may be hammered back in place if the backside is accessible and the metal

is not too thick. However, if the metal has stretched, it will be difficult to hammer it back to its original configuration. Severely damaged sections can be cut out, recast, and reattached by riveting or brazing, a form of soldering with a bronze or brass filler metal. Likewise, missing pieces can be reproduced (figure 154). Some scratches can be buffed to match the original finish and texture, as can brazed joints.

Before bronze or brass objects can be brazed they must be cleaned to provide good bonding. At other times, cleaning may be necessary to remove salts, bird droppings, or dirt. Sometimes cleaning is done only for cosmetic reasons. All cleaning removes some surface metal and patina; therefore, it should not be done without good reason. Excessive cleaning can remove the texture and finish of the metal. Since the patina can protect the bronze or brass from further corrosion, it should be retained if possible. Heat from brazing or welding will affect the patina, causing a change in color that may be permanent. If the patina is removed when repairs are made, it can be replaced slowly by weathering which takes 8-10 years; however, the resulting blotchiness may not be acceptable. The patina can be replaced rapidly by chemical means to match the rest of the work if necessary; however, repatination may also remove a slight amount of surface metal (see below).

Surface deposits and corrosion products can be partially or totally removed from copper, bronze, and brass by various procedures. These range from gentle washing with deionized water, a non-ionic detergent, and natural bristle brushes; to chemical stripping; to air-abrasive blasting, using a variety of abrasive media such as soft organic blasting media like crushed walnut shells or corn cobs, to much harder media like plastic or glass beads. Chemical compounds such as rottenstone and oil, whiting and ammonia, and precipitated chalk and ammonia, can be used along with very mild abrasive techniques such as rubbing with a clean, soft cloth.⁵⁸ Thick crust can be removed by sodium hexametaphosphate and water or dilute sulfuric acid and water prepared and used by persons trained in handling this dangerous acid.⁵⁹ Commercial companies that routinely clean and maintain bronzework use a variety of "secret" formulas which are generally based on their experience and conform to the recommendations of the Copper Development Association. It suggests using a 5% oxalic acid and water mixture together with finely ground India pumice powder.⁶⁰ This slurry mixture is rubbed on with a clean soft cloth. After thorough rinsing with clean water, the surface is wiped dry with a clean soft cloth to prevent water spotting (figure 155).

Sandblasting, a common method for cleaning cast iron, is particularly damaging to bronze surfaces. In addition, the practice of cleaning bronze surfaces with glass bead peening, common during the 1970s, has fallen out of favor. Moreover, cleaning down to a bright metal surface, by any means, is often inappropriate and unnecessary. In recent years, gentler low-pressure blasting procedures have been developed by conservators of outdoor bronze sculpture. Using softer blasting media, (crushed walnut shells are currently the most popular), these cleaning methods seek to remove grime and superficial corrosion products while leaving intact more



Figure 154. Damage to Bronze. *In the Court Square Historic District in Springfield, Massachusetts, five of six bronze street lamps were vandalized or accidentally damaged by automobiles backing into parking spaces. (a) The one lamp that survived intact was used to make new molds. (b) The missing leg and lamp were recast (not shown) and/or repaired with funds from a matching grant from the National Park Service in 1976. The recast pieces were chemically treated to obtain a green patina that matched the weathered appearance of the original sections of the lamps. A plan was drafted to relocate the lamps 12 inches from their previous position at the curb to prevent any further damage from parking automobiles. (Thomas Taylor)*

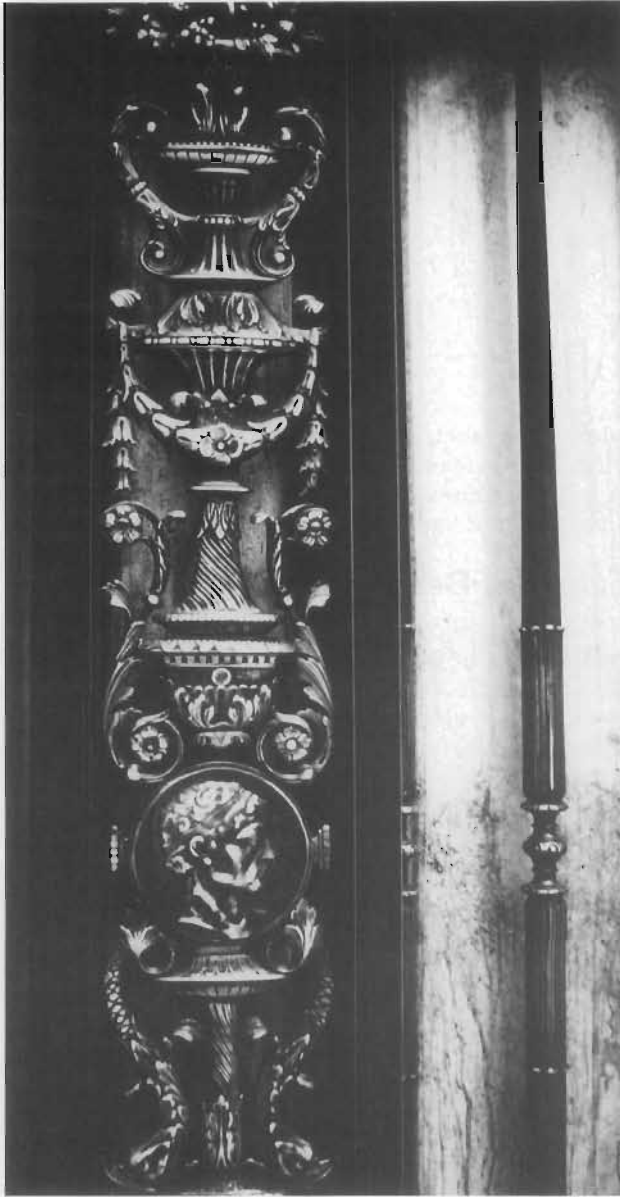


Figure 155. Cleaning Bronze. *Recently, the exterior bronzework was cleaned on the Morgan Guaranty Trust Company on the corner of Wall and Board streets in Manhattan. The original finish of the bronze was a statuary brown artificial patina (a chemical process developed in the 19th century) with the bas-relief sculpture highlighted in a lighter pinkish-gold color, probably just the natural color of bronze without artificial or natural patina. The bronzework was cleaned and sealed with a clear coating. Without a coating, a natural patina would form, causing slow color change from pinkish gold to brown to black and eventually to green over an 8-10 year period. The colors are usually uneven and streaked because of the local pattern of wind and rain. The formation of a natural patina would eventually destroy the contrast between the statuary brown and pinkish gold, which was the original intention of the architects, Trowbridge and Livingston, when the bank was built in 1913. (David W. Look)*

firmly adhered corrosion products, as well as the metal substrate below.

Whether or not surface cleaning produces a bright metal surface, surface coloration can be modified through the creation of chemically-induced patinas. The color range of bronze patinas includes red-brown, gold-brown, shades of green or blue-green, and black. Perhaps more important to the visual appearance is the modulation of specified colors to achieve subtle variations that can enhance highlights and shadows.

Once a bronze or brass surface has been cleaned, some type of barrier coating should be applied to prevent or limit future corrosion. These coatings are designed to prevent or minimize contact between the metal and moisture and pollutants. Original foundry-applied wax or shellac coatings usually deteriorate with time, exposure, and lack of maintenance and therefore need to be renewed. The organic coatings most frequently used for maintaining architectural bronze include waxes, which require reapplication at six-month to two-year intervals; lacquers, which require removal and reapplication at three- to five-year intervals; and combinations of lacquers and waxes.

Lacquer is a type of surface coating in which a binder consists of an organic film-forming substance, often dissolved in a solvent. The term lacquer is usually reserved for coatings obtained by physical drying, whereas a varnish contains a drying oil and is thus dried by oxidation. Upon exposure to the atmosphere, the polymers that make up lacquers tend to attach themselves to each other, a chemical process known as cross-linking. Cross-linked materials are difficult to break up by solvents or by application of reasonable amounts of heat, which makes them nearly irreversible. The potential of some lacquers to undergo cross-linking raises concerns regarding their use as protective coating for bronze sculpture.

Wax coatings are widely used in the conservation of outdoor bronze statuary. Waxes are used in various formulations and are applied using a variety of methods. Both natural and synthetic waxes are commonly applied directly to heated or ambient temperature bronze surfaces, or applied cold as a finish coating over lacquer. While the lifespan of waxes is shorter than that of lacquers and varnishes, waxes tend not to cross-link, making removal relatively easy. Further, waxes are a more forgiving type of coating. Small scratches and pinholes tend to "self-heal" as the wax can soften and redistribute itself somewhat at typical outdoor temperatures. Many conservators of outdoor bronzes add sacrificial cold wax coatings to lacquered surfaces.

The useful lives of present organic coatings differ, depending upon their nature and upon the vicissitudes of the surrounding environment. All coatings should be periodically inspected and renewed when needed. In addition, they should be readily removable through means that will not damage the metal substrate.

The cleaning and repair of copper, bronze, and brass should not be considered a "do-it-yourself" project. A qualified metal conservator should assess the condition of the material and design an appropriate treatment that will then be carried out by the conservator, or an experienced and well-supervised staff of technicians.

1. Material in this report expands John G. Waite's, "Architectural Metals: Their Deterioration and Stabilization," a lecture for the North American Regional Conference convened by the Rome International Centre Committee for Conservation and the International Centre Committee of the Advisory Council on Historic Preservation in Williamsburg and Philadelphia, September 10-16, 1972, *Preservation and Conservation: Principles and Practices* (Washington, D.C.: Smithsonian Institution Press, and Preservation Press, National Trust for Historic Preservation, 1976) pp. 213-242.
2. *Ibid.*, p. 213.
3. Glenn A. Greathouse and Carl J. Wessel, *Deterioration of Materials: Causes and Preventive Techniques* (New York: Reinhold Publishing Corp., 1954), p. 4.
4. W. D. Hoff; John W. Simpson; and Peter J. Horrobin, eds., *The Weathering and Performance of Building Materials* (New York: Wiley-Interscience, 1970), chapter on "Metals" edited by W. D. Hoff, pp. 186-187. Hereafter cited as "Metals."
5. F. L. LaQue and H. R. Copson, eds., *Corrosion Resistance of Metals and Alloys*, 2d ed. (New York: Reinhold Publishing Corp., 1963), pp. 7-37.
6. *Corrosion in Action* (New York: International Nickel Company, 1977), p. 19, and Jerome Kruger, *Corrosion: Facts for the Consumer* (Washington, D.C.: National Bureau of Standards Consumer Information Series 9, March 1978), p. 1.
7. *Ibid.*, pp. 11-18.
8. American Society for Testing and Materials. *Standard Guide for Development and Use of a Galvanic Series for Predicting Galvanic Corrosion Performance - G82-83* (Philadelphia: ASTM).
9. *Corrosion in Action*, p. 15.
10. LaQue and Copson, *Corrosion Resistance*, p. 46.
11. W. H. Munse, J. E. Stallmeyer, and F. P. Drew, *Structural Fatigue and Steel Railroad Bridges* (Chicago: American Railway Engineering Association, 1968), p. 2.
12. Greathouse and Wessel, *Deterioration of Materials*, p. 238.
13. *Ibid.*, p. 301.
14. Robert C. McMasters, ed., *Nondestructive Testing Handbook*, Vol. 1 (New York: Ronald Press Co., 1959), sec. 6-8.
15. Greathouse and Wessel, *Deterioration of Materials*, pp. 264-274.
16. *Ibid.*, p. 275.
17. These are other coatings. Ceramic coatings consist of inorganic glasses loaded with refractory or other materials to aid adhesion, decrease brittleness and liability to break off because of differences in temperature coefficients, and to often achieve decorative colors and texture. The use of this kind of corrosion protection for architectural metals which exist *in situ* is not common because the ceramic coating needs to be applied at red heat. See Greathouse and Wessel, *Deterioration of Metals*, pp. 280-286.
18. *Ibid.*, pp. 291-295.
19. Caleb Hornbostel, *Materials for Architecture: An Encyclopedic Guide* (New York: Reinhold Publishing Corp., 1961), p. 287.
20. Lyall Addleson, *Materials for Building*, Vol. 3 (London: Iliffe Books, 1972), p. 69.
21. Hornbostel, *Materials for Architecture*, p. 287.
22. *Lead in Modern Industry: Manufacture, Applications and Properties of Lead, Lead Alloys, and Lead Compounds* (New York: Lead Industries Association, 1952), p. 51.
23. Addleson, *Materials for Building*, p. 69.
24. *Ibid.*, p. 69.
25. Ulick R. Evans, *The Corrosion and Oxidation of Metals: Scientific Principles and Practical Applications* (London: Edward Arnold, Ltd., 1960), p. 518.
26. In the first case the copper nails, the more noble metal, are much smaller than the lead sheets and deterioration of the lead is only slight. In the second case the iron, the baser metal, is much larger than the lead waterproofing and the iron is almost always painted, so the deterioration of the iron is also slight.
27. Jack Bowyer, *History of Building* (London: Crosby Lockwood Staples, 1973), p. 115.
28. Donald W. Insall, *The Care of Old Buildings Today: A Practical Guide* (London: The Architectural Press, 1972), p. 98.
29. Robert M. Organ, "The Corrosion of Tin, Copper, Iron and Steel, and Lead," in *Preservation and Conservation: Principles and Practices* (Washington, D.C.: Smithsonian Institution Press and Preservation Press of the National Trust for Historic Preservation, 1976), p. 254.
30. Hornbostel, *Materials for Architecture*, p. 515.
31. Henry Leideheiser, Jr., *The Corrosion of Copper, Tin, and Their Alloys* (New York: John Wiley and Sons, Inc.), p. 326.
32. Hornbostel, *Materials for Architecture*, p. 515.
33. A formula for the traditional "inner's red" paint is 10 pounds of Venetian red, 1 pound red lead to 1 gallon of pure linseed oil; Frank E. Kidder and Henry Parker, *Kidder-Parker Architects' and Builders' Handbook*, 18th ed. (New York: John Wiley & Sons, Inc., 1956), p. 2001.
34. Revere Copper and Brass, Inc. *Examination of Corroded Lead Coated Copper Sheet: Austin-Hastings Company Incorporated, Cambridge, Massachusetts* (Rome, New York: Revere Copper and Brass Inc., Research and Development Center, 1964), p. 3.
 "Due to the extremely small solubility of lead in copper, it is difficult to wet a copper surface with molten lead in applying a lead coat. To promote the wetting process, a few percent tin, soluble in both copper and lead, is added to the lead bath. The final product may then be considered as a three-layered composite consisting of the copper substrate, a copper-tin alloy layer, and the lead coat.
 "Pinholes or voids in the coat as produced, gross inclusions in the coat, or abnormal corrosion of the coat all tend to expose the copper-tin alloy layer and the copper substrate to the corrodent. This condition may give rise to a galvanic corrosion all with the copper becoming anodic to the copper-tin alloy, resulting in accelerated pitting of the copper.
 "This particular situation is somewhat aggravated in that the metal is exposed in a horizontal position. This allows rain water and condensed moisture, the electrolytes, to pool in the low spots and remain on the surface for periods much longer than those normally encountered on a pitched roof."
35. Hornbostel, *Materials for Architecture*, p. 592.
36. *Ibid.*

37. *Ibid.*, p. 596.
38. *Ibid.*
39. Ian A. Melville and Ian A. Gordon, *The Repair and Maintenance of Houses* (London: The Estates Gazette Limited, 1973), p. 534.
40. Ian A. Melville, Ian A. Gordon, and Peter Scott, *Structural Surveys of Dwelling Houses* (London: The Estate Gazette Limited, 1964), p. 29.
41. Hoff, "Metals," p. 206.
42. The discoloration caused by white storage stain or white rust can be avoided by dipping the sheets in dilute hydrochloric acid (remembering the zinc will dissolve in it), rinsing, and then dipping in a solution of dichromate, after which final rinsing and drying are necessary. *Ibid.*, p. 208; and Hornbostel, *Materials for Architecture*, p. 596.
43. Evans, *The Corrosion and Oxidation of Metals*, pp. 586-587.
44. Hornbostel, *Material for Architecture*, p. 177.
45. *Ibid.*, p. 105. This page contains additional information regarding the various types of brasses and their compositions.
46. *Ibid.*, p. 91.
47. *Ibid.*
48. *Ibid.*, pp. 91-92. These pages contain additional information regarding the various types of brasses and their compositions.
49. In the past, it was generally believed that the patina was basic copper carbonate but research in the 1930s determined that it was basic copper sulfate. See Donald H. Osburn and John M. Fochlich, "Coloring and Finishing of Copper Metals," *Construction Specifier* (October 1963), pp. 50-55.
50. Organ, "The Corrosion of Tin, Copper, Iron and Steel, and Lead," p. 248. Acetates are salts or esters of acetic acid (found in vinegar and some other organic acids).
51. *Ibid.*, p. 247.
52. H. J. Plenderleith and A. E. A. Werner, *The Conservation of Antiquities and Works of Art: Treatment, Repair, and Restoration*, 2nd ed. (New York: Oxford Press, 1971), pp. 246-250.
53. Hornbostel, *Materials for Architecture*, pp. 91-92.
54. *Kidder-Parker Architects' and Builders' Handbook*, p. 2018.
55. Joseph F. Long, P.E. Manager, Tin Research Institute, Inc., Columbus, Ohio, to John G. Waite, 23 June, 1972.
56. *Copper and Common Sense, Design Principles and Techniques of Sheet Copper Construction*, 6th ed. (New York: Revere Copper and Brass, Inc., 1961), p. 32.
57. *Kidder-Parker Architect's and Builders' Handbook*, p. 2018.
58. Harold L. Peterson, "Conservation of Metals," *History News* 23 (no. 2, Feb. 1968): p. 6.
59. Organ, "The Corrosion of Tin, Copper, Iron and Steel, and Lead," p. 249.
60. *Copper, Brass, Bronze Design Handbook: Architectural Applications* (New York: Copper Development Association, Inc., n.d.), p. 31.
61. Hornbostel, *Materials for Architecture*, p. 330.
62. *Ibid.*, p. 333.
63. *Ibid.*, p. 334.
64. Hard and soft solders are general terms that usually refer to temperature. Soft solders are all soldering alloys that melt below 840°F. and are usually composed of varying proportions of lead and tin. Hard solders are all soldering alloys that melt above 840°F. and are usually silver solders which contain varying percentages of silver, copper, tin, cadmium, nickel, and other metals, but never lead. Hard soldering is the same as brazing. The brazing filler metal (soldering alloy) has a melting point below the melting point of the metal pieces being joined. If the metal pieces being joined, often called the base metal (not to be confused with the baser metal in galvanic corrosion), is melted and fused with the filler metal, the process is welding. In brazing the metal pieces being joined are never melted and the filler metal is drawn into the joint by capillary action. For brazing nickel silver, the filler metal is 10-18 % nickel zinc, and the remainder, copper. *The Brazing Book* (New York: Handy & Harmon, 1977), p. 44.
65. Gerald K. Geerlings, *Metal Crafts in Architecture* (New York: Charles Scribner's Sons, 1929), p. 185.
66. Even at high temperatures, Monel metal is too strong to be extruded. *Practical Design in Monel Metal* (New York: International Nickel Company, Inc., 1931), pp. 9-10, and 25.
67. Hornbostel, *Materials for Architecture*, p. 320
68. *Ibid.*, p. 330.
69. *Ibid.*, p. 333.
70. Geerlings, *Metal Crafts in Architecture*, p. 185.
71. In general, nickel silver and Monel metal can be cleaned using the same methods as cleaning bronze since they all contain copper; however, chemicals should always be spot tested for desired results before general application. *Copper, Brass, Bronze Handbook: Architectural Application*, (New York: Copper Development Association, Inc., n.d.), p. 31; Peterson, "Conservation of Metals," p. 7.
72. "Simple Tests Identify White Metals: Reliable in Result, They Eliminate Guesswork by the Eye and Can be Carried Out With Inexpensive and Readily Available Equipment—Essential in Scrap Recovery, They Also Are Useful for Identification of Materials in Process and Storage," *Inco* 18 (no. 3, 1941): pp. 6-7. (Tests for the identification of nickel, Monel, nickel-silver, steel, cast iron, stainless steel, and Inconel).
73. Hornbostel, *Materials for Architecture*, p. 321.
74. *Ibid.*, p. 334.
75. *Ibid.*, p. 276.
76. LaQue and Copson, *Corrosion Resistance*, p. 305.
77. Addleson, *Materials for Building*, p. 64.
78. Hornbostel, *Materials for Architecture*, p. 285.
79. Addleson, *Materials for Building*, p. 64.
80. *Ibid.*
81. Geerlings, *Metal Crafts in Architecture*, p. 114.
82. Hornbostel, *Materials for Architecture*, p. 283.
83. Geerlings, *Metal Crafts in Architecture*, p. 45.
84. Hornbostel, *Materials for Architecture*, p. 283.
85. Addleson, *Materials for Building*, p. 64.
86. Hornbostel, *Materials for Architecture*, p. 448.
87. Addleson, *Materials for Building*, p. 64.
88. *Ibid.*, p. 66.
89. LaQue and Copson, *Corrosion Resistance*, p. 375.
90. *Metal Product Outline for Classifying Products Manufactured by NAAMM Member Companies* (Chicago: National Association of Architectural Metal Manufacturers, 1989, second edition), p. 10.
91. Plenderleith and Werner, *Conservation of Antiquities and Works of Art*, p. 281.
92. Organ, "The Corrosion of Tin, Copper, Iron and Steel, and Lead," p. 251.
93. *Ibid.*
94. Magnesium oxychloride cements were originally developed in 1867 by French chemist I. M. Sorel, the man who patented the galvanizing process in 1837. Historically, magnesium oxychloride cement was known as Sorel cement, or magnesite cement; today it is known as oxychloride cement. Philip Maslow, *Chemical Materials of Construction* (Farmington, Mich.: Structures Publishing Company, 1974), p. 132.
95. Addleson, *Materials for Building*, p. 63.
96. *Ibid.*, p. 64.
97. LaQue and Copson, *Corrosion Resistance*, p. 367-368.
98. McMasters, *Nondestructive Testing Handbook*, p. 6-1.
99. Hornbostel, *Materials for Architecture*, p. 285.
100. Addleson, *Materials for Building*, p. 64.
101. *Ibid.*, p. 66.
102. Hornbostel, *Materials for Architecture*, p. 461.
103. LaQue and Copson, *Corrosion Resistance*, p. 410.
104. Addleson, *Materials for Building*, p. 67.
105. *Ibid.*
106. Hornbostel, *Materials for Architecture*, p. 444.