Statue of Liberty

by Tom Burroughs

She would be impressive anywhere, standing 151 feet tall, weighing 280 tons, and visible for 42 miles on a clear day. Yet the Statue of Liberty is more than just a monumental figure. She has welcomed generations of immigrants and visitors to New York’s harbor and has come to symbolize the United States of America to millions of people around the world. Today, however, Liberty is nearly lost from sight, encased in aluminum scaffolding, her famous torch removed.

The statue is undergoing extensive restoration, from the base of the pedestal to the tip of the flame, to reverse the ravages of time and weather. “Major renovation work on Liberty, especially on her badly corroded iron framework, is needed to preserve the monument and to avoid serious structural problems in the future,” says Blaine Cliver, regional chief of historic preservation for the National Park Service.

Liberty was a gift from the people of France to commemorate Franco-American unity. She was designed and built in Paris by sculptor Frederic Auguste Bartholdi. His initial concept was influenced by the “granite beings” of Egypt that he favored. But Bartholdi eventually looked closer to home for models: Liberty’s facial features are those of his mother; his wife-to-be inspired the figure.

Construction of the statue was a technological triumph. Bartholdi started with a four-foot clay model, which he scaled up by making progressively larger models in plaster. When she stood 36 feet tall, the model was marked off into 300 sections. Each section was then enlarged to full size, an arduous task that required more than 9000 measurements to translate the dimensions precisely.

Next, carpenters constructed massive wooden forms that followed the plaster contours of each piece exactly. Craftsmen then hammered Liberty’s metal skin into shape against these forms. Bartholdi originally
planned to use bronze, but weight problems forced a switch to copper. The 300 thin copper plates would be joined together by some 300,000 copper rivets.

To create the statue’s structural skeleton, Bartholdi eventually called upon Alexandre Gustave Eiffel, a respected engineer even then, years before he erected his famous tower on the banks of the Seine. Eiffel devised a central iron pylon, adapted from his bridge designs, to serve as the backbone. But most remarkable was the iron skeleton he designed to support Liberty’s copper skin. The skin—fragile yet weighing some 80 tons—needed support not only against gravity but against high winds that would buffet her surface, which is far larger than any sail.

Hundreds of Parisians turned out each Sunday to watch the statue take shape, steadily growing above the nearby rooftops. Then, after Liberty was formally presented to the U.S. ambassador, workers reversed the assembly process, packing the 300 pieces of her copper skin in 49 mammoth wooden crates and the iron framework in 36 others. Thus packaged, Liberty traveled to America by wagon, train, and warship. Unfortunately, she arrived somewhat the worse for wear, with some pieces deformed in transit.

Adding insult to injury, U.S. workers reassembling the statue did not match the French rivet holes in every case. Liberty’s head was thus installed about 2 feet off Eiffel’s original alignment, generating unexpected stresses. The workers also made mistakes in following the plans for the central framework; one of the spikes in Liberty’s crown touched her arm and thus punctured the copper skin. Problems stemming from mistakes during construction, however, are only part of the current woes. Indeed, Liberty’s most serious ailments are due to the slow but steady corrosion that has afflicted her skin-support system, right arm, and torch.

The skeleton that Eiffel designed to support Liberty’s copper skin is formidable. It features a weblike network of ribs, flat iron bars that are precisely bent and shaped to follow the interior curves closely. The ribs are linked to the skin with “saddles”—copper bands that overlap the bars and are riveted in place. The roughly 1500 saddles were designed so the flat bars could slide freely, allowing the skin to move with the wind and expand or contract with temperature changes. Although the idea was ingenious, the system didn’t work as planned.

The problem has been caused by “galvanic” corrosion. This process occurs when two dissimilar metals—in this case, iron and copper—come in contact in the presence of an electrolyte, a solution that conducts electricity by the movement of ions. In galvanic corrosion, the
rate of attack on one of the metals is accelerated, and the corrosion rate of the other is decreased. “The driving force is the electrochemical potential difference between the component metals,” says Robert Baboian, head of the corrosion laboratory at Texas Instruments, which has helped with analytical studies of the statue. “The more active metal acts like an anode in a battery, and the more noble metal becomes cathodic. This means the iron, being more active than copper, corrodes at a faster rate.” (See box *Galvanic corrosion.*)

The designers clearly anticipated this electrochemical effect by installing shellac and asbestos insulator strips to prevent electrical contact between the iron ribs and the copper saddles. But as Liberty’s metal parts expanded and contracted, the insulator strips soon wore away, and the incompatible metals made contact. Water seeping into the statue, especially seawater laden with sodium chloride and other salts, served as the electrolyte. The ribs were inexorably corroded (see Figure 1).

Under these conditions, iron corrodes in several steps. First, electrons leave the iron, forming iron(II) ions. This process is called oxidation (though the element oxygen need not be involved):

\[
    \text{Fe} \rightarrow \text{Fe}^{2+} + 2\text{e}^{-}
\]

The electrons released flow from the iron to the copper. Other electrons leave the copper and react with oxygen that is dissolved in water. In a process called reduction, negative hydroxide ions are formed:

\[
    \text{H}_2\text{O} + 1/2 \text{O}_2 + 2\text{e}^{-} \rightarrow 2\text{OH}^{-}
\]

These ions combine with the iron ions to produce iron(II) hydroxide:

\[
    \text{Fe}^{2+} + 2\text{OH}^{-} \rightarrow \text{Fe(OH)}_2
\]

This compound is unstable in the presence of oxygenated water and is converted to iron(III) hydroxide, one of the components in the familiar orange material we know as rust:

\[
    2\text{Fe(OH)}_2 + \text{H}_2\text{O} + 1/2 \text{O}_2 \rightarrow 2\text{Fe(OH)}_3
\]

Copper is not necessary for the corrosion of iron, but when copper is present the rate of iron corrosion may increase as much as 1000 times. Had the iron ribs been successfully insulated from the copper, they would not have suffered this accelerated decay.
The bars have been dramatically reduced in width and thickness, some losing up to two-thirds of their “cross-sectional area.” Also, the rust gradually built up in the space between the bars and the saddles. The resulting expansive force has partially or totally ripped out the rivets that anchor about 600 saddles, deforming and leaving gaping holes in the copper skin. Together, the loosened saddles and damaged ribs have significantly reduced the integrity of the statue’s skeleton. “All the flat iron bars in the skin-support system—more than 1300 bars totaling 35,000 pounds—are therefore being replaced with stainless steel substitutes,” says Cliver. The stainless steel, an alloy of iron, chromium, nickel, and molybdenum is corrosion resistant and has mechanical properties similar to the iron used in Liberty’s bars. This reflects a guiding principle in historic restoration: Replacements should be as similar as possible to the originals.

Workers will soon begin replacing the ribs one at a time. The iron bars removed must be replaced the same day to avoid leaving the statue overnight without adequate support—a tedious process because only a few crews at a time will be able to work in the cramped quarters. The new stainless steel bars will be shaped on site, piece by piece, to match the twists and bends of their iron counterparts. In addition, the copper saddles will be lined with Teflon—a slippery polymer that is an electrical insulator—to provide added protection and facilitate movement.

The problems afflicting Liberty’s right arm stem from early attempts to make her earn her keep. The statue’s custodians decided that she should also serve as a beacon for ships, so they cut numerous holes in the torch’s copper flame and installed amber glass. Unfortunately, the improvised flame was never watertight. Indeed, the torch “leaks like a sieve,” says John Robbins, National Park Service historical architect. Hence whenever it rained, water entered the torch and ran down the arm, severely corroding its iron supports. Officials feared that the entire arm would have to be removed and rebuilt, but they report that recent analysis indicates that the arm can be strengthened in place.

The upper part of the torch, however, was so corroded that it has already been removed. The new flame will be made of a solid sheet of copper—which should reduce the water leaks that plagued the first flame—and will be covered with gold. “The flame will be illuminated with high-intensity lights, which will make it shine even brighter than before,” says Cliver. “It can even be made to flicker, since the lights will be remote controlled.”

Some critics don’t approve. But Cliver says the new flame will actually be closer to Bartholdi’s original design. “Trying to reproduce
the old design because `it was there' just didn’t make sense,” he says. “This new design makes sense in terms of both history and protection from the weather.” However, there are no plans to reopen the torch’s viewing balcony to the public. It was closed in 1916 when an explosion at the Black Tom munitions plant several miles away in New Jersey popped about 100 rivets out of the arm. Workers quickly replaced the rivets, but officials decided to keep the torch blocked off because the narrow access by ladder was creating congestion problems.

Liberty’s external appearance will be left essentially unchanged. “We are taking every step to assure that she remains as majestic and beautiful as she is today,” says National Park Service director Russell E. Dickerson. Even new rivets will likely be treated chemically to match the statue’s familiar bluish-green patina of oxidized copper. Patina is a product of corrosion that copper develops naturally when exposed to the weather. It forms a tight adherent film on the copper surface, which reduces the rate of corrosion of the copper underneath.

Far from being a precise laboratory reaction, patina is formed under uncontrolled conditions and may be a mixture of three or more compounds. These compounds are formed by a variety of reactions using the chemical species O₂, SO₃, H₂O, H₂S, Cu, Cu₂O, Cu₂S, and CuS. However, analysis of the patina on the Statue of Liberty shows that it consists mainly of basic copper sulfate CuSO₄ · 3Cu(OH)₂, which is also called brochantite. As its formula suggests, brochantite crystals contain three units of Cu(OH)₂ for every unit of CuSO₄. One of the pathways by which brochantite is formed is shown in Figure 2.

The protective patina has served Liberty well over the years. The thickness of the copper skin—originally about 3/32 of an inch—has declined only about four percent. But all the news isn’t good. The effects of acid rain, which have been studied extensively only in recent years, seem to be changing the chemical composition of the patina.

Recent tests of Liberty’s skin indicate that the patina is being changed to a modified form of copper sulfate—CuSO₄ · 2Cu(OH)₂—called antlerite. Norman Nielson, a corrosion chemist working on the restoration of the statue, says, “This change occurs when the pH of the rain falls to 3-3.5. It is likely that dilute sulfuric acid in the rain removes Cu(OH)₂ from the brochantite crystal, but this is not well understood and needs more research.” Antlerite doesn’t form as tight a bond on the copper and is more soluble in water. The modified patina is more easily washed from the surface in a rainstorm, removing the protective cover and exposing the copper for another round of corrosion. “Indeed, this change in patina caused by acid rain is becoming a growing problem for many copper statues and structures in the Northeast,” says Baboian.
“When you look at the base of a statue and see streaks of green, that’s probably patina that has been chemically modified and washed off the surface.” For Liberty, monitoring will continue to see if the copper skin starts thinning at an exorbitant rate.

After the necessary minor repairs to Liberty’s exterior have been completed and the rust stains removed, workers will close the seams between the copper plates with a sealant. She will also be bathed in a mild detergent to remove pollution particles and other foreign materials.

Liberty Island, as Bedloe’s Island is now called, continues to host visitors while the work goes on, although the statue itself is closed. Indeed, Dickerson sees this as the opportunity of a lifetime. “The Statue of Liberty is, in our view, the greatest artistic colossus of all time,” he says. “We hope everyone will come to visit it during this unique period of historic restoration.” Work is scheduled to be complete by July 4, 1986, in time to celebrate the statue’s centennial. She will then be prepared to stand for many more decades, looking as her creators intended “springing from the bosom of the deep, representing Liberty Enlightening the World.”

**SIDE BARS**

**Galvanic corrosion**

Metal atoms have a tendency to lose electrons. The resulting positive ions combine with negative ions to form compounds. The solid metal has lost some of its atoms; it has corroded.

The various metallic elements differ in their urge to discard electrons. When two different metals are in contact, electrons tend to flow from one to the other as an electric current. A conducting solution, such as seawater, completes the electrical circuit and supplies the ions needed to form the corrosion compound. This electrical circuit greatly speeds the corrosion of the more active metal—the one with greater tendency to lose electrons—and slows the corrosion of the other.

The metallic elements are often listed in order from those with greatest to those with least tendency to lose electrons. When studied under ideal conditions, with each metal in a solution of its own ions, the list is called the activity series. Under other conditions the order of elements may be different and a more appropriate list for the Statue of Liberty problem is the galvanic series of metals and alloys in seawater. In the galvanic series iron, Fe, is well above copper, Cu, indicating that the corrosion of the iron ribs in the statue would be accelerated. The replacement ribs are made of stainless steel, which, in the series, is
closer to and below copper. Note that the metals with the least tendency to lose electrons—to corrode—are the metals historically regarded as precious: silver, gold, and platinum.

**CAPTIONS**

Construction of the Statue of Liberty in Bartholdi’s warehouse workshop in Paris during 1882 and 1883 was done with the guidance of wood and plaster mock-ups, which in turn were built from smaller scale models. The sculptor, second from right, a visitor, and several assistants are shown with a section of Liberty’s left arm. Copper sheets were hammered to the shape of the plaster forms and finally riveted together to form the 151-ft-tall statue. (Rare Books and Manuscripts Division, New York Public Library, Astor, Lenox & Tilden Foundations. From “Album des Travaux de Construction de la Statue Colassale de la Liberte Destinee au Port de New York,” Paris, 1883.)

Inside the statue, the iron ribs are contoured to match the Liberty’s shape—in this case the nose and lips (National Park Service, Statue of Liberty National Monument)

Many saddles and ribs have been damaged by the corrosion between them (National Park Service, Statue of Liberty Monument)

Figure 1. Over the years, the insulation that protected Liberty’s ribs wore away. Water from rain and condensation made electrical contact between the copper skin and iron ribs. The resulting corrosion weakened the ribs; pressure from the corrosion products popped rivets and bent the skin

Figure 2. One of the ways in which the green patina is formed on copper exposed to the weather. The process is very slow and requires sulfur compounds in the air and a relative humidity of at least 75%.

**BIOGRAPHY**

Tom Burroughs is a senior editor at Technology Review magazine, published by the Massachusetts Institute of Technology. He has been manager of the American Chemical Society’s News Service, as well as writer of the ACS radio program, “Dimensions in Science.”

**REFERENCES**