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Assessment of Fastener Corrosion and Salt Damage in the Bilge of the *Eureka*

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Abstract

This report summarizes inspection of corrosion and salt damage on the National Historical Landmark ferryboat *Eureka*, built in 1890 and displayed at the San Francisco Maritime National Historic Park of the U.S. National Park Service (NPS). The USDA Forest Service, Forest Products Laboratory (FPL) was contacted by the NPS because of concerns about white “corrosion products” that were forming on metal bolts in the bilge of the *Eureka*. Photographs shared by NPS showed signs of salt damage on the wood in addition to corroded bolts. As a result of conversations between FPL and NPS, an inspection was conducted. This report summarizes the findings of the inspection and gives recommendations that can be used to preserve the *Eureka* and possible actions to take during the next dry-docking of the ship.

Keywords: corrosion, salt damage, brown rot decay, damage mechanisms, condition assessment

Contents

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Assessment of Fastener Corrosion and Salt Damage in the Bilge of the *Eureka*

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Background: Potential Damage Mechanisms in the *Eureka*

Corrosion

Under most conditions, metals are not thermodynamically stable. Corrosion is the process through which metals oxidize (corrode) to return to a more stable oxide state. Although corrosion is nearly always thermodynamically favorable (i.e., it will happen eventually), the kinetics can be so slow that corrosion is not a concern for design.

When wood is wet, metals embedded in wood are subject to corrosion from extractives naturally available in the wood and potentially from external chemicals added to the wood, such as wood preservatives (Zelinka 2014). When the wood moisture content (MC) is below 15% to 18%, embedded metals do not corrode (Dennis and others 1995, Short and Dennis 1997, Zelinka and others 2014). As the moisture content is increased above this threshold, the corrosion rate increases rapidly with increasing moisture content before plateauing at a maximum corrosion rate at approximately 30% MC (Zelinka and others 2014).

The corrosion of metals in wood is greatly affected by preservative treatments; especially wood preservatives that contain copper, such as chromated copper arsenate (CCA), copper azole (CA or CuAz), or alkaline copper quaternary (ACQ) (Zelinka and Rammer 2009, Zelinka 2014). In these wood preservatives, copper ions are reduced at the metal surface, which greatly increases the corrosion rate (Zelinka and others 2010, Zelinka and Stone 2011a). In the absence of wood preservatives, embedded metals are subject to corrosion from native chemicals in the wood such as formic acid, acetic acid, and other small organic acids. Zelinka and Stone (2011b) showed that the corrosion rate in untreated wood could be partially predicted by the pH of the wood and the amount of tannins in the wood.

Corrosion rates cannot be predicted from first-principles and therefore require at least some measurements taken in the conditions of interest (Jones 1996).

Salt Damage

Salt damage occurs in porous materials in a two-step process. First, dissolved salts are imbibed into the material. At a later stage, the water evaporates, causing supersaturation and eventually crystallization of these salts. The crystallization creates internal stresses in the material, which leads to mechanical breakdown (Scherer 2004). Salt damage has been well studied in stone and masonry materials. In these materials, salt crystallization causes cracks to form within the material, which causes the surface to fall off and the mechanical properties to be weakened. In wood, much less is known about the exact mechanisms of salt damage and the extent that salt damage weakens wood (Parameswaran 1981, Johnson and others 1992). Salt-damaged wood is easily identifiable by its characteristic "fuzziness", resulting from wood fibers separating into long strands (Kirker and others 2011).

During the inspection, NPS shared documentation from the mid-20th century indicating that at one point, 540 kg (1,200 lb) of salt were placed in the bilge of the *Eureka* as a wood preservation technique. The bilge of the *Eureka* was thus exposed to salt from the inside of the ship during the salt packing and also through seawater seepage from the outside of the ship.

Biodeterioration

When wood is in the presence of moisture and oxygen, it is subject to biodeterioration from fungi and to a much lesser extent bacteria. Molds grow on the surface of wood but do not impact strength, whereas wood decay fungi are able to degrade the structural components of wood. The following is a general overview of the different fungal types found on wood and how they are diagnosed (Fig. 1).

Mold fungi

Mold fungi grow on the surface of wood but do not actively digest the wood structure. They can cause allergic reactions and discolor paints and coatings but do not significantly degrade any of the structural components (Alexopoulos and others 1996). The colorations of mold colonies are typically

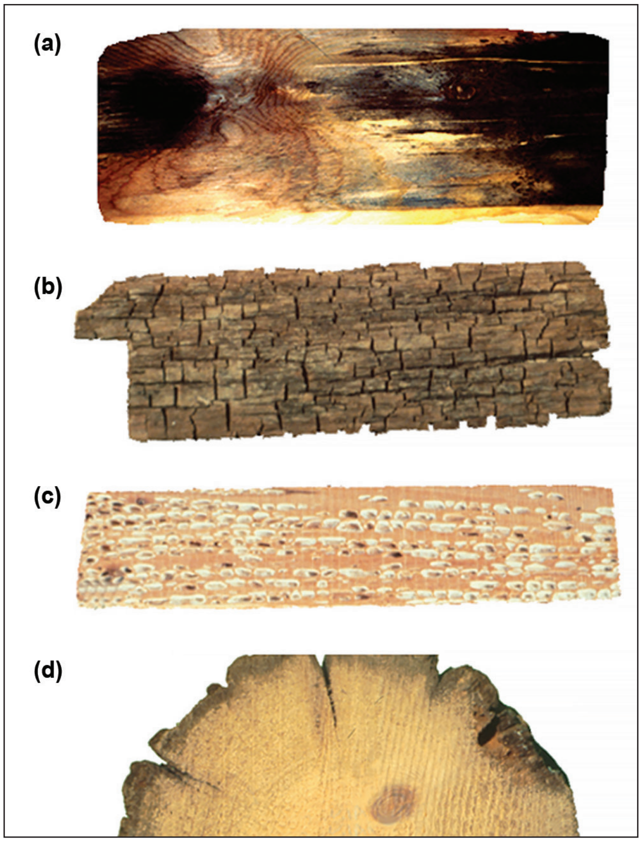

Figure 1. Characteristic images of biodeterioration on wood: (a) mold fungi; (b) brown rot fungi; (c) white rot fungi; (d) soft rot fungi.

caused by the presence of multitudes of pigmented spores that can easily be spread by wind or water. Mold fungi are extremely common and are frequent in areas of high moisture and low air flow.

Brown rot fungi

These fungi are classified as basidiomycetes "true fungi". They produce enzymes and other compounds that break apart and digest cellulose from within the wood structure (Arantes and Goodell 2014). Wood with advanced brown rot has a rusty, cubical pattern on the surface that is mainly the remaining lignin matrix with most of the cellulose removed. Because these fungi are degrading the cellulose, rapid strength losses and structural failures are often associated with brown rot fungi. Brown rot fungi are often associated with softwoods, but they can degrade hardwoods as well (Highley 1987).

White rot fungi

These fungi mostly belong to the basidiomycete fungi, but some are classified as ascomycete fungi "sac fungi" (e.g., *Xylaria hypoxylon*). White rots have more specific enzyme systems that can break down both the lignin and cellulose in the wood. White rots are further split into selective or simultaneous based on their modes of decay. Selective white rots form localized pockets of decay in the wood cell wall, whereas simultaneous white rot fungi degrade both components at the same time. Severely white-rotted wood has a stringy bleached appearance and breaks off in stringy pieces (Schwarze 2007). Rotten firewood is a usually a good example of white-rotted wood. White rots typically impact hardwood species but can cause some decay of softwoods.

Soft rot fungi

These fungi are usually ascomycetes and are often associated with higher moisture contents and high amounts of available nitrogen. Soft rots form localized pockets of rot in the S2 layer of the inner cell wall that can be severe. Soft rot typically occurs in water-soaked wood at the surface of the wood and results in gradual erosion of the wood surface. Advanced soft rot can lead to in-place failures of wood (Savory 1954).

Observations

Observations were taken at two locations in the bilge of the *Eureka* (Fig. 2). The analysis area in the aft of the ship in the bilge below the deck area was referred to as the "junior's hold". There was no similar term for the analysis area in the forward bilge.

Visually, the bilge in the aft of the ship was in better condition. There was less standing water in this bilge. Also, there were new wood beams that had been added to support the deck above. This was important because there were signs of structural failure of some of the old (original) joists (Fig. 3).

The forward bilge had several inches of standing water. According to the park service staff, there was no bilge pump in this section of the ship and there had not been a bilge pump for several years. In this section of the ship, there were large formations of a white substance (assumedly a result of corrosion) on top of each of the large metal bolts in the keelsons (Fig. 4). There was also a section on the ceiling planking of the ship that was exhibiting brown rot decay (Fig. 5).

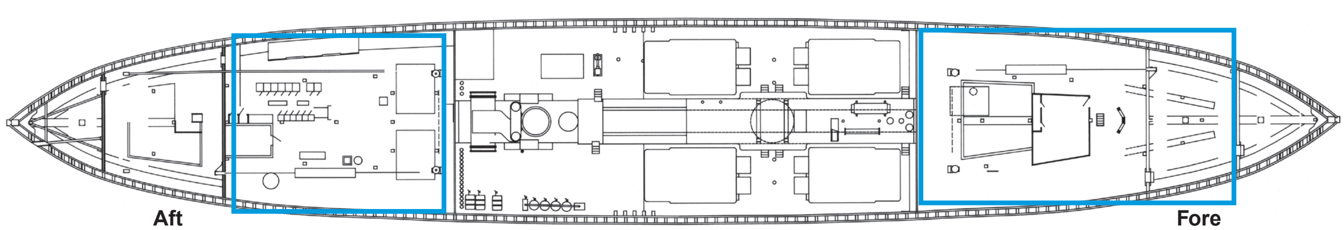

Figure 2. Rendering of the *Eureka*. The blue boxes indicate the areas of the bilge that were analyzed.

Figure 3. (Left) New structural members to hold up deck; (Right) Structural failure of old wooden beams caused by salt damage.

Figure 4. White corrosion product on top of metal fasteners in the forward bilge.

Figure 5. Brown rot decay on ceiling planking (side wall) of forward bilge.

Wood Moisture Content

Wood moisture content is the most important environmental variable affecting corrosion, biodeterioration, and salt damage. The corrosion rate of embedded metals increases rapidly as moisture content increases above 15% and eventually plateaus at a maximum corrosion rate at 30% MC. The optimal wood moisture content for fungal growth is 40 to 80% (Griffin 1977). Salt damage occurs because of fluctuations in moisture.

A Delmhorst (Towaco, New Jersey) RDM3 electrical resistance moisture meter with 75-mm (3-in.) insulated pins was used to measure the wood moisture content. The probe was configured such that measurements could be taken at various depths. Measurements were taken throughout both bilges of the *Eureka*. However, in most of the measurements, the meter read "MAX", indicating that the wood moisture content was greater than or equal to 60% (it should be noted that resistance moisture meters are very inaccurate for readings above 30% MC and all readings above 30% are an estimate (James 1963)).

We believe that resistance moisture measurements were affected by the unusually high amount of salt in the wood. The moisture meter depends on a relationship between electrical conductivity and wood moisture content for a given species. All of the wood in the *Eureka* showed clear signs of salt damage; this additional salt in the wood makes it more conductive, causing the calculated moisture content to be higher than the actual moisture content. Because of the high amounts of salt present in the wood of the bilge of the *Eureka*, electrical measurements of the wood moisture content were inaccurate.

Instead, the moisture content was determined from increment cores (Fig. 6) taken from various locations in the bilges of the *Eureka* (Fig. 2). Increment cores were collected and bagged immediately. The cores were weighed, oven-dried, and reweighed back at FPL.

Figure 6. Increment core being taken on a keelson near two corroded bolts that were identifiable by white corrosion product blossoms.

In total, 16 gravimetric moisture content readings were taken. The moisture contents ranged from a low of 17% in the ceiling planking of the ship to a high of 88%, which was taken in one of the keelsons near a salt pile. The mean moisture content was 45%; the median was 34%. The measured wood moisture contents were in the range in which corrosion and biodeterioration are likely to occur.

Remote Monitoring of Temperature, Humidity, and Wood Moisture Content

Eleven temperature and humidity sensors were deployed throughout the *Eureka* for one year. Seven sensors were in the fore bilge, three sensors were placed below the deck but above the bilge, and one sensor was placed on the deck. Additionally, five sensors that could measure temperature, humidity, and wood moisture content (through an electrical resistance measurement) were deployed in the forward bilge. As with the wood moisture contents measured with the Delmhorst sensor, the moisture content readings from the remote sensors were influenced by the high amount of salt in the wood.

Figure 7 shows the daily average temperature in the forward bilge during the observation period (October 2015 to October 2016). The temperatures were averaged because the temperature differences between the sensors were insignificant.

Figure 8 shows the wood moisture content (averaged on an hourly basis) at five different locations in the forward bilge during the same time period. The sensors cannot read moisture contents above 40%. There was very little movement in the moisture readings throughout the year. All of the moisture readings were above the threshold moisture content for wood damage mechanisms such as corrosion and biodeterioration (Jakes and others 2013). The moisture content was highest in the salt piles near the keelsons and lowest in the posts. It should be noted that salt in the wood will increase measured moisture content by an unknown amount relative to the true, gravimetric moisture content.

Figure 9 compares the average hourly relative humidity (RH) in the forward and aft bilges with the RH on the deck of the ship. Large fluctuations in RH on the deck caused some fluctuations in the bilge. However, the fluctuations were severely dampened. The variations in RH in both bilges responded to changes in RH on the deck in the same way. However, for all measurements, the RH in the aft bilge was lower (by about 5%) than that in the forward bilge.

Evaluation of White Deposits and Salt Damage

To further evaluate and identify damage mechanisms in the *Eureka*, increment cores were taken of the wood and analyzed using scanning electron microscopy (SEM). In

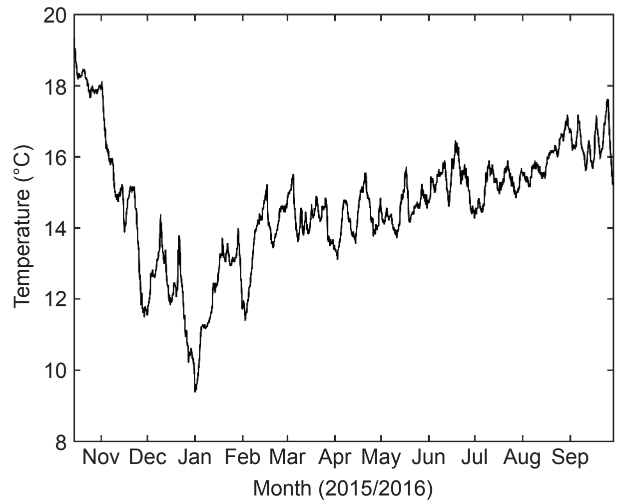

Figure 7. Hourly average temperature in the forward bilge of the *Eureka*.

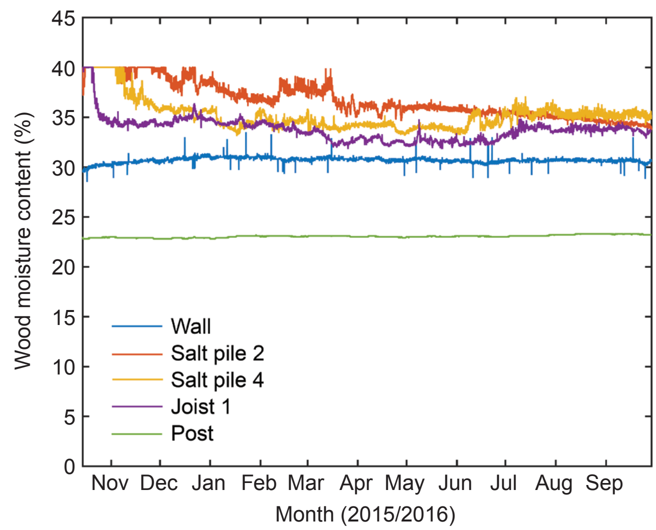

Figure 8. Hourly average wood moisture contents (measured using the electrical resistance method).

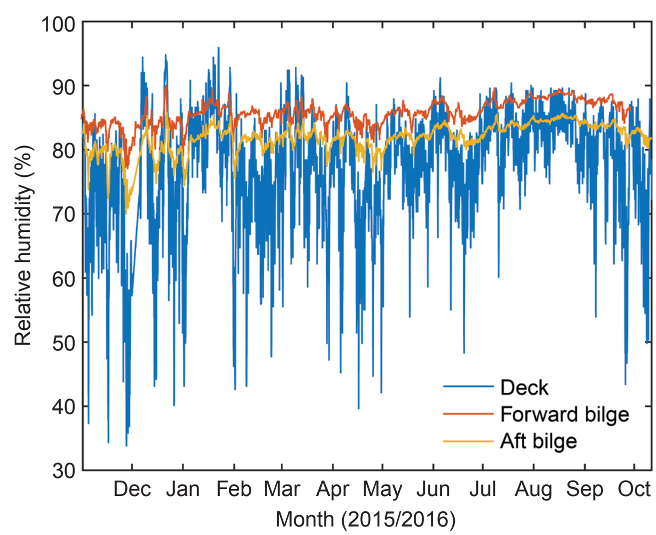

Figure 9. Hourly average relative humidity measurements on the deck of the ship (blue) and in the forward (orange) and aft (yellow) bilges.

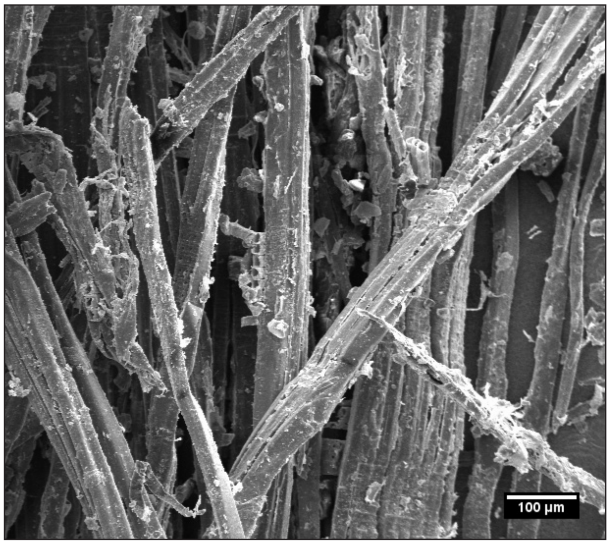

Figure 10. Scanning electron micrograph of salt-damaged wood taken from a joist in the forward bilge.

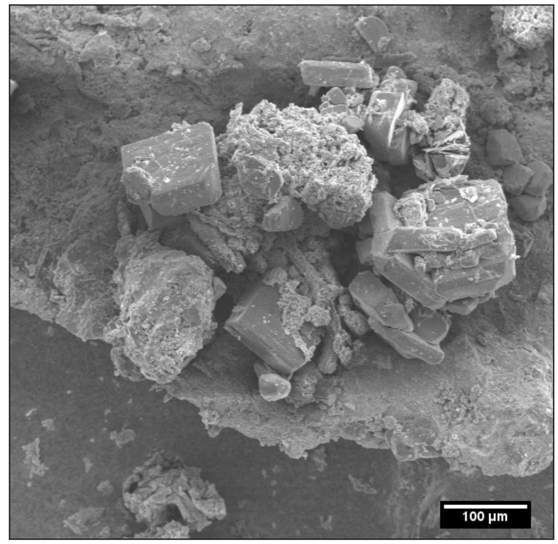

Figure 11. Scanning electron micrograph of a white deposit on top of a corroded fastener (also shown in Fig. 4).

addition, some of the white deposits were also collected and analyzed with SEM.

Figure 10 shows an SEM micrograph of the wood taken from one of the salt-damaged joists (Fig. 3). The SEM shows classic signs of salt damage; the tracheids are separated from each other and embrittled. The embrittlement can be detected by fractured tracheids. The "fuzzy" appearance of the salt-damaged wood in Figure 3 comes from large agglomerates of these separated tracheids. The salt damage can also be observed by salt crystals, which appear as cubes along the tracheids. As part of the SEM analysis, energy dispersive x-ray spectroscopy (EDS) was performed to identify the elements present. In addition to carbon and oxygen, the wood sample in Figure 10 contained large amounts of sodium, calcium, and chlorine, further confirming salt damage in the wood.

Figure 11 is an SEM micrograph from the white corrosion deposit (Fig. 4). The white deposit appeared mostly amorphous but contained some cubic crystals. EDS confirmed that the cubic crystals were indeed crystals of rock salt (NaCl). The amorphous region was predominantly sodium chloride with iron in it as well (presumably from the corroded fastener underneath the surface).

Corrosion Rates

During the inspection, ten carbon steel nails were driven into wood members throughout the bilge of the *Eureka*. Prior to insertion, the nails were weighed and the surface areas determined with the method of Rammer and Zelinka (2010). The nails remained in the bilge for one year (from October 2015 to October 2016) and were then removed by prying them out with a hammer. Only five nails were able to be recovered without damage.

The measured corrosion rates are shown in Figure 12. The nails were driven at similar locations to the wood moisture content probes (Fig. 8). The amount of corrosion exhibited in the fasteners increased with increasing wood moisture content. Two of the recovered nails were driven into posts; these nails had the lowest rates of corrosion. The nails that were driven into the ceiling planking and the joist within the forward bilge both had similar amounts of corrosion. The most corrosion was observed for the nail driven into the keelson near a salt deposit.

The corrosion rate measured near the salt deposit was 40 µm yr^{-1}. For reference, the corrosion rates of steel embedded in preservative-treated wood in a 100% RH environment were less than 35 µm yr^{-1} (Zelinka 2014). Therefore, the keelsons in the *Eureka* represent a relatively severe corrosive environment for the large embedded bolts.

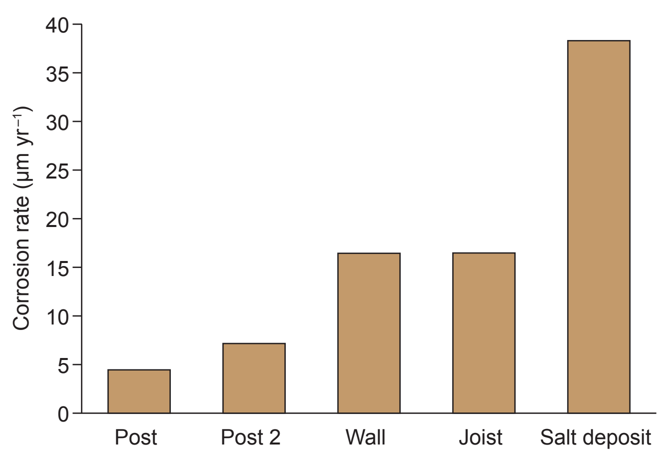

Figure 12. Corrosion rates of carbon steel fasteners measured at various locations in the bilge of the *Eureka*.

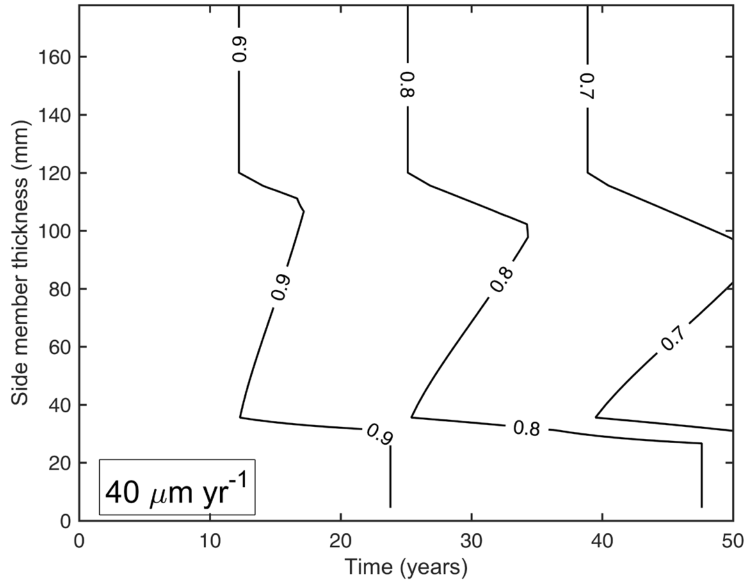

Figure 13. Estimated loss in lateral strength of the bolted connection as a function of time and wooden side member thickness. Each line represents a 10% loss in capacity.

However, the strength loss depends on not just the corrosion rate but the bolt diameter, bolt length, and wood material properties. A corroded bolt (19 mm in diameter and 350 mm long) was discovered in the bilge of the *Eureka* near a salt pile. If that is representative of the other bolts in the keelson, we can calculate the effect of the corrosion on the remaining strength of the bolt using the method of Zelinka and Rammer (2012). This analysis is shown in Figure 13, which presents lines that represent a 10% decrease in the lateral capacity of the joint as a function of time and side member thickness. The lines are not straight because the failure mode changes as the wooden side member thickness changes. The analysis shows that after 50 years, the bolted connection still had between 60% and 70% of its original strength.

It should be noted that the analysis in Figure 13 was based off a single corrosion rate measurement and the bolt geometry taken from a bolt found within the bilge that may or may not be representative of the actual fasteners used in the *Eureka*. This is an estimate of the remaining strength of the bolted connections, and the actual residual capacity of bolts within the *Eureka* may be greater or less than this.

Discussion and Recommendations

This report covers a preliminary investigation of the condition of the wood inside the *Eureka*. During the inspection, extensive salt damage was found throughout the bilge of the *Eureka*. Standing water was found in both bilges, and the RH in both areas was extremely high. As a result, the wood in the bilge of the *Eureka* was dangerously wet and is in the optimal range for corrosion and fungal activity. Failures may occur if mitigation techniques are not taken.

To preserve the *Eureka*, moisture needs to be removed from the bilge. Standing water needs to be removed. Furthermore, the high humidity in the bilge also needs to be controlled. In most modern commercial ships, active dehumidification systems are used to control moisture in the bilge. An active dehumidification system could be placed in the *Eureka* to keep the wood members at an acceptable moisture content and control salt damage. To prevent further salt damage in the wood, the RH in the bilge should be kept below 70% (Price and Brimblecombe 1994).

The current state of the *Eureka* is ideal for conducting several valuable experiments aimed at understanding mitigation techniques and what types of rehabilitation will be most effective in the next dry-docking cycle.

- Corrosion: Currently, the *Eureka* is exhibiting ideal conditions for corrosion of metal fasteners. A corrosion test could be conducted by driving nails made from different metals into the wood. This could result in actual corrosion rates (in μm yr^{-1}) for different metals in the *Eureka*. This information could be used to select the bolt material during the next dry-docking of the *Eureka* and also be used to predict how many years those fasteners will last in the rehabilitated *Eureka*.
- Salt Mitigation: It appeared that the posts in the bilge of the *Eureka* were painted; these posts appeared to have little salt damage and also had lower wood moisture contents than other parts of the ship. The bilge of the *Eureka* could be used to conduct in situ experiments with different sealing materials to compare how well

they could keep the wood dry and free of salt damage. Effective coatings could be deployed on the next dry dock.

- Dehumidification: Because the ship is almost a mirror image of itself and both the fore and aft bilges contained excessive moisture, a commercial dehumidification system could be installed in one of the two bilges, allowing comparative measurements of the effectiveness of the dehumidification system and also allowing the condition of the wood to be examined as it dries out with the dehumidification system. If the system dries the wood to a level where salt damage and biodeterioration are no longer a concern, a permanent dehumidification system could be deployed in the next dry-docking of the ship.

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