Conservation of the RMS *Titanic* "Big Piece": A Case Study and Critical Evaluation

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The salvage and treatment of a significant section of the *Titanic* illustrate the great logistical and technological challenges associated with the conservation of a monumental iron artifact recovered from a marine environment.

Introduction

The RMS *Titanic* is one of the most storied sea vessels in history. Despite sinking a century ago, this massive ship continues to captivate the curious public and vested professionals alike. As the now-familiar history goes, while en route from Belfast to New York, the *Titanic* struck an iceberg. The impact compromised rivet seams in a section of the hull, creating a 32-foot-long gash below the waterline. Under substantial stresses, rivets failed, seams parted, plates cracked, and compartments filled with water, ultimately leading to the sinking of the ship on April 15, 1912. Lost for decades, the wreck site was discovered in 1985, miles below the surface of the North Atlantic Ocean and more than 300 miles southeast of Newfoundland. The hull fractured into two main sections and sank to the ocean floor, landing nearly 2,000 feet apart. As they spiraled downwards, their contents scattered, forming what is referred to as the debris field.

In 1998 a 20-ton fragment of the hull was recovered from the wreck site. The fragment was subsequently identified as shell plating from two empty first-class suites, C-79 and C-81, just forward of the central section of the hull (Fig. 1).[1] Following recovery, the fragment was subdivided into two pieces of unequal size, which are known anecdotally as the "Big Piece" and the "Little Big Piece." The Big Piece is a 17-ton artifact that measures 25 feet by 12 feet and consists of three steel plates, each approximately 1 inch thick, riveted to each other and to eight segments of the original steel frame. Four bronze portholes, three of which retain glass, and a lead methane pipe are part of the piece. In some locations original paint still survives.[2]

This paper discusses how the treatment of the Big Piece evolved over the course of nearly a decade, a period during which the authors had several opportunities to reevaluate and re-treat the artifact. The discussion is placed within the context of several larger themes, including the emergence of new iron and steel materials and fabrication methods at the turn of the twentieth century; substantial metallurgical and forensic testing performed on this artifact; and the challenges associated with recovery of this and similar large-scale marine artifacts. The paper summarizes the treatments performed, which included both traditional and novel meth-

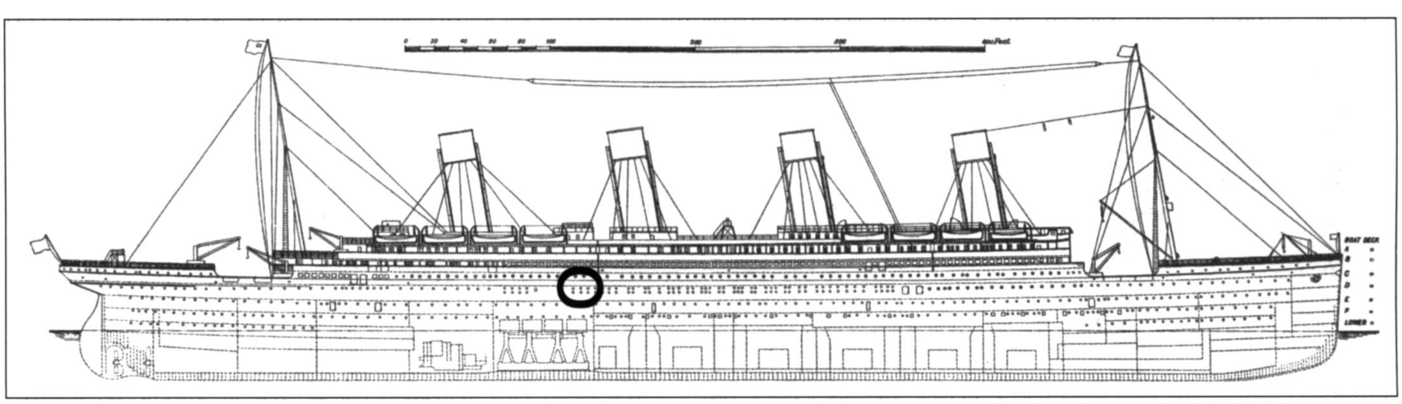

Fig. 1. Diagram illustrating the approximate location of the Big Piece on the RMS *Titanic*. All images by Joseph Sembrat, unless otherwise noted.

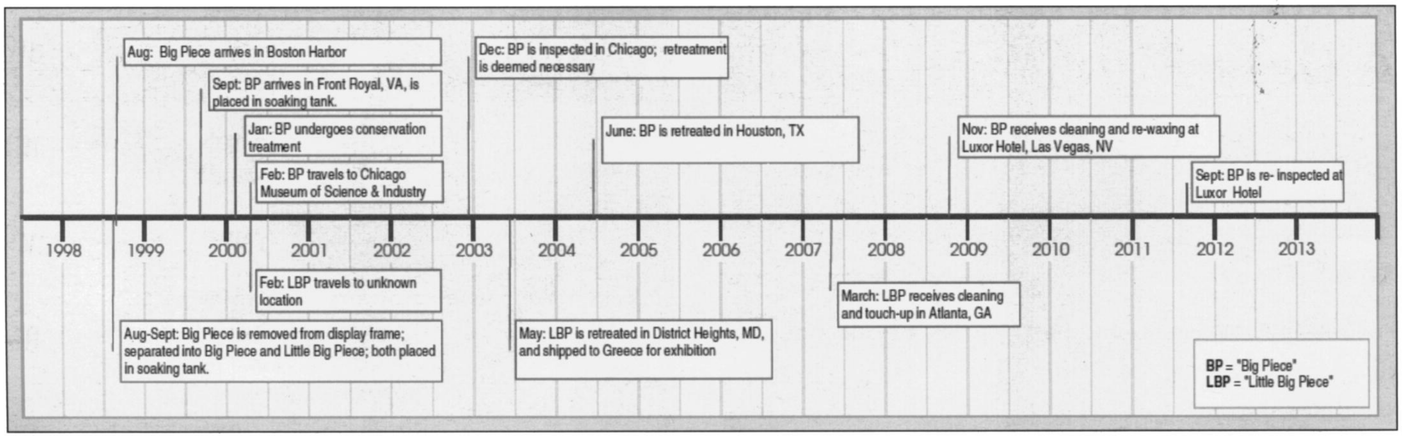

Fig. 2. Timeline of milestones in the recovery and treatment of the Big Piece.

ods, and the reasons for which they were selected (Fig. 2). Finally, the authors evaluate the efficacy of select treatments with the advantage of hindsight, given the curatorial and conservation parameters specific to this project.[3]

Turn-of-the-Century Shipbuilding: Materials and Fabrication

The *Titanic* was one of three White Star Line "Olympic-class" liners constructed by Harland & Wolff in Belfast in the first decade of the twentieth century. Each was touted as having the best the world could offer in a passenger sea vessel: speed, luxury, modernity, and safety. The *Titanic* boasted a length of 883 feet and a gross weight 46,329 tons; contained 3 engines, 29 boilers, and 159 furnaces; and carried more than 2,100 passengers on her maiden voyage.

The Olympic class was conceived during a period of intense competition between Great Britain, Germany, and America for domination in transatlantic transport.[4] Shipbuilding technology was in the midst of being transformed from an industry of manpower to one dominated by the machine. Materials were also changing: wrought iron, used only to clad wooden hulls in the early part of the nineteenth century, was being used with steel in all parts of shipbuilding by the late nineteenth century. Steel-built hull design was common to the industry by the late 1880s; the British Standards Institute followed this trend and officially approved open-hearth steel for rivets and plates in 1906.[5]

The hull of the *Titanic* was constructed of more than 2,000 rolled mild-steel plates 1½ inches thick, 30 feet long by 6 feet wide, triple-layered, and stitched together with more than 3 million rivets in distinct configurations. The design specified double-riveted lap and butt joints for seams at the bow and stern sections. Triple- and quadruple-riveted overlapping joints added strength in the central section, where the ship had to withstand the greatest stresses. Specifications called for hydraulic-machine-driven mild-steel rivets to be used throughout the ship wherever possible; hand-hammered wrought-iron rivets were to be used in construction of all frames and anywhere machine riveters could not be used due to restricted clearance. In general, steel rivets were used in the central hull and deck plates, and wrought-iron rivets were used in the bow and stern plates.[6]

The various types and mixed use of rivets in the construction of the *Titanic* is an indication of how this ship straddled a metallurgical and technological frontier and illustrates a number of competing industrial and economic forces that were at play. Although steel had become the primary hull-plate material in the first years of the twentieth century, wrought iron still held onto a place in shipbuilding. Due in large part to its ductility, wrought iron was reasonably easy to hammer, shape, and form by hand. This workability, combined with its tensile strength, made it a favorable material for rivets in all types of construction of the time, from ships to bridges to buildings. However, shipbuilders had begun transitioning from wrought-iron to steel rivets for the greater strength of the steel rivets. Innovations in the manufacturing of steel meant that its prices were falling at a time when the cost of wrought iron was increasing. Unlike wrought-iron rivets, which had to be installed by hand, steel rivets could be installed by machine, which reportedly increased construction rates twelve-fold. Although labor was generally cheap, a sufficient and reliable pool of skilled labor needed to construct these ships was hard to come by. Therefore, a mechanical innovation such as this appealed to shipbuilders working on compressed timelines with limited resources, further accelerating the technological migration to steel.

Recovery and Research

The discovery of the *Titanic* in 1985 renewed a flurry of interest in the ship, both in popular culture and in scientific communities. Nearly all shared an interest in what sank the *Titanic*. A series of early expeditions by various parties recovered thousands of artifacts, which fueled some early independent research, conservation, and metallurgical testing.[7] However, in an attempt to answer the question as to the cause of the catastrophe, as well as to meet numerous other goals in a more comprehensive way, RMS Titanic, Inc.— the salvor-in-possession — and other invested parties led an expedition to recover a substantial section of the hull in 1996.[8] In this first recovery attempt, the piece was raised to within 200 feet of the surface when retrieval had to be aborted.

Fig. 3. The Big Piece shortly after it emerged from the sea aboard the recovery ship, 1998.

Fig. 4. A surviving bronze porthole and rusticles, which remained intact on the surface of the Big Piece, shortly following recovery, Boston, Mass., 1998.

Although the desired hull piece could not be raised at that time, iron and steel recovered from the wreck site enabled the first authorized forensic testing on the *Titanic*. The team returned to the wreck site in 1998 for a second recovery attempt, tantalized by the opportunities for the continued research that a portion of the hull would allow. On August 10, 1998, the artifact was successfully raised by attaching diesel-filled lift bags and towlines to the element and carefully floating it to the surface, where it was winched aboard a waiting vessel (Fig. 3).[9] Researchers also collected hull debris[10] and 48 rivets, including examples of the four different rivet types: hull, bulkhead, deck, and porthole. A sample of the hull was subsequently removed for testing and also yielded five intact steel rivets.

It is difficult to overstate the importance of the Big Piece and the expeditions associated with it. These recovery ventures have provided the physical materials necessary to undertake the analyses that have provided not only a greater understanding of the role material failures played in the sinking, but have also yielded information that has been valuable in promoting the future preservation of the ship. Initial metallurgical testing and chemical analyses sought to measure the metal's strength, fracture behavior, chemistry, and microstructure to understand the relationship between the behavior of the material and the sinking of the ship.[11] Subsequent analysis focused largely on the rivets; this effort was led by Tim Foecke (National Institute of Standards and Technology, Gaithersburg, Md.) and Prof. Timothy Weils and then-doctoral student, Jennifer Hooper McCarty (Johns Hopkins University, Baltimore, Md.). Their research is documented in McCarty's doctoral thesis and in Foecke and McCarty's book, *What Really Sank the Titanic*.[12] Due in large part to their research, the quality of the rivets and riveting procedures have recently come under scrutiny and have been faulted with the rapid sinking of the vessel.

Challenges Posed by Large-Scale Marine Artifacts

Excavation, removal, or the raising of a shipwreck and its associated artifacts poses many ethical issues that must be addressed prior to any recovery operation. Not only may ownership of the site be disputed, but these vessels can be considered gravesites, serve as memorials, and/or may still contain human remains. The discovery of the *Titanic* famously sent the question of ethics before the U.S. Congress, which in turn recognized the sanctity of the wreck site and developed standards to prevent wanton looting and, through the *Titanic* Maritime Memorial Act (1986), fostered cooperative scientific and cultural research among various countries.[13]

Recovery. Recovery combines enormous feats of engineering, foresight, planning, funding, and determination to further significant research goals. Because of this substantial initial investment, recovery also necessitates a commitment to conservation, management, storage, and long-term care of the artifact, so that the vast efforts expended at the outset yield fruitful long-term results for the future study and display of the artifact. It is imperative that the condition of the artifact be adequately assessed and stabilization efforts be implemented prior to and after its recovery. Failure to do so can lead to catastrophic structural failure during the recovery and the immediate and irreversible deterioration of the object if it is not properly stabilized and stored after it is recovered.

Recovery is complicated by a number of variables. Foremost is the location of the wreck site, including its depth and remoteness. For example, the *H. L. Hunley*, a Confederate submarine, sank in 1864 in the waters of Charleston Harbor in South Carolina. It was rediscovered in 1995 and subsequently recovered in 2000. The *Hunley* was found in harbor waters only 27 feet deep; by contrast, the deep-ocean location of the *Titanic* (approximately 350 miles southeast of Newfoundland at a depth of 12,460 feet) meant that expeditions to the wreck-site were arduous and reportedly cost upwards of $300,000 per day. Recovery is also contingent on the relative fragility or stability of the artifact.[14] Despite its location in shallow waters, the fragility and sensitivity of the *Hunley* presented particularly complex engineering issues, which necessitated the design and fabrication of a dedicated lifting frame.[15] Prior to recovery, the Big Piece was assessed and determined to be a sturdy artifact that could withstand the stresses of the deep-ocean recovery.

Post-recovery treatment: methodology and logistics. Once successfully recovered and situated in a suitable environment, the overall treatment of such a large artifact can be very complex. Manipulation of and access to the artifact will likely involve aerial manlifts, scaffolding, forklifts, cranes, or even specially engineered tanks. Managing each of these variables requires a significant commitment in time and money. For example, the conservative estimate for completion of conservation of all artifacts recovered from the USS *Monitor* is not expected to occur until 2029, although conservators do "hope we can beat that by a good number of years."[16] For the Big Piece, once the challenge of raising the artifact had been conquered, the next hurdle of stabilizing and conserving it began.

The treatment to stabilize metal artifacts recovered from seawater is typically focused on removing concretions and removing chlorides (desalination) as a means of arresting the electrochemically induced corrosion process. Concretions represent a calcium carbonate precipitate that forms on the surface of an artifact and may also include silt, shells, and other sea matter. Concretions may hold chlorides themselves and may also prevent access to the underlying artifact, which has also been permeated by chlorides over the course of the period of submersion. Because the concretion shell is fairly impermeable, the physical presence of concretions can hinder the success of chloride extraction from an artifact. However, concretions can also preserve essential information for the archaeologist and conservator, and therefore should be removed only once they have been thoroughly examined.[17]

The presence of chlorides has been identified as "the major corrosion accelerator within archaeological iron."[18] Chlorides must be removed to limit further corrosion of the metal. Numerous studies have demonstrated that chloride reduction is essential to promoting the long-term stability of an artifact, while recognizing that full chloride removal may not be able to be achieved, or to even accurately measure.[19]

The *Titanic* is well known for its distinctive bio-concretions known as "rusticles." This term was coined by Robert Ballard, based on their appearance resembling a rust-colored "icicle." Rusticles are composed of up to 35 percent iron compounds, including iron oxides, iron carbonates, and iron hydroxides, and inhabited by colonies of bacteria and fungi that are intertwined with corrosion products from the ship and carbonates from the surrounding water (Fig. 4). While typical ocean concretions may act much like an impermeable shell around an artifact, inhibiting ion exchange and slowing corrosion rates, rusticles are, by contrast, quite friable, extremely porous, and hygroscopic.[20] The shell can create a microclimate over the surface, allowing the substrate to continue to corrode unseen. Further, the presence of sulfate-reducing bacteria (SRB) can create locally corrosive conditions that aggravate attack: SRB can lower the pH of seawater from 8 to as low as 4, thus significantly increasing the rate of corrosion.[21]

Stabilization methods. In the planning of appropriate stabilization methods to be used for the Big Piece, conservators began with the evaluation of the most traditional methods used to treat similar large iron artifacts. The majority of methods below were employed in the initial treatment program from 1998-2000 and/or re-treatment in 2004.

Mechanical cleaning constitutes manual de-concretion of the artifact both prior to other cleaning methods and intermittently throughout the stabilization process. Mechanical cleaning is likely to involve a variety of hand tools, including stainless-steel scalpels, picks, chisels, etc. Such cleaning is time- and labor-intensive and has the potential to result in accidental damage to the underlying substrate. Although the extent of de-concretion can vary, some degree of mechanical cleaning will likely be necessary before any other treatment occurs.

Non-destructive imaging (film radiography, digital radiography, etc.) is sometimes performed on a concreted artifact prior to mechanical cleaning to determine how much of the artifact actually remains within the shell. In the case of the Big Piece, no imaging was performed, due to the fact that selective probes and test areas demonstrated that the substrate was stable and that no portion of the artifact had become fully encapsulated. Further, rusticles are softer than typical concretions, and it was possible to remove this material with much less effort than a concretion; thus, mechanical cleaning and crust removal posed less of a risk to the artifact overall.

Passive soaking is a desalination method whereby the artifact soaks in an alkaline bath, which neutralizes the metal surface, significantly slowing the corrosion rate. Chlorides diffuse out of the artifact and into the electrolyte solution. Sodium carbonate (Na_2CO_3) is the preferred electrolyte (5 to 10 percent).[22] Alternate solutions of sodium bicarbonate (baking soda) and sodium sesquicarbonate have also been used, with varying results. Passive soaking is a slow process that may take several years to complete, require regular monitoring of the artifact and bath water, and refreshing of the solution. As discussed below, the efficiency of passive soaking can be increased through the use of sacrificial anodes and electrolysis.

The installation of sacrificial anodes is a low-impact treatment meant to arrest ongoing corrosion of an artifact, either in situ or during passive soaking (Fig. 5). To that end, a more highly reactive piece of metal (anode) is attached to the artifact (cathode), in the presence of an electrolyte. In situ, the electrolyte is seawater itself; in passive soaking, the electrolyte is typically sodium carbonate. In this system, the anode deteriorates preferentially, thereby providing protection to the artifact.

Electrolysis is a method of desalination that operates on principles similar to those of sacrificial anodes, but it introduces an applied electrical current from a direct-current (DC) power supply to the cell. Chlorides and other anions are drawn from the artifact toward the positively charged anode (usually type 316 stainless-steel mesh) by electrolytic attraction. One of the advantages of this system is that the externally applied electrical current can be controlled to effect different results, such as to promote more or less aggressive cleaning.[23]

Fig. 5. Sacrificial anodes (indicated by arrow) attached to the Big Piece to help facilitate the extraction of chlorides during the soaking process of the compromised artifact, Boston, Mass., 1998.

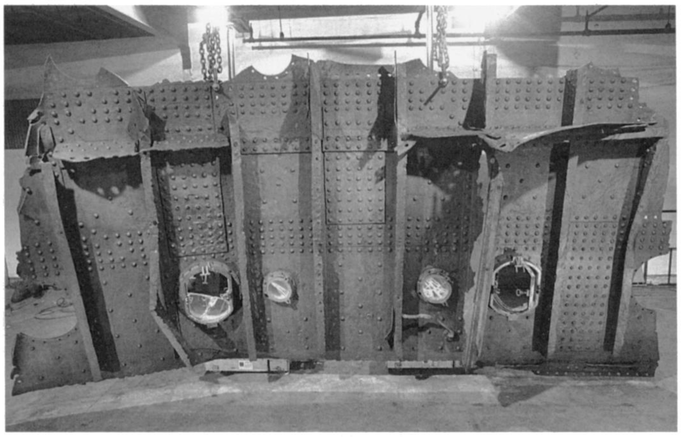

Fig. 6. The interior of the Big Piece, following completion of initial treatment in 2000, Front Royal, Va.

However, despite the applied current, months or, more commonly, years of closely monitored electrolysis are often necessary to stabilize an artifact satisfactorily.[24]

Steam, low-pressure (<2,000 psig), and medium-pressure (2,000–4,000 psig) water-jetting are often used by conservators for rinsing, cleaning, and corrosion removal. All methods can be useful to assist in the removal of concretions. The flooding of microscopic surface pits using medium-pressure water can also assist in flushing away surface contaminates, such as soluble salts.[25]

Ultra-high-pressure (UHP) water-jetting is a technique that the authors and other conservators have extensively researched and demonstrated as a viable method for the removal of both existing coatings and surface soluble salts without damaging the underlying metal or necessitating use of additional chemicals. UHP is an optional tool that may be used in combination with other treatment methods to augment chloride removal.[26]

The authors have also investigated the use of ultrasonic cleaning methods to facilitate concretion removal and chloride extraction, performed most recently and successfully on select objects recovered from the wreck site of the RMS *Carpathia*, the very ship that rescued survivors from the *Titanic*.[27]

Cleaning may be further facilitated through the use of chemical rinse aids (CRAs), which are simply additives to wash water used to assist in cleaning. Industrial CRAs used in the steel industry are generally designed to assist in degreasing, removing chlorides and chloride compounds, and preventing flash rust. The active agents in industrial CRAs may consist of patented mixtures of amines, surfactants, and acids. CRAs should be used on artifacts only following extensive testing. The authors have worked directly with chemical manufacturers to select and modify material-appropriate CRAs.

Initial Treatment Period: 1998-2000

Investigating a range of potential treatment techniques was only one of several significant hurdles involved with developing a comprehensive plan for the conservation of the Big Piece. Logistically, treatment posed several challenges from the time it was received at the Boston harbor. Because the Big Piece was so difficult to handle and maneuver, it was decided to separate the artifact into what were to be two more manageable sections. Determining how, when, and where to perform this separation was another hurdle that needed to be overcome. This decision proved successful in terms of facilitating handling, display, and treatment. Treatment was implemented on the Big Piece and Little Big Piece as separate artifacts, but in an identical manner, during this initial phase. Each piece subsequently followed a separate exhibition trajectory, and it is unfortunate that they were never again displayed together.

The second-biggest challenge encountered was the expectations of the client, RMS Titanic, Inc., as to how long it should take to properly desalinate and conserve the artifact. Although other *Titanic* artifacts had gone through similar treatments, the client was extremely eager to display and capitalize on its greatest find. As a result, extensive discussions arose concerning the client's wish that the piece(s) be on display during the desalinization process; about how the pieces were to be displayed; and about the fact that it would be necessary to remove them from their alkaline environment during times of transport from venue to venue in an unclimatized vehicle. There were also points of contention regarding the sacrificial anodes that were necessary to help expedite the chloride-extraction process but that were considered unsightly. Ultimately, the parameters set by the client and presented to the conservators were that the piece(s) would be placed on a display stand; that the sacrificial anodes could be visible; and that caustic water sprays would be needed to keep the pieces continually wet instead of fully immersing them in a soaking tank.

Given these stipulations, conservators proceeded with desalination. They established baseline chloride levels, both on the surface and internally. Filings collected when sacrificial anodes had been attached to the artifact were analyzed to determine the depth of chloride penetration. Findings from these tests determined that the salts were contained to the rusticle crust layer, outer surface pits of the metal, and crevices, and that they had not migrated deeply into the substrate.

Even given the fact that the presence of chlorides was, fortunately, concentrated near the metal surface, the use of water sprays proved to be an ineffectual method of desalination; it also posed a safety risk to the viewing public, since the fine caustic mist generated by the spray heads drifted with the slightest breeze. This approach was abandoned shortly after it was implemented (approximately one month), and the pieces were placed in a large soaking vessel (an above-ground swimming pool) filled with a 4- to 5-percent solution of sodium carbonate and allowed to soak intermittently for a total of 16 months. During this time the pieces traveled to several different venues, which required that the pool be drained and that the pieces be transported on an unclimatized flatbed truck. Towards the end of this time the pieces were transported to a conservation facility in Virginia, where they were allowed to remain in the soaking vessel undisturbed for four months. Chloride concentrations were monitored using an Orion conductivity meter and Merck Quantab titrators throughout the soaking process. Make-up water and sodium carbonate levels were adjusted as needed.

At the end of the soaking period, the pieces were removed from the vessel; the sacrificial anodes were removed; and all surfaces were treated using waterjets operating at 3,000 psig. Rusticles were removed to the pre-determined extent, using pressurized water and rotating nozzles down to a stable layer but not down to the metal substrate. Crevices and interstitial areas were mechanically cleaned using picks and scalpels and then cleaned again with the waterjets. At this point in the treatment, the pieces should have been returned to the caustic bath and allowed to soak for an additional period of time, but the client decided that the pieces should be prepared for exhibition immediately.

In order to protect and stabilize the metal surfaces, the iron components of the pieces were heated and treated with a 5-percent tannic acid solution to help convert iron-corrosion products to a more stable state. Loose fragments of the hull were fastened with ferrous hardware to help secure them for transport and display. Iron stains on the glass were removed or reduced using multiple applications of a 3-5 percent solution of ethylene diamene tetraacetic acid (also known as EDTA).[28] All metal surfaces were treated with a protective barrier coating of thermally applied microcrystalline wax. Once the metal cooled, the waxed surfaces were polished using Tampico natural-needle buffing wheels fitted on an electric drill (Fig. 6).

A custom-built skid was constructed, and the hull fragments were set on Ethafoam blocks to help prevent chafing and reduce the effects of vibration during transport. A wooden frame was constructed around the piece, and rubber tarps were used to protect it from the environment. No other attempt was made to climatize the environment within the enclosure.

A Reassessment and Reevaluation: 2002-2003

After several years of cyclical transportation and display, conservators were asked to reexamine the Big Piece in December 2002. This request was prompted by client observations that rusticle crusts had been delaminating and that white deposits were forming around some of the rivet heads. Where rusticle crusts had become detached, active corrosion was seen on the underlying metal (Fig. 7). A thorough surface examination was performed, and samples of rusticle/crust, corrosion products, and the white deposits were removed for qualitative analysis. Results of the testing revealed that the white deposits consisted of carbonates (residue from the electrolyte) and low levels of chlorides and were most likely emanating from between the steel plates. The active corrosion appeared to be contained to the surface of the metal and did not possess chlorides.

Conservators initially believed that unclimatized transport likely played a significant role in causing the conditions observed. Oversized as the piece is, the most cost-effective and practical way of transporting a large, heavy, and cumbersome artifact was on a flatbed truck. This scenario made it nearly impossible and cost prohibitive to climatize its environment. Conservators suspected that the environmental fluctuations to

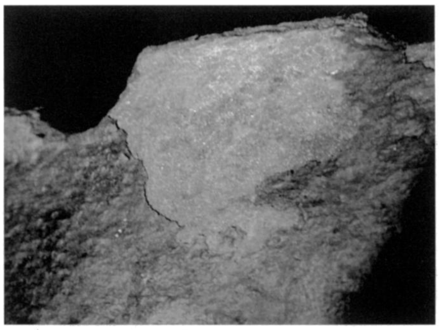

Fig. 7. An area of rusticle crust delamination, revealing the metal surface that had continued to corrode underneath, Chicago, Ill., December 2003.

which the artifact was subjected probably destabilized the crusts through cyclical swelling and shrinking and that the constant vibration of the flatbed truck likely caused rusticle crusts to detach from the substrate. Further, when samples were removed for analysis, it readily became apparent that although the wax had penetrated the porous rusticle crust, it had not saturated sufficiently through to protect the underlying steel, which continued to corrode. Chloride activity was found to be localized around rivets and in multi-plate construction.

The conservation treatment that was performed in 2000 should be considered a limited success in light of some of the obstacles and restrictions that the conservators encountered in the design and implementation of the work. It produced relatively stable and sturdy artifacts that were of excellent material quality and capable of withstanding the environmental changes to which they were subjected. However, both the conservative preservation approach and aesthetic requirements mandated by the client meant that the unstable rusticle materials had to be retained; because the rusticles are somewhat delicate formations with a tenuous hold to the underlying metal, this necessarily put the artifact at risk of rusticle loss due to the less-than-ideal transport, storage, and display environments to which it was subjected.

In hindsight there are certain aspects of the treatment that could have been performed differently and might have better promoted the long-term stability of the pieces. This includes the following alternatives:

- The pieces should have been returned to the soaking bath after the water-jetting and detailed cleaning processes.
- The addition of impressed current to the soaking bath would most likely have made the desalinization process more effective and efficient.
- More of the rusticle crust should have been removed during the initial conservation treatment. The long-term retention of the rusticle crust was largely contingent upon the artifact being transported, stored, or displayed in a climate-controlled environment. The client and conservators should have realistically acknowledged that this might not always occur; accordingly, the client should have allowed some rusticle removal at the outset.
- If more of the rusticle crust could have been removed, ultra-high-pressure (UHP) water-jetting could have been used to reduce soluble salts more effectively than the 3,000 psig pressure that had been used.
- A conservator should have been engaged to provide oversight during the many rigging and moving campaigns to limit avoidable damage.
- Once the pieces were on display, regularly scheduled inspections by a competent conservator would have identified problems earlier so that corrective measures could have been implemented in a timely manner.
- Regular maintenance would have greatly improved the aesthetic appearance of the pieces.

Re-treatment: 2003-2004

Although the treatment in 2000 preserved as much of the rusticle crust as possible, by 2003 it was agreed that the crust should be removed down to stable metal. Conservators also decided to flush all accessible interfaces between plates and around rivets to the greatest extent possible in order to remove residual chlorides. It became clear that manual scraping, picking, or pneumatic tools would not be a viable method for full crust removal, as their use was neither time- nor cost-effective. Microabrasion — cleaning using a fine abrasive blasting medium — might remove the crusts efficiently, but it was considered too aggressive and would still not have accomplished the necessary flushing and removal of salts. For these reasons, conservators looked to alternative cleaning methods.

Ultra-high-pressure (UHP) water-jetting was considered because of its ability both to offer controlled removal of rusticle crusts and to mobilize and remove soluble chlorides (Fig. 8). UHP emerged as an industry standard for metal-surface preparation in the second half of the twentieth century. UHP water-jetting technology consists of highly specialized pumps, hoses, nozzles, and accessories necessary to create and deliver water at a pressure up to 35,000 psig.[29] Pressurized water has two working components: direct impact (shear force) or erosion effect, which is controlled principally by the pressure of the stream, and hydraulic or lifting effect, which is controlled principally by the volume of the stream.

The effective design of a proper UHP cleaning protocol must balance a number of variables, including pressure as measured at the gauge (psig), nozzle design, the diameter of the opening in the nozzle for the water stream (orifice size), the angle at which the water stream meets the artifact surface (angle of incidence), the working distance between the artifact and nozzle tip, and dwell time.[30]

The conservators partnered with a team of industrial-corrosion professionals to quantify the concentration of salts on the surface and to develop a proper cleaning methodology that could be safely used to achieve the intended goals. Through testing mock-ups, it was determined that the hull could be cleaned using waterjets at 10,000-20,000 psig, depending upon the thickness of the crusts to be removed. Utilizing a rotating nozzle at a standard surface-to-tip distance of 2 to 4 inches, the high-pressure water rapidly and safely removed crusts and crust residue and unstable corrosion products. It also flushed pores, cracks, and interstices between plates with heated, filtered water. Specialty tips were utilized to introduce pressurized water into tight spaces and between plates.

Fig. 8. Ultra-high-pressure water-jetting being performed on the Big Piece, Houston, Tex., July 2004. Courtesy of Steve Dunne.

Performing UHP according to these parameters greatly reduced the amount of time conservators had to spend removing the remaining crusts by hand.[31] Fine picks were still used to remove crust and corrosion material within pits and especially between plates around rivet heads. The result was that some rivets became loose in their hole, though not entirely free, a change that actually became beneficial later in the process, as the entire rivet and the exposed edge of the plate could be coated with wax.

After cleaning, the hull piece remained uncovered for two days, allowing it time to "flash rust." This was done in part to allow the corrosion converter to achieve a uniform and dark (near black) oxidized finish, at the request of the client. The oxide layer was then stabilized with a new proprietary solution of tannic and phosphoric acids (Fertan). Use of this product effectively converted the corrosion and generated a uniformly black surface color. A chemical rinse aid (Cortec Corporation) was used near the end of the cleaning to remove excess tannic acid solution while preventing flash rust.

Following cleaning, it was necessary to remove any remaining moisture before the final protective coating could be applied. The approach was two-fold: first, surface moisture was driven off using heat from propane torches, after which the Big Piece rested in a dehumidification chamber (40-50% RH) for several weeks. When the artifact was once again reintroduced to unclimatized conditions, some salts did appear again around rivet heads, but the incidence was extremely minor. These salts were allowed to dry and were removed by vacuum, and the surrounding area was then wiped clean with ethanol. Finally,

Fig. 9. A torch being used to heat the surface in order to apply a protective wax coating, Houston, Tex., July 2004.

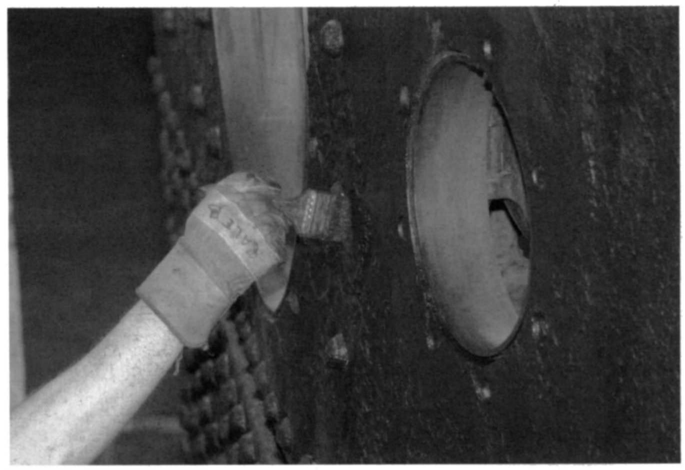

Fig. 10. The wax coating was applied by both spray and brush, Houston, July 2004.

the surface was treated again with two coats of a thermally applied microcrystalline wax (Figs. 9 and 10). The formula had been modified since 2000 and now included a solvent-based blend of contact and vapor-phase corrosion inhibitors (VpCI) (M-238, Cortec Corporation).[32] A series of minor salt blooms developed on the surface shortly after the piece had been waxed; however, the period of salt activity was extremely brief and was understood to be part of the initial acclimation of the newly exposed steel surface to the coating.

Aside from the long-term benefit of improved material stability imparted by this treatment, practical benefits were realized in the short-term, as well. For instance, the surface was now easier to clean and maintain; no rusticle crust losses were sustained during transit; and, due to the darkened surface appearance, one could more readily identify fresh corrosion if it did occur (Fig. 11).[33]

The Little Big Piece: 1998-2003 and 2007

Although it is not the focus of this study, the treatment of the Little Big Piece should also be considered for the purposes of comparison, both today and in the future. The Little Big Piece was initially treated at the same time and using the same methods and materials as the Big Piece. As it was smaller in size and weight, it was easier to transport and was exhibited throughout Europe and Asia.

In 2003 the piece was stored outdoors unprotected for several months, resulting in significant failure of the protective coatings, loosening of the concretion layers, and active corrosion in the presence of the residual salts. Failures were extensive enough to warrant re-treatment over maintenance. Conservators opted for a treatment that went further towards removal of all existing rusticle crust in an attempt to remove all potential for chloride activity in the future.

Steam was used at a temperature of 300°F to assist in the removal of existing wax. Medium-pressure water-jetting at 3,000 psig using 180°F water was used to assist in the removal of rusticle crust and to help solubilize and flush away sodium chloride salts. Mechanical cleaning was performed using dental picks and wooden skewers to remove harder rusticle accretions and debris from crevices. The surface was again water-jetted at 3000 psig using 180°F water and a 2 percent solution of a chemical rinse aid (Chlor*Rid) to help remove loose areas of the rusticle crust and to help solubilize and flush away sodium chloride salts. Areas of loose or flaking paint were consolidated with a dilute (10 to 15 percent) solution of Paraloid B-72. Conservators then treated the surface with a solution of tannic and phosphoric acids (Fertan) and applied multiple coats of a microcrystalline wax containing VpCI to a heated surface. Because its size allowed for it, the Little Big Piece was hermetically sealed in a foil bag with desiccant and crated for shipment.

Thus far, only maintenance of the Little Big Piece has been required since re-treatment. In 2007 the surface was washed with sponges, the protective wax coating refreshed and buffed, and loose paint was stabilized. The Little Big Piece continues today to travel in North America and Europe.

The overall success of this treatment in 2003 was a key factor in the decision to completely re-treat the Big Piece in 2004. Many of the materials and techniques, including water-jetting, were seen as significant improvements upon the initial treatment.

Critical Evaluation: 2008-2011

The Big Piece was exhibited at three different locations between 2004 and 2008. The first opportunity for inspection and maintenance of the Big Piece was in 2008. The conditions observed were overwhelmingly stable, requiring only surface cleaning and rewaxing. In 2008 the Big Piece was installed at the long-term exhibition space at the Luxor casino in Las Vegas. The artifact was inspected again in September 2011; this investigation confirmed the soundness of the artifact. The only notable condition observed at that time was an accumulation of dust.

The soundness of the artifact as seen in both 2008 and 2011 is likely to be a testament to improvements in the treatment design and execution, improved storage conditions, and a significant

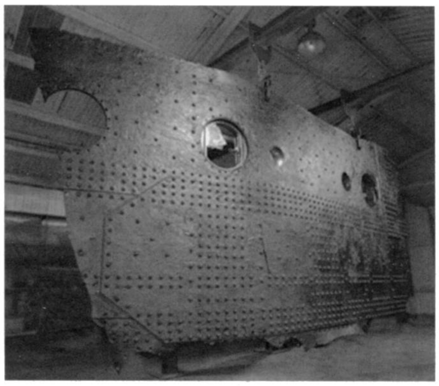

Fig. 11. The Big Piece following treatment, Houston, July 2004.

reduction in the amount that the artifact is handled and transported. The opportunity for the same conservators to reassess and re-treat these artifacts between 2000 and 2004 led to significant improvements in treatment design and technological innovation. The 2004 treatment was one of the first examples of ultra-high-pressure water-jetting that was used successfully in a conservation treatment of a marine archaeological artifact. Additionally, the use of vapor-phase corrosion inhibitors in the 2004 treatment seems to have provided an added level of protection to the artifact. The decision to substantially remove the rusticle crust eliminated a condition that would have continued to be problematic had it been allowed to remain on this artifact. Lastly, understanding the practical limitations of the environments to which these artifacts would be subjected to during transport, storage, and display helped tailor the treatment design to one that would be successful in these circumstances.

New Frontiers in Treatment Methodology

One of the greatest challenges to the conservation of recovered marine archaeological artifacts is the time necessary to properly conserve them — and, by extension, the human resources and money that need to be sustained throughout this process. Thus, one of the most exciting advancements in the conservation of marine artifacts is that of subcritical water treatment, which has the potential to significantly reduce treatment times. This methodology is currently being developed by scientists and conservators at the Warren Lasch Conservation Center at Clemson University, in Charleston, South Carolina, where this research was driven by the *H. L. Hunley* project. Subcritical water is heated and pressurized to a temperature between 100°C (normal boiling point) and 374°C (critical point). As water temperature increases, its viscosity decreases, while the rate of chloride diffusion increases. Research to date demonstrates that the use of subcritical water solutions dramatically increases the rate and efficiency of chloride ion removal, significantly reducing treatment times of both cast and wrought iron. This effect may be further accelerated by the use of an alkaline solution.

However, because treatment requires submersion in a suitable pressure vessel, there are strict limits to the size of the artifact that can be treated. Expanding this technology to treat large-scale metal artifacts remains daunting. Challenges are myriad and include the financial and logistical issues associated with building, housing, and maintaining a sufficiently large treatment vessel. There may also be difficulties associated with handling and manipulating such large, heavy artifacts, particularly those whose stability may be questionable or compromised due to advanced deterioration.[34] If subcritical water treatment can successfully be scaled up to treat larger artifacts, the potential for reducing treatment times as compared to passive soaking or even electrolysis is enormous. Until that time, the proper treatment of similar large-scale artifacts is likely to remain a fairly slow process.

Conclusions

The desire to recover a significant portion of the hull of the RMS *Titanic*, for both study and exhibit, was finally realized in 1998. Through the combined efforts of hundreds of professionals, the retrieval and conservation of the Big Piece has been a source of the physical material for analyses that have provided a greater understanding of the tragedy of her sinking. It is an important artifact that illustrates history in a way that both inspires and humbles the viewer. However, the Big Piece has acquired its own complicated history of challenges along the way. The multi-campaign conservation process to preserve the Big Piece and make it available for exhibit to the public has led to significant advancements in treatment design and technology that can now be evaluated by other conservators for use in the large-scale metal maritime artifacts.

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Notes

1. Susan Wels, *Titanic: Legacy of the World's Greatest Ocean Liner* (New York: Time-Life Books, 1997), 152-169.

2. Joseph Sembrat, Patty Miller, and Lydia Frenzel, "Use of Waterjetting in Conservation of Historic Structures," The Society for Protective Coatings and Painting & Decorating Contractors of America (SSPC) presentation for PACE 2005 Expo (Jan. 23-26, 2005, Las Vegas, Nev.).

3. Since its recovery, the Big Piece has received maintenance by conservators other than the authors; the results will not be addressed at this time due to a lack of familiarity with that work and a lack of published documentation of the treatments. Because the authors were primarily responsible for the two most substantial treatment campaigns, these form the basis of the discussion.

4. John P. Eaton and Charles A. Haas, *Titanic: Triumph and Tragedy,* 2nd ed. (New York: W. W. Norton and Co., 1994), 12-18.

5. Jennifer Hooper McCarty and Tim Foecke, *What Really Sank the Titanic* (New York: Kensington Publishing Corp., 2008), 36-38.

6. The central portion of the ship afforded much more space in which to operate the hydraulic riveting machines than did the bow and stern (more confined spaces where a person could fit but a machine might not be able to), another possible reason why different rivets were chosen.

7. McCarty and Foecke, 15-16.

8. Numerous parties teamed to achieve these expeditions, including RMS Titanic Inc. (RMSTI), co-supported by the Discovery Channel; the Marine Forensics Panel of the Society of Naval Architects and Marine Engineers (SNAME) was also consulted on these missions. Recovery efforts had to be abandoned when the artifact was just 200 feet shy of the surface, due to an oncoming hurricane. The artifact drifted back to the ocean floor, fracturing into two pieces.

9. William J. Broad, "Effort to Raise Part of Titanic Falters as Sea Keeps History," *New York Times*, Aug. 31, 1996.

10. The right to access, recover, and profit from the *Titanic* and its artifacts has been highly litigated and contentious since its discovery. Multiple laws and regulations were generated out of early court proceedings, including the *Titanic* Maritime Memorial Act, designating the wreck as international maritime memorial, legally maintained and protected by the United States, Canada, France, and the UK, with the U.S. National Oceanic and Atmospheric Association (NOAA) named environmental steward of the wreck site. NOAA went on to publish "Guidelines for Research, Exploration and Salvage of RMS *Titanic*," explaining these international standards. At the time of writing, RMSTI, a subsidiary of Premier Exhibitions, Inc., currently retains its status as "salvor-in-possession" of the wreck site and artifacts.

11. Metallurgical testing on the hull steel was directed by H. P. Leighly, of the University of Missouri-Rolla, assisted by Tim Foecke, of the National Institute of Standards and Technology. Chemical analyses were performed by Prof. Leighly and Dr. Harold Reemsnyder of the Homer Laboratories of Bethlehem Steel in Bethlehem, Penn.

12. Jennifer Jo Hooper, "Analysis of the Rivets from the RMS *Titanic* using Experimental and Theoretical Techniques" (doctoral dissertation, Johns Hopkins University, Materials Science and Engineering, 2003). Foecke and McCarty.

13. Kieran Hosty, "A Matter of Ethics: Shipwrecks, Salvage, Archaeology, and Museums," *Bulletin of the Australian Institute for Maritime Archaeology* 19, no. 1 (1995): 33-36.

14. Martin Weaver, "Heritage Conservation of Submarines," *APT Bulletin* 35, no. 2-3 (2004): 51-59.

15. Paul Mardikian, "H. L. Hunley Conservation Plan." Unpublished internal document, copyright by Friends of the Hunley, Inc./Warren Lasch Conservation Center, Clemson Univ., Charleston, S.C., May 2006, pp. 14-15.

16. Scott C. Boyd, "USS *Monitor*'s Turret Has Surprises for Conservators," *Civil War News* (Sept. 2011), http://www.civilwarnews.com/archive/articles/2011/sept/monitor-091102.html (accessed Feb. 2, 2012).

17. Although the formation of new concretions will be slowed or stopped once the artifact has been removed from the ocean, the existing shell creates a microenvironment on the surface of the iron object that can allow complex corrosion mechanisms to continue to occur unnoticed. In the case of the Big Piece, the crust was found to be hygroscopic (attracting water) and kept the surface moist, i.e., provided a means for corrosion to occur. Additionally, the non-porous calcium carbonate shell can inhibit ion exchange, which may hinder and prolong treatments such as electrolysis. Bradley Rodgers, *The Archaeologist's Manual for Conservation* (New York: Kluwer Academic/Plenum Publishers, 2004), 79-80.

18. D. Watkinson, "Chloride Extraction from Archaeological Iron: Comparative Treatment Efficiencies," in *Archaeological Conservation and Its Consequences, Copenhagen Congress, 26-30 August 1996*, ed. A. Roy and P. Smith (London: International Institute for Conservation, 1996), 208.

19. Mardikian, 72.

20. D. Roy Cullimore, Charles Pellegrino, and Lori Johnston, "RMS *Titanic* and the Emergence of New Concepts on Consortial Nature of Microbial Events," *Reviews of Environmental Contamination and Toxicology* 173 (2002): 117-41.

21. Rodgers, 89-90.

22. Mardikian, 97-100.

23. Texas A & M University files: File 1 OA Iron Conservation Part I: Introduction and Equipment and File lOB: Iron Conservation Part II: Experimental Variables and Final Steps, http://nautarch.tamu.edu/class/anth605/File10a .htm and http://nautarch (accessed Feb. 19, 2012).

24. Al Kazunias, Kathy Pearl, and Rolf Schlake, "Metal Artifact Preservation Using the Subcritical Water Extraction Technique," presented at Pittcon 2010 (Feb. 28-Mar. 5, 2010, Orlando, Fla.).

25. J. Sembrat, P. Miller, J. Skavdahl and L. Frenzel, "Conservation of Historic Metals by Waterjetting Techniques," *Cleaning Techniques in Conservation Practice, Journal of Architectural Conservation* 11, no. 3 (Nov. 2005): 121-146.

26. Ibid.

27. Treatment of objects recovered from the RMS *Carpathia* was performed in 2007-2008. These objects are also currently owned managed by Premier Exhibitions, Inc./RMSTI.

28. A heated solution of 3 percent EDTA in warm water was applied to the glass by cotton swab and carefully scrubbed with natural bristle brushes. Additional EDTA solution was injected into cracks in the glass using a syringe to promote cleaning in inaccessible areas.

29. PSI, pressure measured in pounds per square inch, is referred to in the water-jetting industry more specifically as PSIG, the pressure as it is measured at the pump gauge (pounds per square inch at gauge) where the operator controls are located.

30. Sembrat et al., 123-124.

31. Sembrat et al., 130-131.

32. M-238 product data sheet, Cortec Corporation, http://www.cortecvci.com/Publications/PDS/M238.pdf (accessed Feb. 20, 2012).

33. The treatment methods used on the Big Piece in 2000 were also applied to other large artifacts from the collection around the same time. Despite better transport conditions, climate-controlled trucking, and dedicated crates with silica packs, these elements also displayed similar loss of the rusticle crust. It was determined that the lack of wax penetration to the steel-and-cast-iron substrate that allowed these crusts to detach. Several large artifacts, including the Bollard, D-Deck Door, and Eccentric Strap, were similarly re-treated with waterjets, chemical rinse aids, and wax after the 2004 treatment of the Big Piece. This treatment yielded similarly successful results, and far fewer salt breakouts were observed.

34. Mardikian, 107.