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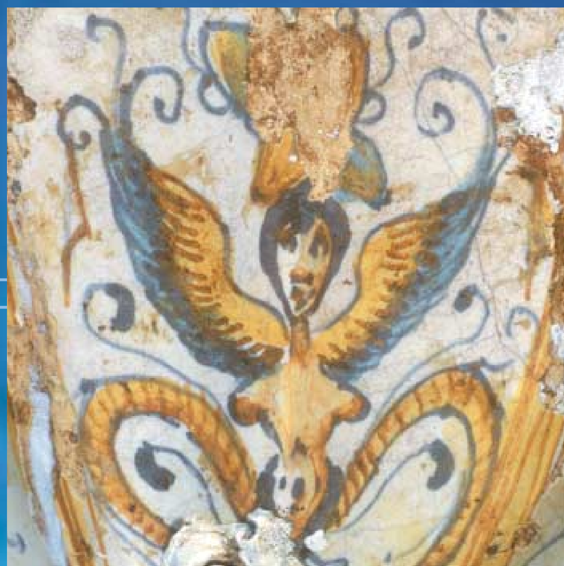

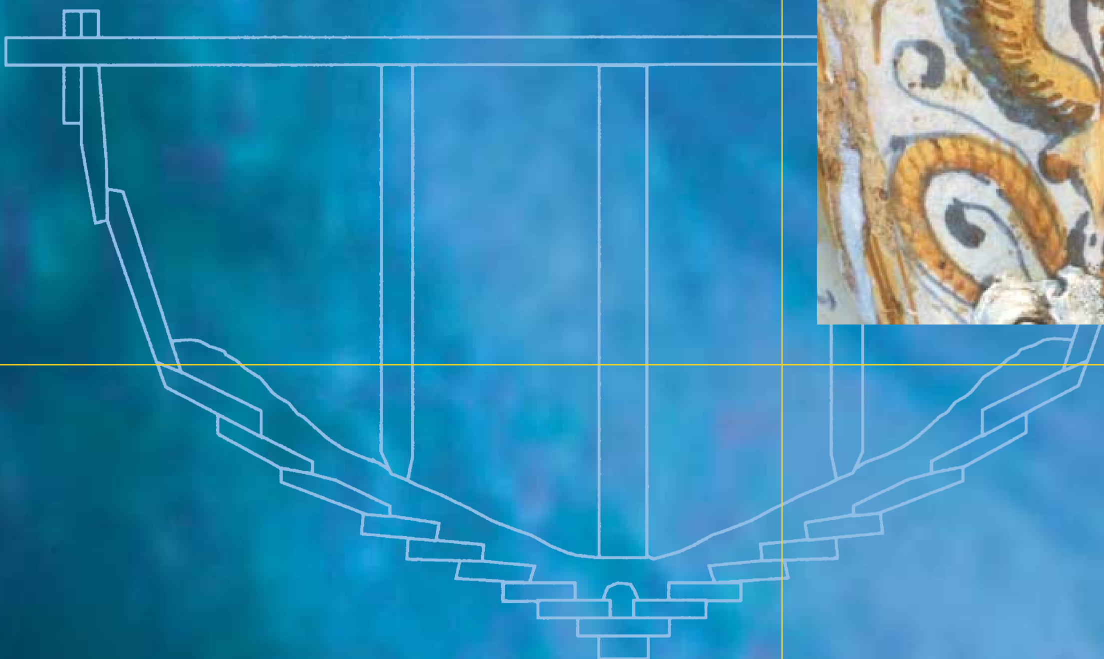

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Conservation and Management Strategies Applied to Post-Recovery Analysis of the American Civil War Submarine *H. L. Hunley* (1864)

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The 12-m long submarine *H. L. [Horace Lawson] Hunley* was successfully recovered from the Atlantic in August 2000 after nearly 140 years of immersion, and immediately brought to the Warren Lasch Conservation Center to be excavated in a controlled environment. In 2001 a multi-disciplinary team excavated the crew compartment and uncovered numerous fragile artefacts and human remains. This paper describes the conduct of the excavation and technological advancements developed to work with this complex and unstable iron vessel. Impressed current technologies, automated tank controls and water monitoring systems; laser mapping; fibre-optics; database management; *in situ* x and gamma rays; moulding and protection of fragile archaeological features; and protocols for moving artefacts to the laboratory will also be discussed.

Key words: Hunley submarine, maritime archaeology, conservation, marine corrosion, chloride, cathodic protection.

It is no secret that 'underwater cultural heritage' is fragile and can easily be destroyed if it is not excavated and treated properly. Examples of degraded or lost artefacts are numerous, especially when it comes to maritime objects. Heavily transformed after centuries of immersion, the recovered materials are structurally altered and usually do not respond well when suddenly exposed to the atmosphere. Materials such as wood or iron are prone to great instability and disintegrate in a matter of weeks if not treated properly. Generally speaking, the conservation difficulties are more acute on materials retrieved from a maritime environment than those from fresh water, chiefly because of the presence of dissolved species in the water. Chloride is the most abundant inorganic anion in sea water and it not only has a boosting effect on the corrosion rates of metals but also serves as a catalyst during the corrosion cycle after exposure of the contaminated metal to the oxygen (Gonzalez *et al*., 2003). Salt water also hosts a variety of marine borers that can survive in brackish water[1] and consume ligneous materials above the sea bed. One way to preserve these artefacts is simply to leave them *in situ* with minimum disturbance. The alternative is to excavate them properly and take full responsibility for their long-term preservation and curation. Making this decision is difficult and requires a scientific and social consensus to be reached beforehand. Any project involving complex artefacts and long-term conservation goals needs to be sustainable over a long period.

> A step forward in iron and steamship archaeology post-*Xantho* was the detailed preparation for the raising of the Confederate wrought-iron submarine *H. L. [Horace Lawson] Hunley* and its crew. This included the prior obtaining of finance, social and political backing, expert staff, a large conservation facility and an existing and well-regarded exhibition venue in Charleston, South Carolina. The convening of an international forum designed to air the many conservation, ethical, and archaeological issues, with a view to their satisfactory resolution well before the excavation and lift occurred, was another step toward the establishment of best practice in iron and steamship archaeology (McCarthy, 2000: 189–90).

After an initial survey in 1996 by the National Park Service's Submerged Resources Center (SRC), South Carolina Institute of Archaeology and Anthropology (SCIAA) and the Naval Historical Center's Underwater Archaeology Branch, *Hunley* was formally identified (Murphy, 1998). A feasibility study was implemented in order to determine approximately what it would

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cost to bring *Hunley* back to port, and excavate and conserve it for future generations.

Action plan

In 1998, Dr Robert S. Neyland, head of the Naval Historical Center's Underwater Archaeology Branch, was appointed Hunley Project Director and started to recruit his core scientific team. In 1999 Maria Jacobsen and Paul Mardikian were chosen to serve as the project's Senior Archaeologist and Senior Conservator respectively. Shortly thereafter, plans were made to recover the submarine in the year 2000. This plan would be peer-reviewed by a scientific committee before it was submitted to the South Carolina Hunley Commission and Friends of the Hunley. At the same time, a 4274 m^2 (46,000 sq. ft) building on the former Charleston Naval Base was retrofitted into a world-class facility, constructed within six months at a total cost of $3 million.

This figure does not include a significant number of in-kind donations, services and equipment given to the Hunley Project between 2000 and 2001. The Hunley Project has been receiving funding through three different sources: Department of Defense Legacy Resource Management funds; the South Carolina Hunley Commission; and Friends of the Hunley Inc., a not-for-profit corporation which administers funding and raises private money.

There may have been an idea to excavate the interior of *Hunley* while it remained on the seabed, but this option would have made the Hunley Project extremely difficult, perilous to divers and artefacts, and prohibitively expensive. Instead we opted for a more 'holistic' approach where the *Hunley* and its contents would be safely relocated within a conservation laboratory. The *Hunley* was finally raised on August 8, 2000 and transported to the conservation facility (Fig. 1). There the submarine would be accessible at any time during

Figure 1. The *H.L. Hunley* on the barge en route to Charleston. Note the 45° angle of the submarine on its starboard side and the spray down system attached to the truss. (Copyright, Friends of the Hunley Inc., 2000)

the excavation and subsequent conservation phases. The only way to achieve this ultimate goal was somehow to predict a worst-case scenario for every single problem. The unstable iron might react with oxygen upon exposure to the air during its shipment to the laboratory or during the course of excavation. The corrosion rate in the oxygenated storage tank might rise to unacceptable levels. The submarine could not be entered in a way that would not excessively damage the hull. The radiation survey conducted on the submarine might alter the DNA of the crewmembers' remains. The presence of human remains with important soft adipocerous tissues would be significant. These are a few of the instances where both the archaeological and conservation teams had to work side by side to research the proper ways to handle various technical problems for which there was simply no existing precedent.

The philosophy behind the Hunley Project has always been to step back when needed and evaluate every situation. This principle ensures that nothing is done hastily, but is instead well planned and tested beforehand. The six months between the time of the recovery and the actual beginning of the excavation was spent doing a thorough survey of the submarine and putting a final action plan together.

This plan included four important steps. Firstly the assessment of the stability of the *Hunley* in its new environment with regard to its mechanical support in the lifting truss, its corrosion behavior, and biological activity. Secondly, the study of the mutagenic properties of ionizing radiation (x and gamma rays) that could be used to analyse the submarine and its possible impact on the DNA of the crewmembers' remains (Downs *et al.*, 2002). Thirdly, to test all non-invasive techniques that could possibly be used prior to entering *Hunley* in order to establish the protocols for opening the hull and excavating the central compartment. And fourthly a detailed plan to excavate and maintain the submarine during its exposure to an oxygenated environment.

Laboratory settings

Each piece of equipment in the laboratory area had to be tested before the day of the recovery. The 50-ton steel tank was leak-tested, and the time needed to fill or empty the tank recorded (approximately 4 hours for each process). The water (or any chemical mixed with it) would be transferred into six 15,000-gallon, fibreglass-mixing tanks located outside the building (Fig. 2). These tanks would serve a dual purpose. To provide temporary storage for tank water when the submarine was to be exposed (afterwards, the solution would be pumped back into the storage tank), and as a waste neutralization system if the chemicals used for the treatment had to be tested before discharge in the sewer or neutralized within the discharge limits of the Navy's Pretreatment Discharge Permit (6.5–9.5 pH). Every batch under or above these values would need to be corrected with either sodium hydroxide or nitric acid before the solution could be tested by an independent analytical laboratory and then slowly released into the sewer system at a rate of 95 litres (25 gallons) per minute.

The water quality in the tank, including levels of dissolved oxygen, pH, water temperature, water level, conductivity, oxygen reduction potential, and electrochemical parameters are monitored with a combination of measurement instruments donated by Thermo-Orion and Rosemount Analytical. These monitors are connected to a Rockwell Automation industrial touch-screen computer that operates on software designed by W. R. Riggs & Associates, Inc. This system allows us to program the tank's draining and filling sequences, and therefore offers great flexibility over manual operations. The additional option to check the status of the sequences remotely via the Internet also enhances the overall design. The industrial computer was generously donated by McNaughton-McKay and was operational by the day of the recovery.

A 100-m^2 mezzanine was built adjacent to the tank to support the excavation and conservation efforts. A smooth transition of archaeological material from the submarine to the laboratory was deemed critical to the success of the project. Two 20-ton top-running double-girder cranes were installed over the submarine and allow us to move practically anything in the tank room (from the submarine itself to small, fragile artefacts). The cranes can also be used to manoeuvre critical equipment like the x-ray tube or Cyrax Scanner. A scissor lift was attached to the mezzanine and enables us to move the most fragile items to the morgue without using the stairway. A 20-m^2 morgue was built in the clean lab and is large enough to hold ten body trays and hundreds of artefacts in their chilled water containers. In order to introduce natural light to the *Hunley* holding tank and clean laboratory areas, several windows were added to the building. The Canadian Institute in Ottawa tested a glass sample to insure that the level of filtration for both ultra-violet and visible

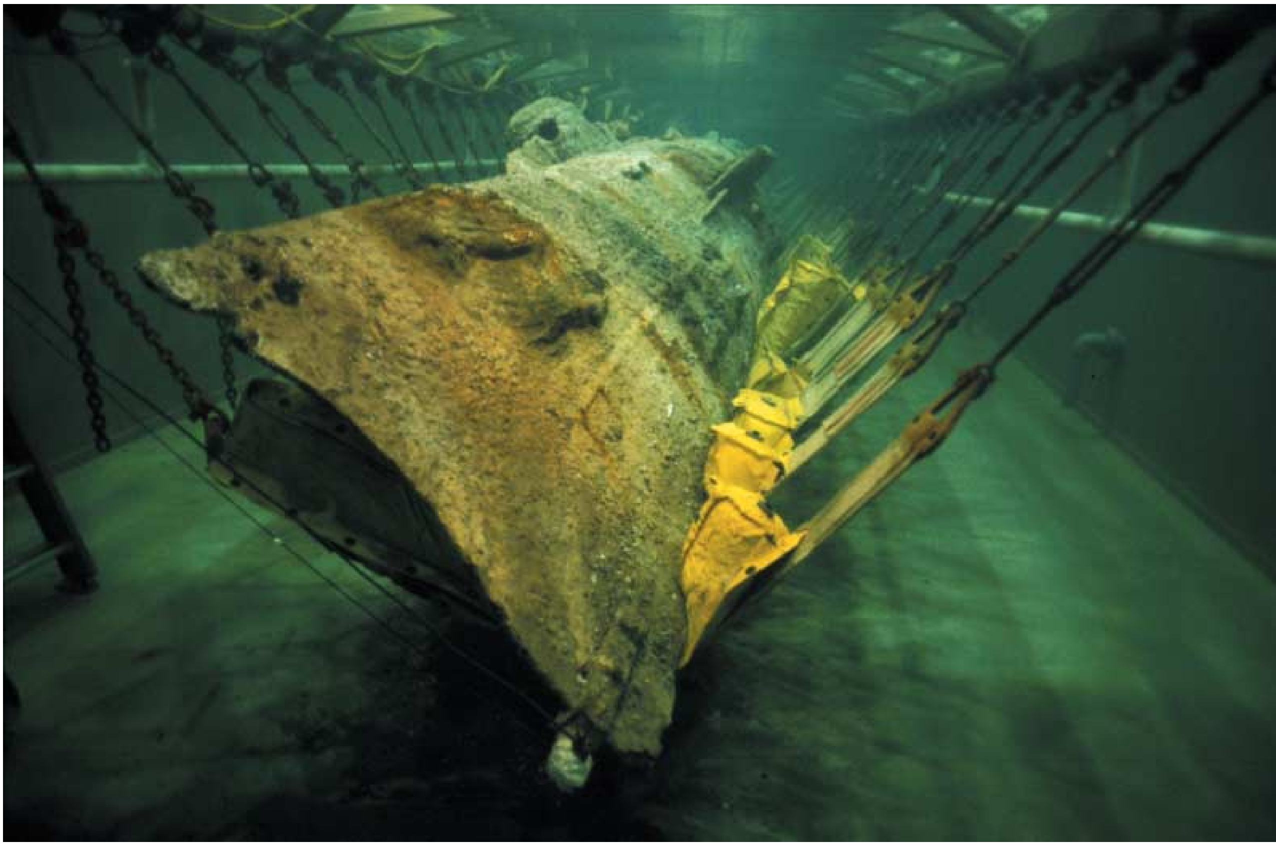

Figure 3. H.L. Hunley resting in its tank at the Warren Lasch Conservation Center soon after its recovery. Note the anodes in the white perforated pipes parallel to the hull. (Copyright Friends of The Hunley Inc., 2001)

light was correct. In addition, the Warren Lasch Conservation Center purchased a mobile 300 keV x-ray tube coupled to a computed x-ray system offered to the Project by the Fuji NDT Corporation.

Since the surface area of the tank was 93 m^2, we hypothesized that several 50-mm diameter hollow plastic spheres could be used to create a 'floating blanket' on the surface of the tank. This would reduce surface exchange and evaporation losses, as well as improve energy conservation. Although the plan would theoretically have achieved all of these goals, we realized that the submarine would be hidden from view. Consequently, we elected to not use the 'floating blanket'.

Handling the corrosion and the human remains

One critical aspect of the *Hunley* recovery was that, once retrieved from its watery grave, the submarine would be at high risk. This was principally due to the abundance of oxygen available to react with its iron components at the first break in the shell-like layer. Fortunately, this protective concretion remained attached to the hull during the lifting and transportation operations by Oceaneering International. Since the concretion covering the hull was apparently intact after the raising, there was no need to use hydraulic cement or other products similar to those used in 1996 and 1999 during underwater surveys of the submarine.[2] The objective was to make sure that exposure of *Hunley* to the atmosphere would not induce adverse chain reactions. Since the surface of the hull would remain sealed off whether intact or patched, and the amount of time between *Hunley*'s recovery and placement in its tank would be less than eight hours, the decision was made to keep the submarine visible to the public once it was on the recovery barge. However, the submarine was constantly wetted with salt water during its trip back to Charleston so it would not dry out.

Stability studies on the *Hunley* started immediately after the recovery. City water in the storage tank was rapidly chilled over a 24-hour period to approximately 10 °C (50 °F). This critical step was performed to minimize the impact of potential enzymatic reactions on organic remains. It was also intended to slow down the corrosion activity in the iron hull. Although it is a physical fact that decreasing the water temperature from 20° to 10 °C can theoretically increase the solubility of the water's oxygen content by 22%, we knew it would reduce the velocity of any chemical reactions between 2 and 70 times and thereby benefit *Hunley*.

Soon after the recovery we discovered that algae were blooming in *Hunley*'s holding tank in spite of its low water temperature. To combat this problem, one more type of filter was added to the filtration system's original sand filters, limiting the introduction of particles 20 microns or larger. Aqua Blue Pool, Inc. replaced the two existing circulation pumps with new Pentair® pumps and Pentair® diatomaceous earth swimming pool filters. Within two days of its installation, the new system cleared the water in the tank substantially. The combination of this filtering device and the sand filters has proven to be the most efficient means of removing biological growth in the tank, and precluded the use of potentially harmful chemicals or chemical agents.

The decision to increase the pH of the water with corrosion inhibitors was initially rejected because the introduction of any sort of chemical could lead to uncontrollable effects on materials other than iron or copper (i.e. fragile artefacts such as fabrics, soft human tissues, glass, wood and leather items). The use of sodium carbonate or sodium hydroxide would have been necessary to attain a pH adjustment greater than 11 and prevent the corrosion of the metal in a chloride-rich environment. After the recovery, the electrochemical behavior of the hull was recorded[3] and compared to measurements taken two-and-a-half months before the actual raising and summarized in Table 1 (West, 2000). This information served as a starting point to assess the stability of *Hunley* in its new environment and make the necessary adjustments. It soon became apparent that *Hunley* was more prone to degradation in the tank than it was *in situ* and that one additional step to insure its protection in the tank would be to install a proper protection system.

In 1999, a Hunley Symposium was held to determine the best means to recover, excavate and conserve the submarine. Among other things, the symposium's participants discussed the use of galvanic protection as a means to protect *Hunley* while it was still *in situ* or in the tank. The discussion produced no real agreement on the subject: sacrificial anodes were deemed too cumbersome to attach to the hull, and the difficulty of controlling current densities and by-products of the anode reactions too great. The maximum current density required to protect the hull and the supporting truss would be 3.50 Amperes. To supply this amount of current it would have taken 50 (20 kg each) high-potential magnesium anodes. When the subject was discussed with corrosion engineers shortly before the submarine was raised, they suggested that a more convenient and flexible impressed current be used (Meier and Mardikian, 2004).

Probably for the very first time in the history of underwater archaeology, impressed current technology was applied to a large, intact composite artefact as a safe alternative to the use of chemicals. This was done to prevent the most perishable remains and artefacts from being severely altered or destroyed by chemicals. The pivotal role of corrosion experts and electrochemists like Craig Meier from Corrosion Control, Inc. or Steve West from Thermo Orion cannot be stressed enough. The degree of specialized expertise required to implement efficient and safe corrosion protection for *Hunley* has included a variety of entities and individuals in the field of corrosion science. With the assistance of these experts, the conservation team was able effectively to tackle the problem of stabilizing a greatly altered composite artifact.

Electrochemical potentials recorded before the submarine was raised clearly indicated that the submarine's potential had shifted from a greater reducing environment and slower rate of corrosion to the exact opposite. This shift was confirmed by Craig Meier's analysis:

> even at 48°F, the increase in oxygen from 1.9 ppm to 8 ppm will result in an increase in corrosion rates from 0.02 mils per year to 50 mils per year. This represents an increase in rate of 2,500 times! In less than six (6) months, the hull could experience more corrosion related metal loss than in the 136 years it was buried in the mud (Meier, 2000: 2).

Table 1 *E_{corr} values on H.L Hunley excavation site compared to readings in conservation laboratory*

	E_{corr} (NHE) Volts	O_2 mg/L
Hunley excavation site 2000	–0.360 (–0.560 vs. Ag/AgCl)	1.9
Hunley in tank without impressed current	–0.250 (–0.450 vs. Ag/AgCl)	8
Hunley in tank with impressed current	–0.620 (–0.820 vs. Ag/AgCl)	8

Figure 2. View of the 6 mixing tanks located outside the building. (© Friends of the Hunley Inc., 2000)

We elected to install the impressed current system in the tank and were assisted by Corrosion Control, Inc., who provided all of the engineering work. The protection system is safe for the submarine and those working on it,[4] is simple to install in the tank, and can be easily modified to suit the particular needs of the excavation and conservation teams. It consists of two 40-foot long anode segments[5] (Fig. 3). These are suspended from the truss and oriented parallel to the hull in pre-drilled PVC pipes. The pipes support the anodes, ensure that they do not come in contact with the truss, and provide more uniform protection for the submarine. Fig. 4 shows how the negative cable is attached to the former spar connection. The decision was made also to protect the mild-steel truss with the impressed current.

To monitor the cathodic protection levels and make rectifier adjustments accordingly, six silver/silver-chloride permanent saturated gelled

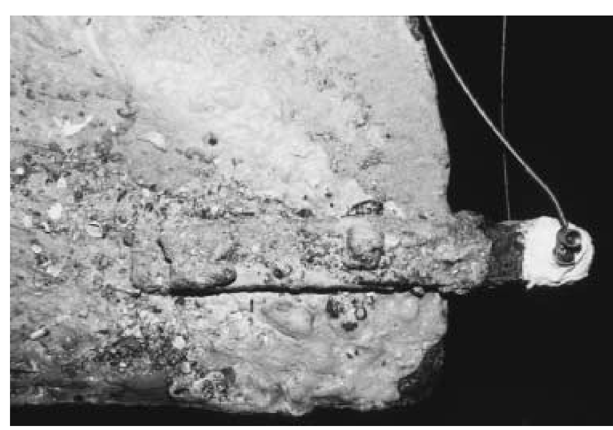

Figure 4. The resistive effect of the riveted seams being negligible, the main connection to the hull was made at the former spar connection using a modified bolt covered with an epoxy coating. (Copyright Friends of The Hunley Inc., 2000)

reference cells were positioned along the hull. The rectifier plugged into a standard 120 VAC outlet and draws approximately 1.6 amps. Adjusting the rectifier transformer settings controls the output of the anodes. This system is critical because it enables conservators to monitor the level of potential on a selected reference cell and automatically adjust the output in a potentiostatic mode.[6] Almost six months elapsed between the actual raising and the opening of the submarine. During this time, the submarine was placed under cathodic protection and displayed to the public.

Protecting the Hunley during the excavation

The formal excavation of the central compartment started at the end of January 2001 and ended in December 2001. A total of 195 working days (10–15 hrs per day) were required to complete this phase, which represents approximately 2,400 hours during which the submarine was exposed to the ambient air. Recent studies (Gonzalez *et al.*, 2003) have demonstrated the importance of minimizing the exposure of marine iron to the atmospheric oxygen.

The primary concerns and responsibilities of the conservation staff during the excavation were to ensure that proper monitoring and control of the physical integrity of the submarine and associated contents as described in Fig. 5, would be effective at all times. These duties included: cathodic protection control; control of tank water parameters, including draining and filling sequences; control of the water and sediment temperature; physical protection of the sub when exposed

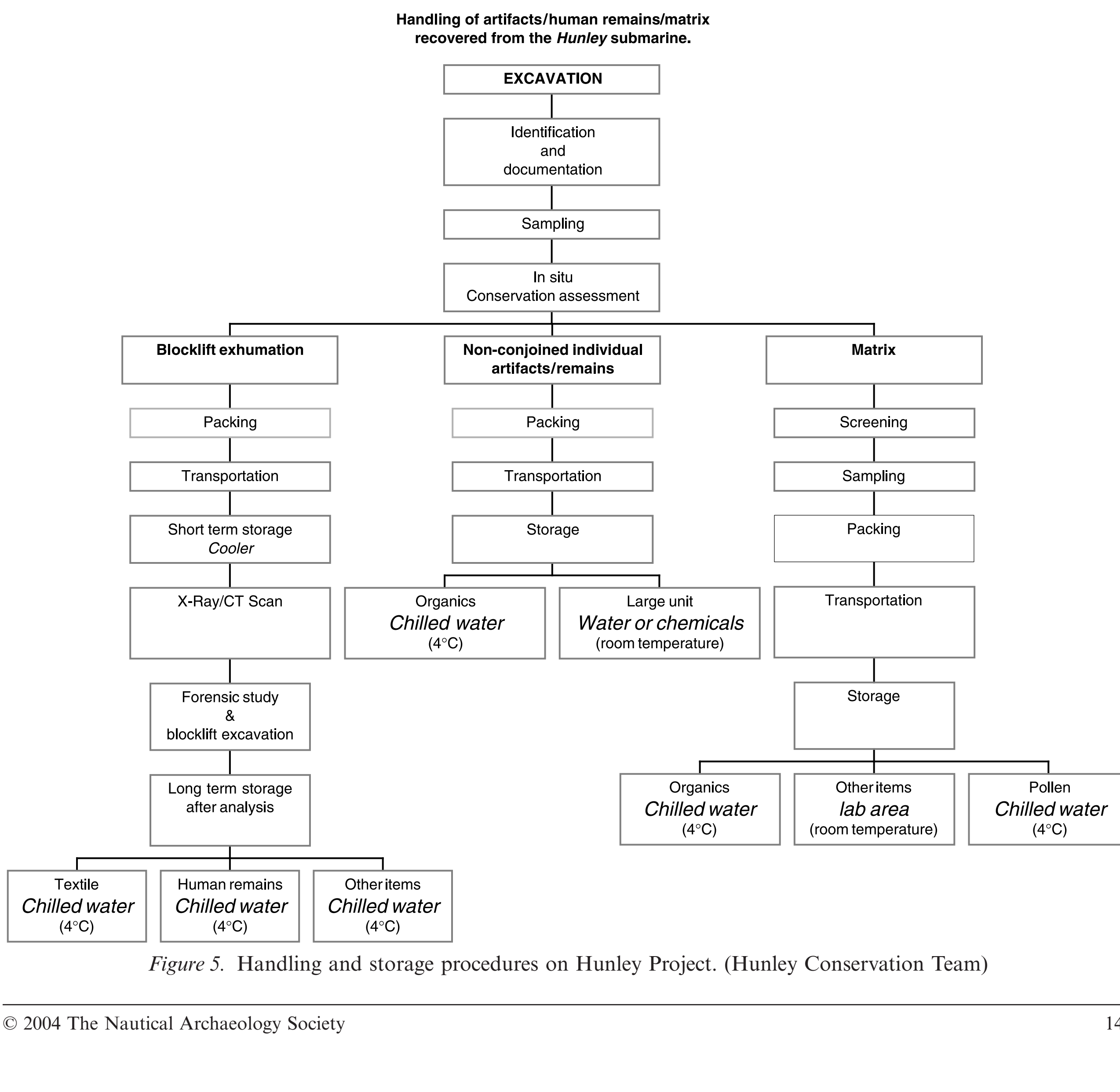

Figure 5. Handling and storage procedures on Hunley Project. (Hunley Conservation Team)

to air; identification of materials and sampling; stability and conservation assessments; artefact photography (when needed for conservation purposes); *in situ* x-ray studies; *in situ* moulding; transportation and handling of materials during CT Scanning studies at the Medical University of South Carolina (MUSC); excavation of extremely fragile artefacts and human remains; separation of conjoined artefacts and human remains; block-lifting of priority groups of artefacts and human remains; *in situ* support and consolidation of artefacts and archaeological features; packing of artefacts and human remains; transportation of artefacts and human remains into the clean laboratory; short-term storage of artefacts and human remains (Storage 1); textile assessment and consolidation during forensic study; long-term storage of artefacts and human remains (Storage 2); safety issues related to mercury spills (such as that discovered in the submarine's depth gauge); water treatment and coordination with the North Charleston Sewer District and the South Carolina Department of Health and Environmental Control; and database management of artefacts and samples inside the laboratory (approximately 7,000 entries).

Working inside *Hunley* through the openings created by the removal of the four top plates provided enough access for the archaeological team to accomplish its goals. However, working conditions were difficult and lighting was critical. One significant addition to the design plan was to install several fibre-optic systems offered by Teledyne Larrs®. These enabled lighting to be used in or out of the water without endangering the archaeologists or creating heat that could damage artefacts.

Concerns about lowering and raising the water level every day and its potential effect on archaeological features and fragile artefacts were discussed during the planning phase. Additionally, provisions for exposing the submarine for longer periods in the event of an emergency had also been planned, but the general rule was that the tank would be empty by 8 a.m. and filled again by 6 p.m. In the event that the submarine would need to be exposed overnight, each open section would be fitted with a plastic cover to prevent chilled water from being directly sprayed on the interior. The submarine was kept refrigerated and wet at all times. The chilled water system was designed so the bottom of the tank retained enough water to be circulated through the chiller and redistributed on the surface of the submarine. Scaffolding was assembled around the submarine just above the water table and provided a stable and safe platform for archaeologists and conservators during the excavation.

In order to keep the submarine wet during the excavation, two plastic partitions were installed to isolate the central compartment from the intermittent chilled water sprinklers used to keep the bow, stern and two conning towers wet. After the discovery of a 5-m-long painted wooden bench, a drip hose was installed to prevent it from drying out. The chilling system was run at maximum capacity and kept the water temperature as low as 6.3 °C (43.3 °F). The temperature of the sediment was recorded every morning at several locations in the submarine and stabilized at 10 °C (50 °F) during the excavation of human remains. The commercial chiller originally installed in the tank proved inappropriate for our needs and failed on a number of occasions: six months into the excavation it stopped functioning entirely. Fortunately, a new unit was installed by Aqua Blue Pool and Pentair® free of cost.

During the excavation, the impressed current was interrupted during the week and turned back on during the weekend to minimize the corrosion process. Deconcreted areas on the hull's exterior were protected as much as possible and signs of active corrosion kept under close observation. The 'weeping chloride' phenomenon[7] was detected only once—the affected area was located on one of the wrought-iron stiffeners and emerged shortly after the first plate (CT5) was removed. This active sign of corrosion can be seen in Fig. 6. No major cracks occurred in the submarine's concretion layer as a result of the corrosion process. During the excavation, portions of *Hunley*'s lower hull were de-concreted in order to free artefacts fused to the hull or to the submarine's assemblage of iron ballast blocks. With the exception of a few zealous de-concreting efforts made to identify various features and search for humans bones embedded in the concretion, the hull was impacted as little as possible, and concrete patches were used on exposed areas as needed. The day-to-day protection and survey of the submarine led us to consolidate or reinforce weakened features that could not be safely removed from the submarine. Waterproof signs were installed near fragile areas to remind those working in the submarine to stay away from them. Again, mutual understanding and respect between the archaeologists and the conservators enabled the project to proceed smoothly.

Figure 6. Rivet head from the *Hunley* exposed to the air for only a couple of days: Note initial indication of active corrosion in the form of the weeping phenomenon. (Copyright Friends of The Hunley Inc., 2000)

In order to reduce the exposure time of the submarine and facilitate the work of the archaeologists, a new surveying technology was utilized. Pacific Survey Supply, an Oregon-based surveying company, was able to literally scan the submarine and any other complex feature within it in a matter of hours. The device, manufactured by Cyra, Inc., is capable of acquiring 1000 measurements per second and then rendering the data to produce a 3-D digital model with a 3-mm margin of error. In the words of Senior Archaeologist Maria Jacobsen, 'this technology has moved archaeological mapping into the 21st century. The extremely accurate, three-dimensional digital data recorded during the excavation now becomes a very powerful analytical tool'. In terms of direct benefit to the conservation effort, this technology has improved our ability to work more efficiently and has drastically minimized the exposure time of fragile and reactive artefacts to the atmosphere. Working on any kind of shipwreck out of the water generates problems (e.g. drying of wooden structures, iron instability) that digital mapping might actually ameliorate:

> The total number of survey coordinate xyz points on the *Hunley* is in excess of 22,400,000 points. A survey crew will record a thousand points per day using conventional methods. To equal the amount of data we recorded would take a crew working 8 hours a day, 5 days a week, a total of 86 years. We completed the job in 4 days. The ability to probe into the remote confines of the submarine and record the position of hidden artefacts to within millimeters, without the requirement of being level or plumb, proved to be invaluable. In this way, our team was able to recreate the position of each item when the *Hunley* sank (DeVine, 2002: 12).

After six months of excavation the project was shut down for the summer. Before doing so, electrode potentials inside the submarine were recorded and the impact of sediment removal and de-concreting the interior of the hull were assessed. The electrochemical readings inside the hull clearly demonstrated that the potential had shifted to a more positive value than the exterior. This indicated that it was now corroding at a much faster rate. In order effectively to neutralize the interior's corrosion rate, a third anode was installed inside the hull. This addition greatly improved the corrosion protection of the interior of the submarine.

In order to quantify and visibly assess the effect of the impressed current on metal similar to the hull of the Hunley, two mild steel probes connected to a MS0500 corrosion-monitoring meter were placed in the Hunley tank soon after its recovery (Fig. 7). Visible changes have occurred on both electrodes: electrode 1 is covered with a white deposit (possibly carbonates) but still has a smooth surface, while electrode 2 is showing a disrupted surface and signs of active corrosion. Using the corrosion meter readings shown in Fig. 8 a corrosion rate can be calculated. The calculated corrosion rates and other data are summarized in Table 2. The last reading, taken on August 27 2003, indicated that the unprotected control probe 2 was corroding at a rate almost 8 times

Table 2. *Calculated corrosion rates*

	Metal lost, mils (mm)	Corrosion rate, mpy (mmpy)
Protected Probe #1	2.0 (0.005)	1.34 (0.034)
Non protected Probe #2	15.5 (0.400)	10.43 (0.265)

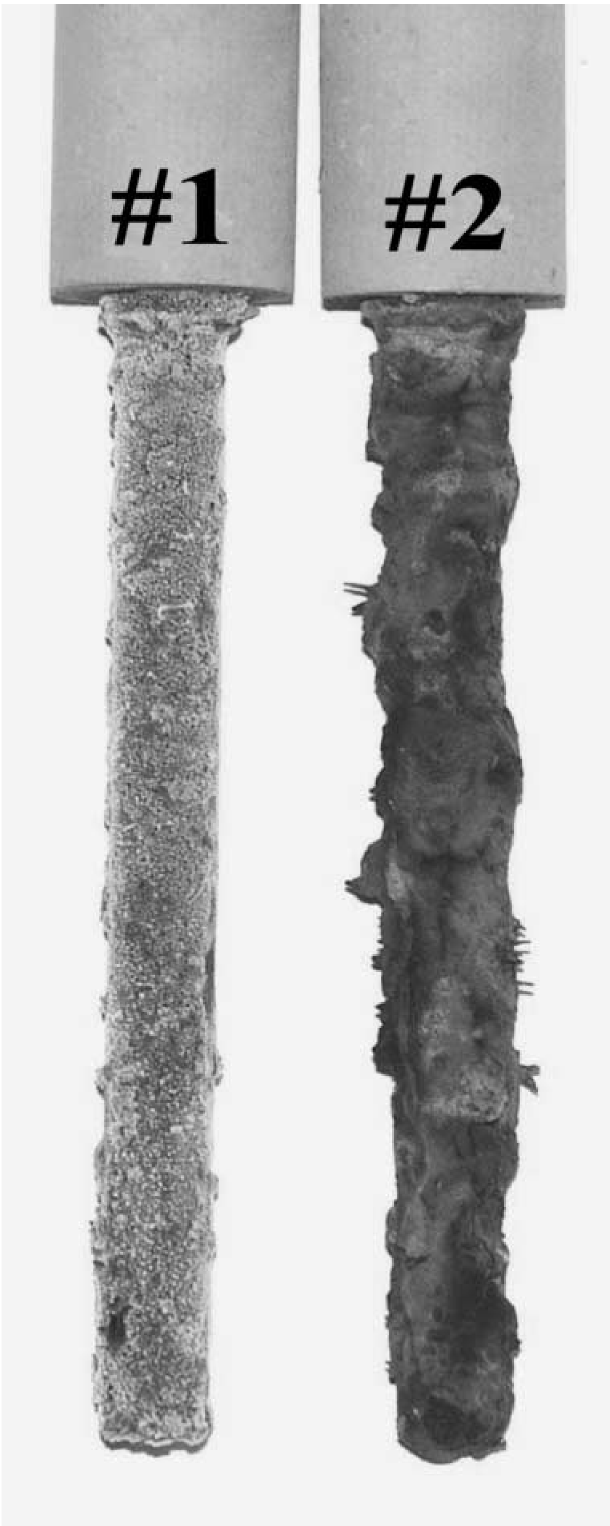

Figure 7. Photograph of mild steel test probes taken on August 27, 2003. (Copyright Friends of The Hunley Inc., 2003)

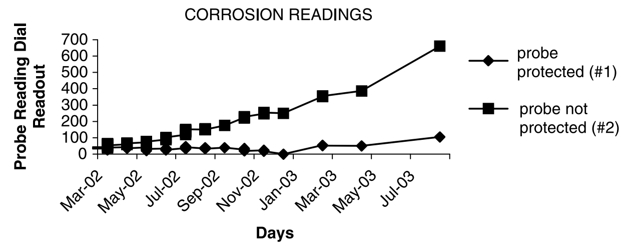

Figure 8. Probe corrosion readings.

faster than the protected probe 1. Based on these results, we would expect a similar level of protection on the submarine. It should be noted that the measured value of 0.034 mm/year on the protected probe is identical to the long-term corrosion rate (0.03 mm/year) predicted by Dr Ian MacLeod in 1998 (Murphy, 1998: 117). These data seem to indicate that the impressed current protection has brought the submarine back to its pre-disturbance long-term corrosion rate.

In terms of soluble chloride released from the submarine since inception, the value is approximately 223 kilograms. Based on our work on measuring the chloride content in the rivets and plates from the submarine, we do not believe that this represents a significant amount of the chloride from the corrosion products (Gonzalez *et al*., 2003). This value is **not** representative of what we might have extracted from *Hunley*'s structure but rather an indication of the bulk of chloride ions present in the 10 tons of sediment removed from the submarine during the excavation of the central compartment. It is unlikely that much of the chloride ions trapped underneath the concretion or deeply embedded in the metal could be removed by changing the electrical field around the submarine.

To conclude, a combination of techniques has assisted in preserving the *Hunley*'s integrity without changing the water chemistry and has enabled us to meet the complex challenge of dealing with a large unstable vessel containing fragile artefacts and human remains. The corrosion rates were significantly reduced and the submarine's electrochemical stability enhanced during its time in the tank. We believe that reducing the water temperature down to 10°C (50°F), limiting the deconcreting to the working areas, patching any non-working surface with hydraulic cement, filling the *Hunley* tank every night and using the impressed current technology whenever possible has limited the deleterious effects due to air exposure during excavation.

Conclusion

The first phase of the Hunley Project has proven to be an extremely demanding and challenging task for both the archaeological and conservation teams. Meticulous planning was critical for the successful recovery and excavation of *H.L. Hunley* to become a reality. Excavation of the submarine's forward and aft ballast tanks was recently completed and a collaborative effort with Clemson University's School of Materials Science and Engineering to research the stabilization of the hull is currently under way. The technological improvements and methodologies applied to *Hunley* will hopefully serve as a benchmark and a source of inspiration for future shipwreck projects of this magnitude.

Acknowledgements

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For further information on the Hunley Project and its contributors and sponsors please consult our website at www.hunley.org

Notes

1. Water between 1 and 17 gr of dissolved solids per kg of water is called brackish (e.g. estuaries where river water meets salty ocean water).
2. To avoid unnecessary corrosion, portions of the hull that were de-concreted in 1996 (and 1999) for corrosion potential measurements and inspection of the hull (Murphy, 1998: 111) were patched with a material called Devclad 182® (an epoxy-based splash-zone barrier coating). Inspection of the hull after the recovery revealed that difficulties existed when Devclad 182® was applied to a smooth metallic surface underwater. As a consequence, the poorly patched areas had visibly corroded to a greater extend within years. Consequently, the conservation team incorporated the use of hydraulic cement as a more appropriate patching material. This has proven more manageable and can easily be removed—in much the same manner as ferrous concretion. By contrast, removing Devclad 182® from fragile metal surfaces is considerably difficult. Additionally, the alkaline pH of the cement helps neutralize the corrosive tendencies of iron. It appears that hydraulic cement is an ideal patching material, and can be used either *in situ* or in a laboratory environment. However, there might be some restrictions when working with composite material such as wood or aluminum
3. A sealed, gelled Ag/AgCl reference electrode Orion Model 9179BN ORP with 6.25 mm diameter platinum pellet sensing half-cell saturated with AgCl and KCl electrolytes was used for this purpose. Due to the archaeological activity on the submarine and partial exposure of the hull, these measurements are probably not a true reflection of the Hunley site previous to its discovery in 1995. Attempts to record corrosion potentials on the *Hunley* in 1996 by The National Park Service led to inconclusive readings in the range of –0.620 V vs. Ag/AgCl (Murphy, 1998: 115). Unfortunately, the value of the reference electrode was not indicated so we can only estimate the range of the final result versus the Normal Hydrogen Electrode by 88 mV (+0.200 (sat) to +0.288 (0.1 M). However, it is our opinion that the most likely reference should be between +0.200 and +0.240 mV and would place the submarine between –0.420 and –0.380 vs. NHE. The underlying meaning of these values tends to indicate that Hunley had reached a fairly negative low Ecorr prior to major disturbance.
4. Impressed protections are used in aquariums where certain species of fish are susceptible to DC currents. They are also used in large steel tanks where astronauts are trained.
5. The anode material is a conducive ceramic coating on a ductile titanium substrate and includes a thin Arc-Plasma Spray (APS) of Enhanced Mixed Metal Oxide (EMMO). The average metal composition is generally a 50/50 atomic percent mixture of iridium and titanium oxides with a small amount of tantalum.
6. A theoretical value of –0.800 V vs. NHE. (–1 Volt vs. Ag/AgCl) was used as a conservative value to minimize gas evolution and the possible embrittlement on the cast-iron parts at more negative potentials.
7. Weeping is the formation of drops of acidic liquid (often described as 'tears' or 'sweat') on the surface of excavated iron. The liquid in these drops has a low pH (1–3), a high concentration of $Fe2^{+}$ and Cl^{-} ions, and relatively little Fe^{3+} ions. Weeping is attributed to the hydroscopic nature of iron chloride salts. Crystals of pale green $FeCl_2{\cdot}4H_2O$, for example, form when an iron (II) chloride solution dries rapidly. If these crystals are then exposed to a relative humidity above about 56%, the salt deliquesces and forms bubbles of liquids (Selwyn, 1999: 4).

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