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From the Micro- to the Macro-: Managing the Conservation of the Warship, *Vasa*

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Summary: Sweden's famous warship, *Vasa*, sank on her maiden voyage in August 1628, and remained on the bottom of Stockholm harbour for 333 years. Raised in 1961, she became the first large-scale wooden object to be treated with polyethylene glycol (PEG). In the summer of 2000 a number of acidic salt precipitations were noticed on the surface of the ship and on wooden artefacts in the storerooms. An international research project has been established to look into the causes of this problem and suggest possible re-treatments. Meanwhile projects are underway to monitor movements in the ship, to build a better support system, and to replace the thousands of iron bolts holding the structure together, while a sophisticated new climate system has recently been installed in the museum.

Keywords: complexing agents; conservation; management; polyethylene glycol; sulfuric acid

Introduction

Sweden's famous warship, *Vasa*, built between 1626 and 1628, was a symbol of Gustav Adolf's ambitions to be a major player in international politics in the Thirty Years War. Armed with 64 bronze cannon, she was also adorned with over 800 sculptures depicting classical and religious themes, and was intended to be a propaganda tool stating the king's claim to the throne of Sweden in his war against his cousin, King Sigismund of Poland.

Glory turned to disaster, however, when, 1500 m into her maiden voyage on August 10th 1628, in full view of Stockholm's dignitaries assembled on the shore, a gust of wind heeled her over, water entered her lower gunports, and she sank into the murky waters of Stockholm harbour. Despite various salvage efforts over the centuries, she was all but forgotten until the late 1950s, when Anders Franzén, a civil engineer working for the Navy, relocated her and initiated the mammoth effort to raise her. After 2 years of gradual winching from the seabed, she broke the surface once more in April 1961.

Time, and the anoxic waters of Stockholm harbour had apparently done her no disservice. She remained largely intact, although her stern castle had collapsed, probably in later years due to anchors lodging in the structure, and there was some erosion from exposure to sediment-rich currents. Many of the sculptures had long since fallen into the silt, saving them from decay and erosion. The oak structure was generally in excellent condition, with a sound core often equal in strength to new oak, and only the outer 1–2 cm showed any microbiological degradation, much of the cellulose and hemicellulose having deteriorated to leave a lignin skeleton. The Baltic is too cold and brackish for the survival of *Teredo navalis*, and other marine wood-boring molluscs, which can do so much damage to shipwrecks in warmer waters, and together with the fact that *Vasa* was a new ship, she was spared more invasive attack.

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Original Conservation

Conservation of this 800-tonne ship presented a huge challenge. Although archaeological wood had been preserved previously using various methods, including glycerine, creosote and alum, the last of which was used to conserve the Norwegian Viking Ships from Gokstad and Oseberg, this was the first time anything on such a gigantic scale had been attempted. Two possible methods were examined: carboxymethylcellulose (CMC) used by archaeologists in the Netherlands, and a new material developed by the Swedish company, Mo and Domsjö, Inc. to stabilise green wood, polyethylene glycol (PEG), which had already been used successfully on some of *Vasa*'s sculptures.

PEG was chosen for a number of reasons, including its compatibility with borax (the anti-fungal agent used on the wood), its ease of handling, and its ready availability in quantity. Successful impregnation of wooden objects was achieved by immersing them in a solution of PEG 4000 heated to 60 °C, but this method was impractical for the entire ship. The only approach for a structure of this size was to spray the conservation solution over the surface. Spraying commenced by hand in April 1962, but when an automatic spray system was installed in 1965, it was soon found that PEG 4000 clogged the spray nozzles, and so this was changed to PEG 1500. Lars Barkman and his team of conservators continued to test the suitability of different molecular weights over the years, and in 1971, the PEG was changed yet again to molecular weight 600, as tests suggested it had better penetration. The intermittent spray treatment continued for 17 years, starting with a 10% solution of PEG and 6% borax, gradually increasing total concentration to ca 45%. Core samples were taken at regular intervals to assess penetration of the PEG. The exterior and upper parts of the ship were finally hand-sprayed with PEG 4000 to provide a protective finish. There then followed a 9-year period (1979–88) of gradual air-drying from ca 95% to 60% relative humidity (RH).[1] The moisture content of the outer planking sank from 70 to 40% during spraying, and to 15% during the drying.[1] The wood's moisture content today varies between 9–15%.[2] Reconstruction of the hull structure, including the beakhead and sterncastle, continued throughout the spray treatment, and sculptures were later re-attached by aligning the original nail holes. All the while, *Vasa* was on display to the public in a temporary museum, but in December 1988, *Vasa* was transferred to the purpose-built Vasa Museum. Resting on the pontoon on which she had been placed in 1961, she was sailed through the open southwest wall, in what is often described as her only successful voyage! Once in the museum the excess PEG 4000 was removed from the surface using hot air blowers. The ship on display today is over 95% original, 69 m from stem to stern, 11 m wide and 20 m high at the stern.

Acidic Salt Precipitations

It had been assumed that once the conservation treatment was finished and the ship installed in the new museum, that preservation work would consist largely of periodic cleaning, and monitoring of the climate to assure optimum temperature and humidity. The conservation department was downsized and the large conservation facility was partially dismantled.

However, all this changed after the wet summer of 2000, which, combined with a record number of visitors to the museum, caused the RH within the ship hall and stores to exceed levels of 65%. A large number of yellow and white acidic salt precipitations were noticed on artefacts in the stores and on the ship itself, although early indications had been noticed by conservation technicians in the 1990s. These areas were often softer than surrounding wood, and showed pH levels of less than 3, and sometimes as low as 1, when measured with pH indicator paper. Core samples taken from various places around the ship and from objects in the magazines were analysed by Magnus Sandström, Professor of Structural Chemistry at Stockholm University, using X-ray powder diffraction. The deposits were revealed to be sulfur salts; yellow natrojarosite, bluish-white melanterite, ordinary white gypsum, and elemental sulfur.[3] Sandström's initial analyses indicated that where there are high levels of sulfur, there are correspondingly high levels of iron.[4] Iron is a strong catalyst for many chemical reactions, and clearly plays a role here. *Vasa*'s wood has a high content of iron corrosion products from the thousands of iron fasteners which held the structure together but corroded underwater, and the hundreds of cast iron cannon balls and other projectiles stored onboard.

But where did the sulfur come from? For hundreds of years the waters of Stockholm harbour were polluted by sulphate-rich natural sewage. In this largely anaerobic environment, sulfur-reducing bacteria metabolised this waste, utilising the oxygen from the sulphate ion to produce hydrogen sulphide, which was converted and stored as elemental sulfur in the porous wood structure. Hydrogen sulphide is toxic to many microorganisms, and this, combined with the low oxygen levels, contributed to *Vasa*'s good preservation – while under water. However, when the ship was raised, oxygen again became available, and with the higher humidity levels in the museum environment, conditions were optimal to produce sulfuric acid in the wood, which precipitated on the surface as the white and yellow sulfur salts. Moreover, the solution of PEG had never been changed during the entire spray period of 1962–79, and the automatic spray system had probably redistributed any acid and soluble iron over the whole ship, thus exacerbating the problem. While only the outer 2 cm of wood is affected, it is this surface layer that contains tool marks and pigments, the cultural information that allows archaeologists and conservators to understand the ship. Therefore this problem cannot be allowed to continue unchecked even if the ship's structure can take it.

The acid problem was deemed urgent enough that grants were made by a number of Swedish agencies to provide 8 million SEK (ca 1.5 million EURO) to study this problem. In October 2003, the "Cure the *Vasa*" research project was launched, with Prof. Lars Ivar Elding of Lund University as Coordinator. Researchers at 5 institutions from 3 different countries are looking at different aspects of the problem.[5] The main focus has been on the role of sulfur, the role and possible removal of iron, whether the PEG is degrading, and how the wood is affected by these conditions. Part I of the project also included microbiology specialists from Portsmouth University, UK, who used advanced DNA/RNA techniques to determine whether bacteria were playing a role in the production of acid. It has since been determined that while bacteria were instrumental in converting the sulphates to sulphides during burial, they are not the major cause of the acid outbreaks in the museum environment.[6]

Vasa is not unique in suffering these problems, as other conserved ships from around the world are also exhibiting signs of sulfur precipitations, including the Skuldelev Viking ships in Denmark, *Mary Rose*, Portsmouth, and the Dutch East Indiaman, *Batavia*, in Western Australia. The National Maritime Museums of Sweden (SMM), the parent organisation of the Vasa Museum, has consequently developed a number of excellent cooperative relationships with these institutions.

Potential Reconservation Measures

The research project has just begun its second phase, looking more closely into practical treatments. Some first aid measures have already been suggested for dealing with the sulfuric acid spots. Since 2001, we have once a year been neutralising about 1700 salt outbreaks on the ship, that show a pH of less than 4, using cloth poultices wetted with sodium carbonate/sodium bicarbonate solution, then covering with polyethylene sheeting to prevent too rapid evaporation. Although the pH initially rises to about 7–8, within 6 months or so, it often drops to levels below 4 again, and it seems that only the outer 0.5 cm of wood is actually neutralised, so this is clearly not a long-term solution.[7] One drawback is that the solution is aqueous, and hence may be promoting the formation of sulfuric acid. We have now decided to stop this treatment, but will continue to monitor the affected areas, and replace the surface PEG, which was removed during the treatment.

Another complicating factor is that although sulfuric acid is concentrated at the surface of timbers, not all surfaces are accessible, as the ship is built in such a complex structure with up to 5 layers of timber, and thicknesses sometimes exceeding a metre. Potential treatments are limited because of the ship's size and the fact that it cannot be moved, so that any treatment will have to take place inside the museum. Therefore, gas, rather than aqueous, treatments are currently being discussed for use on the ship itself. One possibility may be fumigation with ammonia, which is commonly used to neutralise acidic pyrite in geological collections, and was also used to treat the *Batavia* ship in Western Australia, though the effects of an alkaline treatment, even for a very short time, on the wood, is unknown, as are the long-term effects of adding yet another agent to the wood structure.

For the hundreds of loose wooden objects affected with sulfuric acid, a wider range of solutions is available to us. One approach is to remove the iron corrosion products from the wood. Experiments by Prof. Ingmar Persson have shown that the chelating agent, ethylenediamine(*o*-hydroxi-*p*-methylphenylacetic) acid, or EDMA, can effectively be used to remove iron compounds from wood. EDMA was originally developed as a fertiliser for citrus trees growing on carbonate-rich alkaline soils in order to supply iron as water-soluble complexes in aqueous solution.[4] In the experiments on *Vasa* wood, this procedure is reversed. The Akzo Nobel Rexolin AB company of Sweden has produced iron-free EDMA for experiments on *Vasa* wood. When iron-impregnated wood is immersed in a bath of 1–2% EDMA, the solution changes rapidly to a deep-red colour, indicating the formation of the Fe-EDMA complex, and hence the extraction of the iron. This method removes iron more efficiently than EDTA, for example, as well as removing much of the acid, but there are some drawbacks: the solution is quite alkaline, pH 9–11, which we know is potentially damaging to hemicellulose and possibly lignin, especially as the natural pH of oak is 4.5 to 5.5. Also, the artefact needs to be rinsed thoroughly after treatment to remove the red colouration, before being impregnated once more with PEG. This therefore places huge stresses on already weakened wood, and it may only be possible to treat fairly robust objects.

While EDMA may provide a chemical solution to removing iron, at the museum, we are also considering a larger scale approach. When the ship was raised, over 5,500 iron bolts were inserted in place of the original bolts to hold the structure together. At the time, stainless steel was considered too expensive, and so mild steel bolts covered with epoxy or galvanized steel was used. These 1960s bolts are now themselves corroding, and need to be replaced with something more stable. A range of possibilities is being examined including stainless steel and titanium, and particularly carbon fibre embedded in a proprietary polymer matrix, which is light, strong and inert to the chemicals in the ship, and may be combined with glass fibre to provide some flexibility, and possible fibre-optic capabilities. However, it is not proving easy to put a head or a nut on a carbon fibre bolt, and the engineering design of a new bolt is turning out to be more complicated than anticipated. Equally, the old bolts must be removed first. Many of these are now corroded firmly into the surrounding timber, and cannot be driven out without damaging the wood. In the lower parts of the ship, the settling of the last 40 years has pinched and bent the bolts in many places, and it may only be possible to remove half of the bolts now in the ship.

Geodesic Documentation

To help us understand the structural movements of the ship, we have been monitoring the structure using a digital theodolite, measuring in about 400 marker points placed all over the ship, inside and outside.[8] We now have about 5 years of data, and know that the ship is settling downwards about 1 mm per year and the stern is twisting slightly to port. All measurements are tied into the building, which in itself is problematic, as cracks have now been noticed in the 40 year-old pontoon structure.[9]

This geodesic data is helping us in designing a new support system, as the current cradle, which is also over 40 years old, is providing insufficient support for the ship. A method must be found to lift some of the weight of the deck structures off the sides of the ship, as she is gradually being crushed under her own weight. A design project is now under way, in cooperation with the Royal Institute of Technology (KTH), Stockholm, to develop a new cradle for the ship, which includes an internal framework to carry the heavy deck loads separately from the rest of the hull. We cannot alter the original structure, and as a crane cannot be used inside the ship, all of the internal components must be small and light enough that they can be moved and placed with human muscle power only. They also must be non-corrosive, not react with the conservation chemicals already in the wood, and should be compatible with any future conservation treatment. A number of design solutions have been proposed, and a pilot project is being tested on the 12-m-long boat contemporary to *Vasa*.[10]

Climate in the Ship-Hall

One of the most important aspects in dealing with the sulfuric acid problem is maintaining a stable climate inside the museum. The ship sits in a large open space, and there is a huge volume of air (about 125000 cubic metres), which must be conditioned to 55% RH (±4%) and 18–20 °C (±2 °C). The original climate system from 1989 clearly was not up to the task. In 2004, an entirely new system was installed, at a cost of over 40 million SEK (ca 6 million EURO). It has a much greater capacity and finer sensitivity, and a combination of sensors placed around the ship and a central processing unit allows the system to respond in real time to fluctuations in climate that fall within our target levels. It may also be possible to lower the target levels slightly in order to slow down the chemical processes. The effects, of course, must be offset against potential dimensional changes which could affect the integrity and stability of the ship structure, since the ship is a large, complex assembly of thousands of individual elements.

Conclusion

Preservation of a huge structure such as *Vasa* involves a number of different disciplines and projects, and good understanding and coordination of these projects is vital to ensure a successful outcome with maximum efficiency. The sulfur issue tends to attract media headlines, but it is only part of the overall preservation strategy, and a large part of our challenge is to integrate crisis management into everyday preservation work, such as the mundane but still important task of keeping the ship free of dust.

Our problems may be on the large-scale, but so is our public image. *Vasa* is a Swedish icon, and is so viewed by the Swedish government and funding organisations, who continue to give generous financial support. But *Vasa* gives back to the community: we are located in a major metropolitan centre and we attract huge numbers of tourists each year, which have steadily increased to over 850 thousand annually. It was estimated in 1988 that revenues generated annually into the Swedish economy by *Vasa*'s tourists were 275 million US dollars. By now that number is probably over 500 million euros. This visibility also means that conservation challenges at the Vasa Museum are an issue of national public interest as well as international professional interest, so that failure to solve this problem is simply not an option.

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[1] B. Håfors, "*Conservation of the Swedish Warship, Vasa from 1628*", The Vasa Museum, Stockholm, 2001.
[2] Personal communication, Ka-Lai Pang.
[3] M. Sandström, Y. Fors, I. Persson, "*The Vasa's New Battle: Sulphur, Acid and Iron*", Vasa Studies 19, The Swedish National Maritime Museums, 2003, pp. 43–44.
[4] M. Sandström, Y. Fors, I. Persson, "The Vasa's New Battle: Sulphur, Acid and Iron", Vasa Studies 19, The Swedish National Maritime Museums, 2003, pp. 50–55.
[5] The teams include: Prof. Magnus Sandström, and doctural candidateYvonne Fors, from Stockholm University, who are studying the role of sulfur in the wood; Prof. Ingmar Persson and doctural candadate Gunnar Almkvist from the Chemistry Dept. of the Swedish University of Agricultural Sciences (SLU), at Uppsala, who are focusing on the role of dissolved iron in the wood, and methods to remove it, while also analysing the PEG; a team from the National Museum of Denmark, led by Dr. Jens Glastrup, is looking at the possible breakdown of PEG, as well as its role in the other chemical processes; and finally wood specialists, Prof. Thomas Nilsson and Dr. Charlotte Björdal, together with SP-Trätek (Swedish Institute for Wood Technology Research) and STFI Packforsk in Stockholm are looking at the wood structure, and how it has been affected by exposure to sulfuric acid.
[6] K-L. Pang, R. Eaton and J. Mitchell, Molecular detection of bacteria in the seventeenth-century warship, *Vasa*, in *Proceedings of the 9th ICOM Group on Wet Organic Archaeological Materials Conference, Copenhagen* 2004, 243–257.
[7] Y. Fors, "*Sulfur Speciation and Distribution in the Vasa's Wood*" Licentiate Thesis, Dept of Structural Chemistry, Stockholm University, 2005, pp. 50–51.
[8] Initiated by Leif Malmberg in 1998, this study is undertaken by students from the Royal Institute of Technology, Stockholm (KTH) and Vasa Preservation Unit staff.
[9] In October 2005, a three-year study began by Luleå Technical University to examine the extent of these cracks.
[10] Some initial proposals appear in J. Ljungdal, "*Computer based FE-model for evaluation of the support system to the Vasa ship*" Masters Thesis, Royal Institute of Technology, Stockholm, 2004.