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CONSERVATION OF THE WARSHIP VASA
- THE TREATMENT AND THE PRESENT PROBLEMS

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ABSTRACT

In 1628, the Swedish Royal warship Vasa capsized on her maiden voyage. She was salvaged in 1961 and became the first major object to be treated with polyethyleneglycol, PEG. The extensive conservation treatment lasted for almost 30 years. Today a new problem has risen as sulphuric acid is formed in the wood, causing acid hydrolysis of the cellulose.

1. INTRODUCTION

The Royal warship Vasa was built between 1626 and 1628 on order from the Swedish king Gustavus II Adolphus. The ship was to be the foremost of Sweden's warships in the fleet that controlled the Baltic Sea, which at the time was a turbulent area.
Approximately one thousand oak trees were used in the construction of the hull at the naval shipyard in central Stockholm. The total length was 69 meters and the masts measured 52,5 meters in height. With double gun decks carrying 64 large bronze guns and many hundred gilded and painted sculptures decorating the hull, she was the most expensive ship ever to have been built in Sweden.

On August 10 the Vasa set out on her maiden voyage. It was a great ceremonial occasion with the guns firing salute and crowds of curious spectators gathered in the harbour. At the royal castle 120 tons of ballast was loaded and 100 of the total 450 soldiers and crew members boarded the ship. The rest were waiting to be picked up further out in the archipelago. Four of the ten sails were set as the Vasa sailed out of the Stockholm harbour. As the ship left the sheltered position a strong wind entered the sails and made her heel over to the right. Water started to gush in through the gun ports and she sank after sailing only 1300 meters (4000 feet). About 30–50 people drowned in the catastrophe.
The disaster was caused by bad stability as the Vasa was too top-heavy and narrow. Most of the valuable bronze guns were salvaged already in the 17th century, but then the embarrassing wreck sank into oblivion.

2. THE SALVAGE

The Vasa remained forgotten for more than 300 years when an engineer, Anders Franzén, relocated the wreck in 1956 after years of research in archives and searching the seabed of Stockholm harbour with grapnel and sounding line. The very next year divers brought up the first spectacular artefacts, and after an intense "save the Vasa" campaign, foundations and companies donated money and materials in order to salvage the ship. The Swedish Navy made a great contribution by making staff and boats available.

On the bottom of Stockholm harbour the Vasa had sunken deep into mud and gravel. Preparing for the salvage operation, divers from the navy began to flush out tunnels beneath the hull using hosepipes. The work was carried out in complete darkness and the six necessary tunnels took two years to complete. Through the tunnels cables were laid beneath the hull which were attached to water-filled pontoons on the surface. When the water was pumped out of the pontoons they started to rise, stretching the cables and lifting the Vasa from the seabed. The wreck was lifted to shallower water in 16 steps, during which a lot of preparations were made before the final lift. On April 24, 1961 the Vasa finally broke the surface, and once again countless spectators could watch her, on she shore as well as around the world in live broadcast.

3. CONSERVATION OF THE VASA

When flushing the tunnels and lifting the Vasa from the place of loss at 32 meters' depth, it was, despite careful calculations of the vessel's strength, impossible to be totally sure wether the hull would stand the stress or not. Almost all of the iron bolts in the construction had rusted away and the ship was held together only by the numerous wooden bolts driven into the hull. However, the wood the Vasa was constructed from turned out to be very well preserved for several reasons. Firstly because the Baltic Sea has cold, brackish water with a too low salt content for the shipworm to live in. Secondly a great part of the Vasa was covered with anaerobic mud. Parts sticking out were protected from degradation by surrounding water deficient in oxygen, due to oxygen consuming garbage dumped nearby. Furthermore, the Vasa was built mainly of durable oak heartwood, and she was brand new when she sank.

When salvaged the Vasa was put on a concrete pontoon for archaeological excavation and conservation. The mud lay thick on the decks and during 5 months archaeologists uncovered a piece of untouched 17^{th} century by registering 16000 loose finds of varying materials. The artefacts were put into water storage awaiting conservation.
In the meantime the ship was continuously sprayed with water to keep the wood wet. The long-term watering also helped to wash away clay and impurities from the wood. Particularly exposed parts like bare top timber were wrapped in plastic to prevent uncontrolled drying and deformation.
To give the Vasa shelter during the winter period, a building was erected around the ship on the pontoon. Air-conditioning was also installed. In the building the Vasa was to stay for 27 years undergoing conservation treatment. At the same time the building was used as an open exhibition room where visitors could walk on scaffolding watching the ship during the ongoing work.

The salvaging of the Vasa also implied the start of one of the world's greatest conservation projects. At the time of the salvage the conservation question had hardly been discussed. There was no prepared treatment as this was the largest massive find of waterlogged wood ever recovered and that there was no previous practice in the field to draw from. Therefore a Vasa preservation committee was set up with experts in all the different materials likely to be found onboard the Vasa as well as a preservation section. Lars Barkman, a civil engineer from the oil industry, was hired as head of the Vasa preservation department.

The committee was facing the gigantic task of preserving a waterlogged wreck hull with an area of more than 15000 m^2 or 160000 square feet, where 90 % consisted of oak. The others mainly consist of pine, but also for example linden and spruce. Tests proved that the degree of degradation of the wood depended on weather it had been lying in mud or water. Surfaces covered in mud were hard and very well preserved, while those in contact with water, e.g. the upper parts of the boarding and the underside of the decks, showed a well preserved core surrounded by a up to 1 cm thick softer and more degraded surface. Analyses showed an overall moisture content of 150% in the hard wood, while the degraded layers could contain up to 800%. A water content of 1000% was not unusual in smaller findings made from other kinds of wood than oak.

Many statements about the preservation of the hull were made, ranging from the position that no treatment was necessary as she was built of heart oak, to the opposite opinion that the whole project was an impossible task. However, it was quite soon established that some kind of preservation treatment was necessary as tests with controlled drying of untreated wood, showed a shrinkage of 15 % and more, which of course was unacceptable.
Many suggestions of treatments were received. Some, as those based on "miracle-working preparations" were of less use, while others were of great help. A large number of tests with conservation methods and materials used for smaller objects were carried out, but it soon became clear that no suitable ready-made preparation was available that was both rot protecting and stabilising to the wooden structure. Consequently new conservation treatments had to be investigated.

The most promising results were obtained by using polyethyleneglycol (PEG), a water-soluble polymer used in the industry. Previously tests on small waterlogged, wooden objects had proved PEG to be able to enter the wooden cell, replace the water molecule and thus preventing the wood from shrinking and cracking. The Vasa was to be the first major object to be treated with PEG.
To develop a tailormade PEG treatment method for the Vasa, research was still necessary to carry out in order to decide the most effective molecular weight, suitable concentration, treatment temperature and required time for impregnation. For experimental purposes planking from a contemporary ship with similar burial conditions, were used. To start with a 100 % PEG impregnation during strong heat was attempted, but soon showed to block the wooden cells causing a to low moisture content with resulting cracks. Instead the experiments showed the benefits of a long-term impregnation followed by a slow, controlled drying process preventing the PEG to be drawn to the surface again.

When all loose finds on board had been taken care of by the archaeologists a rough washing of the hull and the decks was carried out with water to prepare for conservation treatment. To clean the mud from all the hollow spaces inside the very closely built hull, specially made 3.5 meter long brushes were used.

In April 1962 the spraying of the Vasa with PEG begun. A team of five men sprayed the hull by hand during the first three years. They used PEG 1500 on the well-preserved wood and PEG 4000 on the more deteriorated areas. A complete treatment was carried out in five hours. The relative humidity in the hall was kept at 95 % to delay the drying of the wood and to obtain a maximum absorption of the PEG.

To control the treatment process, core-samples of the wood were analysed. For each run about 30 cores were taken. Over the years a total of 41 runs was performed. The regular measurements of the amount and degree of penetrated PEG after a few years established the fact that there wasn't enough PEG in the wood. To increase the effectiveness a fully automatic spray system was installed in 1965. Pipes with 500 nozzles covered the areas inside as well as outside the hull. In the pontoon a tank was filled with 30000 litres of PEG 1500. The concentration, 10 % initially, was gradually increased. The original aim was to finally spray with 100 % PEG, but the maximum was reached at 43 % as the pumps couldn't handle a thicker solution.
To avoid rot and microbial growth approximately 2 % of a mixture consisting 7 parts boric acid and 3 parts borax, was added as a fungicide to the PEG solution.
Between 1965 and 1972 the ship was sprayed for 25 minutes every 20th minute, or 32 times a day. In 1971 the spraying medium was replaced by the smaller molecular weight PEG 600 in order to further increase the penetration of the PEG molecules, as experiments had shown the wood to be too well preserved to let PEG 1500 in the cell structure. In 1972 the treatment was reduced to two times a day and in 1977 to once a day. After 17 years of impregnation, the spraying was brought to an end in 1979. Excess PEG was led down a floor drain to be collected, then filtered from bigger particles and finally reused. When required the tank was filled up with more PEG and water, but the spraying constituted mainly a closed system.
After the spraying was terminated the wood was slowly dried by a gradual lowering of the relative humidity in the hall during 9 years. It has been estimated that a total amount of 580 tons of water has left the wood during conservation treatment and drying. The goal was to adjust the Vasa to a 60 % relative humidity. Today, the dried wood has a moisture content of 12 – 15 %.

In 1988 the Vasa sailed into her new museum standing on the pontoon. Today the pontoon constitutes the floor in the museum, and inside it the artefact storage is located. At the prospect of opening the new museum in 1990, the hull was surface-treated with 45 % PEG 4000. The PEG was sprayed on and later melted further into the wood with industrial heaters.

4. LOOSE FINDS

Among the loose finds were about 500 figure sculptures and more than 200 ornaments carved in wood. Most of these originated from the Vasa's stem and stern, but came loose when the attaching iron nails rusted away. Some parts were also knocked off as boats have tried to anchor in the area. About 40 anchors from different periods were found in and around the Vasa. The sculptures that fell down were buried in the surrounding anaerobic mud. Many of them are therefore very well preserved compared to sculptures that were fastened with wooden bolts that kept them in their original place on the ship.

To conserve the sculptures and other loose finds a conservation lab was built in connection with the salvage of the Vasa. In the hall two twenty-meter long conservation tanks of stainless steel were constructed. The tanks had automatic circulation and temperature control. Larger objects, like planking, were stacked with small blocks in between to allow circulation of the treatment liquid and smaller artefacts were fastened to prevent then from floating to the surface. It took a fortnight to load a tank. The artefacts were impregnated with PEG 4000 for one year, starting with plain water the concentration of PEG was gradually increased over the treatment period to 45 %. To increase the penetration of the PEG molecules the temperature was kept at a constant 60°C.
After the finished impregnation the artefacts were moved to a, for the purpose purchased, boat nearby the conservation lab, in which the air humidity could be carefully controlled. Like the hull, the artefacts were dried to equilibrium with 60 % relative humidity and finally surface treated with 45 % PEG 4000.

The treatment worked very well on compact and more robust finds, but some of the more delicate artefacts were considered too fragile to be treated with slow drying. As there were no alternatives good enough, it was decided that they should be kept in water storage awaiting a new and more suitable conservation treatment to be developed. This proved to be a wise decision as the freeze-drying was introduced as a method for preserving waterlogged wood in the beginning of the 1970's. The saved artefacts were impregnated with 5 % PEG 400 for a month, after which they were freeze-dried with excellent result.

5. RESTORATIONS

When the Vasa was salvaged the hull was intact but most of the stern was crushed as well as the upper deck and the head of the ship. Since 1961 the ship has gradually been restored and most of the sculptures have been put back in place. The Vasa has been called the world's largest jigsaw puzzle, since about 13500 pieces were to find their original place on the ship. By bushing a thick steel wire through the old nail-holes in the loose finds, it was possible to relocate the original place by looking for matching holes on the hull.

Today the stem, as well as the stern and upper deck are restored with both original and new material. About 95 % of the ship is original. To make it clearly visible to the visitor, which parts are new and which are original, the new wood have in most places been given a lighter colour and a smoother structure than the original parts. During the last years the Vasa has also been rigged with lower masts and reconstructed tops, shrouds and stays.
Today the Vasa is the best preserved 17th century ship in the world. She is an important source of knowledge as to the naval architecture and conditions of life onboard a ship, as well as the numerous sculptures constitutes a unique collection of art from late Renaissance. About 750 000 visitors per year, makes the Vasa Museum Scandinavia's most popular museum.

6. PRESENT PROBLEMS

In the autumn of 2000, numerous stains of precipitation were observed inside the Vasa's hull as well as on belonging wooden artefacts on display and in the storage room. The stains varied from crystalline white shadows on the surface, to deeper, yellow stains where the wood had softened. As pH was measured, values below 3 were obtained. Such a low pH is particularly unsuitable for the wood as it causes acidic hydrolysis of the cellulose. The discovery therefore initiated an intense research to find out the nature and character of the problem.

By using x-ray powder diffraction analyses (XRD)*, the surface deposits were identified to consist of various crystalline hydrated sulphates. Most frequent was gypsum, but also sodium-, ammonium-, potassium-, magnesium-, iron- and calcium-hydrated sulphates as well as crystals of elemental sulphur (brimstone S_8) were identified.
The sulphates originate from the Vasa's 333 years on the seabed when reducing bacteria stored it into the wood as elemental sulphur and sulphides. Since the ship was salvaged and brought into the air, the reduced forms of sulphur have been oxidising through a number of intermediary steps. In present aerobic condition sulphate is the thermodynamic stable end product. Unfortunately what seems to be sulphuric acid is also formed during the oxidising process, which explains the very low pH measured at the Vasa.

To establish the amount and gradient of the sulphur in the wood, x-ray photoelectron spectroscopy (XPS, also called ESCA)** were used. Core samples from the Vasa showed the total sulphur content to have a concentration of 6 mass %, which decreased with the depth into the wood. The surface level was almost 20 times higher than the lowest measured level.
By further analysing wooden core samples with x-ray absorption near-edge spectroscopy (XANES)*** the oxidation states of the sulphur were estimated at various depths in the wood. The result showed that about 65 % of the sulphur on the surface were oxidised to sulphate. Closely below the surface the relative amount of reduced forms of sulphur increased into the centre of the core.
The XANES spectra also clearly showed several intermediate oxidation states, between 0 and VI, in the wood. This proves a continuous oxidation process of the reduced sulphur, which is alarming, as it shows the forming of sulphuric acid still to be an ongoing process. Probably the formation process is being catalysed by the presence of iron in the wood.
In the wood of the Vasa, a large amount of elemental sulphur is subject to oxidation. If the introductory analyses done are representative, calculations show that as much as 5000 kg of sulphuric acid is waiting to be formed in the wood!

As the sulphur has been oxidised ever since the Vasa was salvaged, sulphuric acid must also have been formed during the 17 years of spray treatment. Actually, the sulphates present today corresponds to the prior formation of about an equal amount of sulphuric acid.

* The analyses have been performed at the Swedish National Heritage Board in Stockholm.
** The analyses have been performed at Uppsala University, Sweden.
*** The analyses have been performed at the Stanford Synchrotron Radiation Laboratory (SSRL), USA.

It's likely that the acid has then been washed away and neutralised by the borates that were added as fungicide to the PEG-solution. By ESCA a fairly high concentration of borates has been detected all the way down to 80 mm depth, which indicates that the boric acid has had a remarkable ability to penetrate the wood. Analyses are to be done on saved examples of the used PEG-mixture to find out what it consists of.

Resembling problems with salt precipitation have previously been reported from the PEG impregnated Dutch ship Batavia that sunk outside Australia in 1629, and the Danish Viking ships (11th century) from outside Roskilde. Their analyses have shown a considerable amount of pyrite (FeS_2) in the wood. The pyrite is formed when iron is present at the reduction of hydrogen sulphide. When pyrite is oxidised it forms sulphuric acid, as is the case with the elemental sulphur in the wood of the Vasa. Furthermore, oxidation of pyrite causes an up to 25 times volume expansion of the salt, which can damage the wooden cell from the inside. In the Vasa, luckily, so far only traces of pyrite have been detected.

Actually, this is not the first time precipitation of salts has been noted on artefacts from the Vasa. Already in the 1960's salt precipitation was observed on objects brought up between 1957 and 1961, before the Vasa had been salvaged. These artefacts were only treated by having a few coatings of PEG painted on, in order to quickly be put on exhibition. As salt begun to appear most of the objects were soon retreated with a full tank treatment as explained above.
Being attended to precipitation on objects, the conservators working with the Vasa early on emphasised a careful washing and desalination of the wood. In practice the loose artefacts were as a rule kept in water storage for at least one year prior to conservation.
Also later on salts and discoloured stains have occasionally been noted on the artefacts, but as they have been few and sporadic no pH value has been measured. Therefore no one has seen the problem coming and the wood has consequently remained untreated.

7. THE CAUSE OF THE PROBLEMS

The major outbreak of salt precipitation in the autumn of 2000 was caused by the exceptionally rainy summer in Sweden. Rain doesn't only mean suitable weather for visiting museums, but also contributes to visitors bringing wet clothes and umbrellas inside. During the summer months the humidity in the exhibition hall therefore increased to an extent where the climate distribution system couldn't keep to the set standard of 60%. In fact at several occasions the relative humidity rose all the way to above 70 %. In the humid air, the wooden ship adjusted to a new equilibrium moisture content, and the hygroscopic PEG 600 helped to absorb even more water. As most crystalline sulphate salts found on the Vasa are easily dissolvable they were solved when the water-PEG content got high enough, and wandered back and forth in the wood as the relative humidity fluctuated. Furthermore, oxygen was transported in the water, oxidising more sulphur.
When the relative humidity decreased in the autumn the wood again released water, implying the sulphate concentration to become higher and finally the salts to precipitate.

It's obvious that parts of pine are the most affected on the ship, as it's a porous wood where sulphur easily has penetrated. Oak is considerably harder and denser and therefore used for the carrying construction parts. Where oak is affected from sulphuric acid, it's mainly in the sapwood. Other leafy trees are not numerous, but are when present generally as badly affected as the pine.

Totally about 500 sites of salt precipitation have so far been detected inside the ship. Examination of the exterior of the hull has just recently started, but already precipitation has been detected there as well.
Comparing different areas on the ship, it seems like the two lowest decks, i.e. the hold and the orlop deck, are the worst affected. There, yellow stains with pH between 3 and 1, are to be seen in large amounts. The yellow stains consist of natrojarosite ($NaFe_3(SO_4)_2(OH)_6$, formed by sulphur ions reacting with sodium and iron at a low pH.
The unevenly dispersed precipitation is probably to some extent caused by differences in the conservation treatment. The whole ship, except for the hold and orlop deck, have been surface treated with high molecular PEG 4000. There is reason to believe that this coating has protected the wood underneath by forming an oxygen barrier, preventing the sulphur to oxidise. Moreover it has delayed the rapid moisture absorbency into the wood.
The hold and orlop deck are also probably badly affected as there are more construction parts of pine than on the other decks, as well as the amount of very thick oak beams with remaining parts of the sapwood.

8. ACUTE PROCEEDINGS

By regularly pH measurements carried out during 6 months, the acidic values have been shown to decrease further if nothing is done. To protect the wood from further hydrolysis, an acute treatment therefore has been initiated with the purpose to momentarily neutralise the acid. Detected acidic stains are covered with highly absorbing cloths soaked in a 5% solution of sodium hydrogen carbonate (bicarbonate, $NaHCO_3$) and sodium carbonate (Na_2CO_3) in the proportions 2:1. The solution has pH 10. The cloth is covered with plastic to prevent a too fast evaporation. When the pH 4 is exceeded, iron precipitates on the surface as iron hydroxide.
After the treatment measurements have shown the pH to immediately rise, and then slowly decrease back over a few months as new sulphuric acid is being formed in the wood. By retreating when necessary, the pH can in this way be controlled while waiting for the development of a more efficient treatment method. However, there are concerns regarding the hidden surfaces inside the hull that can't be examined nor treated in this way, but possibly the access of oxygen is less in those places and the problems less developed.

To further decrease the oxidation rate, a temporary and more powerful air condition system was installed at the Vasa Museum in the beginning of the summer in 2001. As the oxidation of sulphur requires a certain amount of water, the relative humidity standard was lowered to 55 ± 4 % in order to arrest the reactions. Also the temperature is kept as low as possible, e.g. maximum 20°C, to slow down the chemical processes. There are limits though, as there must be a balance where the visitors are comfortable.

21 permanent and 10 mobile relative humidity- and temperature sensors, placed in different levels on the ship, measure the climate. The sensors read a value into a computer every ten minutes.
However, the decrease of the relative humidity must be carried out carefully, as too dry a climate causes shrinkage and cracking of the wood. Deformation is of a prime concern since even a slight change can have serious implications on the complex structure of the ship.
Therefore continuous controls of the state of the ship have been made since the salvage. Movements of the board planks are measured with a sliding calliper at fixed points, and the whole ship with a geodetic total station. Together with weighing of reference planking a very precise picture of the trends is given.
The measurements made in the autumn 2001 were the first to be done since the temporary air condition system was installed and the relative humidity lowered. As expected, the wood showed greater movements than before. It is a matter of millimetres, but during the last months the whole ship has leant towards port side. Therefore the limit of lowest possible relative humidity in the exhibition hall must be considered reached. From now on, the most important thing is to keep an even climate in order to prevent water and salts from wandering and transporting oxygen in the wood, due to fluctuating moisture content.

9. THE FUTURE

It's obviously not possible to terminate the ongoing oxidation process only by drying the wood without jeopardising the stability of the ship. Probably there is not one single solution to the problem, but an arrest will require a combination of several measures.
As the reduced sulphur requires special circumstances to be oxidised, there are following factors to work with:

- access to water
- access to oxygen
- the temperature
- presence of a catalyst

By eliminating or decreasing one or more of those parameters, a considerable delay in the formation of sulphuric acid can be achieved.

A factor of the problem that particularly requires further research, is the presence of material catalysing the oxidation process of sulphur. In the wood of the Vasa, such a catalyst is iron. Possibly there are also catalysing bacteria present, however such has not yet been detected.
Considerably amounts of iron from corroding iron bolts have penetrated the wood during the time on the seabed. Furthermore, in 1961 about 8500 new iron bolts were put into the old holes, to strengthen the hull of the Vasa before the salvage. In contact with moist and PEG, these bolts are now corroding, constituting a long-term source of iron ions if not removed. Inversely, there are also indications of the iron causing degradation of the PEG.
Obviously there are several important reasons for removing the iron in the wood. There are considerations concerning exchanging the iron bolts with a more inert material. The best to use would probably be bolts of titan. To neutralise the iron ions a chelating agent, EDDHMA (ethylene-diimino-bis(2-hydroxy-4-methylphenyl)acetic acid) is being tested. The chelate is particularly interesting as it can form exceptionally strong complexes with iron, and is effective

on a wide pH scale, from at least 4 to 11. The only unsuitability effect might be a red colouring of the wood where the complex is formed. Due to the circumstances this must however, be considered as less of a problem. Furthermore most of the Vasa consists of black oak, why the colouring probably hardly will be visible.
To secure the most delicate work, a project is running where the sculptures are being copied and cast in epoxy.

10. COLLABORATION

The Vasa Museum is performing the research work concerning the problems with sulphuric acid being formed in the wood, in co-operation with Swedish National Heritage Board and professors at Swedish Universities. This has turned out to be particularly giving, for example the analyses with the ESCA and XANES techniques earlier mentioned, have not been applied on this type of problem before. Furthermore, within a short time two Ph.D. students will begin to look deeper into the problems.
The worldwide similarities in the problem with salt precipitation make an international collaboration important. Already an exchange of tests and information has initialised between the Vasa Museum and Western Australian Maritime Museum.

Today, about a year after the first major salt precipitation was detected inside the Vasa, an intense work is in progress in the search for a long-term solution of the problems. Therefore, parallel with acute proceedings in order to freeze the present state, more analyses are being performed, throughout research is planned and founding is searched for.
What ever a future treatment of the ship will look like, one thing for sure is that it will require more than one throughout going working moment. For example: due to the iron source, it's pointless to start any major treatment until the present bolts have been exchanged, and the bolts can't be exchanged in an effective and secure way until a new cradle for the Vasa to rest on has been constructed.
We must be patient and realise that this is a problem that will take a long time to solve, as there are still many questions to be answered.

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