Maintaining a Stable Environment: *Vasa*'s New Climate-Control System

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An extensive upgrade to the air-conditioning system of the Vasa Museum in Stockholm is playing an instrumental role in preserving the seventeenth-century Swedish warship *Vasa*.

Introduction

The Vasa Museum in Stockholm, Sweden, houses the seventeenth-century warship *Vasa*, the largest and best preserved wooden ship ever salvaged from the seabed and conserved. The warship, adorned with hundreds of painted sculptures, was commissioned by King Gustav II Adolf, who had ambitions to dominate the Baltic region. It was thus a huge embarrassment when the ship sank unceremoniously in Stockholm harbor on its maiden voyage in 1628. Salvaged in 1961, the ship underwent a pioneering conservation program for 26 years.[1] In late 1988 the conserved ship was floated on its pontoon into a dry dock through the open wall of the purpose-built Vasa Museum, which has since become the most visited maritime museum in the world. Although the ship is not open to the general public, museum staff regularly go onboard for research or maintenance purposes.

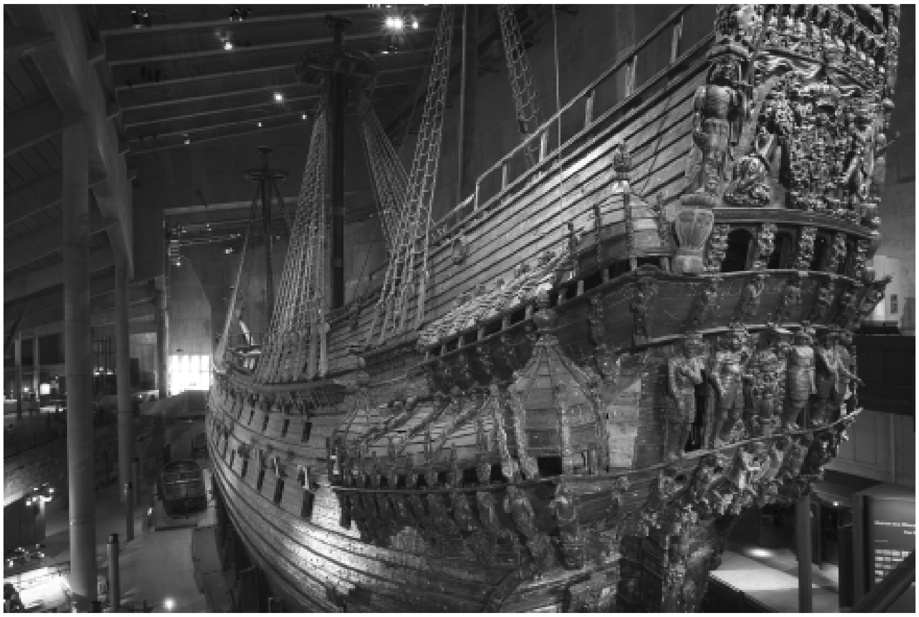

Fig. 1. The hull of *Vasa* on display in the purpose-built Vasa Museum in Stockholm, as seen from the viewing galleries at level six. Photograph by Karolina Kristensen, all images courtesy of Swedish National Maritime Museums.

Although the largely anoxic (oxygen-deficient) burial conditions in the Stockholm harbor had generally favored wood preservation, there was sufficient oxygen available in the murky waters of the harbor immediately after the sinking to allow micro-organism degradation of the outer 3/4 in. (2 cm) of wood. In order to prevent shrinkage and collapse of these weakened wood cells once the ship was raised, a material that would diffuse into the wood and take the place of the water in the cells was needed. The material chosen was a water-soluble wax, polyethylene glycol (PEG), which was sprayed over the hull in increasing concentrations over a 17-year period, followed by a 9-year period of slow air drying, during which the relative humidity (RH) around the ship was gradually reduced from about 90% to 60%.[2]

Built predominantly of oak, the ship is a monumental structure, the equivalent of a 7-story building; it weighs approximately 900 tons. The hull is 226 ft. (69 m) long, including the bowsprit; 63 ft. 6 in. (19.4 m) high at the stern; and 105 ft. (32 m) to the top of the existing masts (Fig. 1). Unlike a wooden building, however, a ship is designed to sit in water, where its weight is evenly supported. Exhibiting such a complicated, curved structure on dry land is problematic, and *Vasa* currently sits on a steel support cradle of 18 pairs of stanchions connected by large I-beams. Wooden wedges between the stanchions and the hull must be adjusted periodically in order to provide good contact and even support. The enormous weight is therefore concentrated at point loads, which has resulted in the sagging of the weakened wood structure between the stanchions and the crushing of the keel.[3]

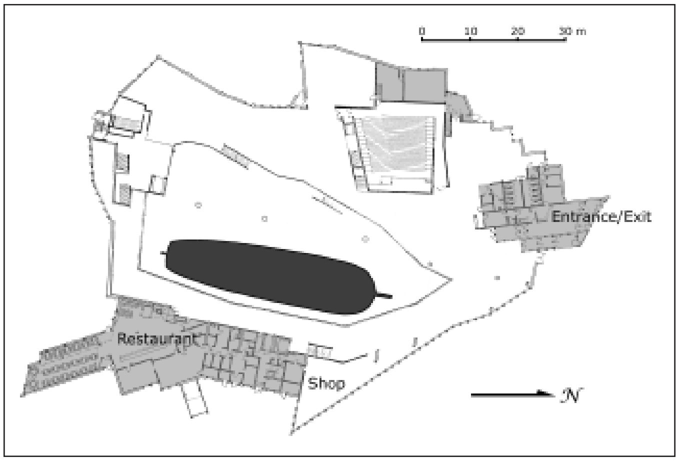

Fig. 2. Plan of the Vasa Museum. Shaded regions signify areas outside the climatized spaces. Illustration by Fred Hocker.

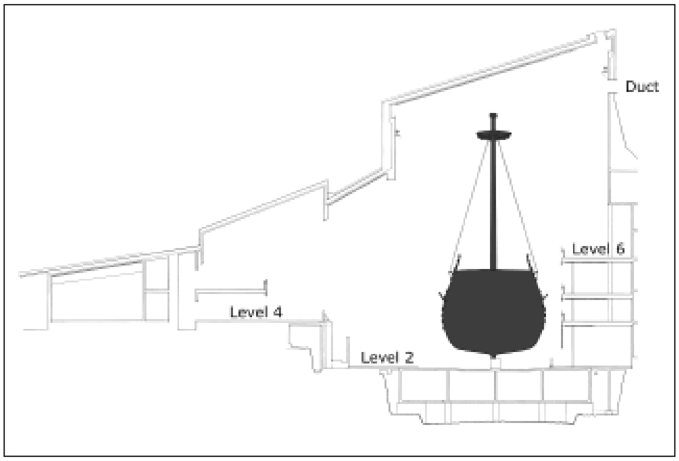

Fig. 3. North-south section through the museum. Illustration by Fred Hocker.

Work is underway to document the structure as it sits today and to examine the ship's movement in relation to seasonal changes in order to design a new support system. Another future task is to replace the mild-steel bolts that were inserted in the 1960s to hold the ship's timbers together, a measure that will improve the hull's structural integrity.

Entering the Display Case

The museum was designed with an internal airspace of about 3,708,000 ft.^{3} (105,000 m^3) and with a maximum ceiling height of 119 ft. 10 in. (36.5 m). The hull is placed towards the east wall, with the bowsprit pointing towards the main entrance to the north. Exhibit areas are concentrated on the port side to the west (Figs. 2 and 3). The museum is entered via double air locks from outside or single air locks from the offices and restaurant. This setup presents an unusual challenge in climate management, as it results in a very large air volume that must be maintained at very close tolerances of temperature and humidity but subjected to high traffic. This situation is further complicated by the enormous heights necessary to accommodate the masts and tops (the round platforms at the mast heads). Naturally, temperature gradients occur, especially in the warmer summer months, which in turn produce RH gradients, with more humid air concentrated at lower levels.

One aspect not fully appreciated when the museum was built was the enormous public interest in the ship. During the 1990s visitor numbers exceeded the original predictions of 600,000 per year by 33%, and since 2004 visitor numbers have steadily increased, mostly due to the museum's deliberate marketing strategy combined with more cruise-ship arrivals in Stockholm, which culminated in almost 1.2 million visitors by 2009. Fire-safety regulations restricted the number of visitors inside the museum at any one time to 1,440, but this number was only recently enforced; as a result of the extra visitors, the climate system was often overloaded during the summer. The museum is understandably more popular on rainy days, and wet clothing and large numbers of exhaling visitors therefore create very humid conditions, which the air-conditioning plant must deal with. Visitors to the Vasa Museum essentially enter a huge display case, and maintaining the environment in this air volume is no easy task. While light levels can be minimized and dust removed, the control of temperature, and especially RH, in such a large building volume requires special measures.

Consequences of an Unstable Climate

A stable RH is an essential part of the long-term preservation of archaeological wood treated with polyethylene glycol (PEG). Not only is organic material particularly sensitive to fluctuations and extremes of humidity and temperature, but the conservation agent, PEG, is hygroscopic, meaning it will readily absorb and desorb moisture from the atmosphere. Humidity fluctuations can therefore lead to moisture transport within the wood, which causes both physical and chemical problems. Too high a relative humidity (over 70%) can promote the growth of mold and other micro-organisms on the wood, as well as make the surface of the PEG sticky. These changes in turn increase the ship's weight, thus increasing the stress on the support structure. Too low an RH will cause shrinkage and cracking of the wood, which is compounded in a large, three-dimensional structure, where complex wooden joints are subject to extra strain. Regular monitoring of the ship between 2001 and 2003 using a total station revealed seasonal movement and twisting of the hull, mainly due to humidity fluctuations.[4]

One of the effects of moisture transport caused by fluctuating RH has only been recognized in the past decade, primarily through visual evidence found on the ship's timbers. Sulfur compounds in the polluted waters of Stockholm harbor remained in the wood, and upon exposure to air they reacted with iron from corroded bolts and moisture in the museum environment to form a range of acids and other harmful compounds, which can potentially deteriorate the wood and reduce its mechanical strength. A secondary problem is that cycles of wetting and drying in the museum environment have caused these compounds to be drawn to the surface of the wood, where in drier conditions they precipitate as a range of acidic iron

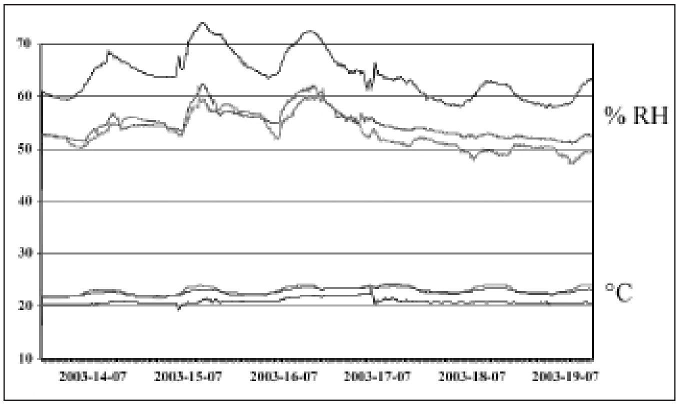

Fig. 4. An example of the fluctuating temperature and RH taken from three sensors on the ship in July 2003.

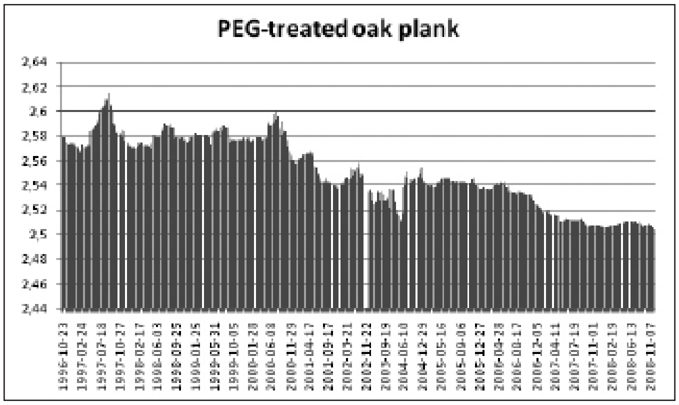

Fig. 5. Weight fluctuation in kg of an oak plank impregnated with polyethylene glycol that has been stored on board the ship since 1996.

sulfate salts, predominantly yellow in color.[5] The volume increase of the salts as they crystallize has caused the surface of the wood to spall off in places, resulting in the loss of surface detail on carved elements. Although it is likely that these processes had begun after the ship was raised, the results became particularly apparent after the wet summer of 2000, which, combined with large numbers of visitors, saw dramatic fluctuations in the RH. An example of the museum climate from July 2003 taken from the climate sensors onboard the ship shows the RH at some points lower down on the ship hull rise above 70% and then drop by 10% overnight (Fig. 4).

Once moisture was identified as a problem, it was decided that the average RH in the exhibit hall should be reduced from 60% to 55%. The ship continues to dry out and is only now approaching a stable condition. Much of this climate history can be seen from the weight fluctuation of a PEG-treated oak timber from *Vasa*, which has been stored on one of the lower decks since 1996 (Fig. 5).

The Need for a New Climate-control System

The museum's original climate-control system from the late 1980s was designed to handle 3,178,000 ft.^{3}/h (90,000 m^3/h) of air, distributed through 20 cylindrical drums situated around the hull on level two. The conditioned air was directed upwards, creating a protective air curtain around the ship rather than conditioning the entire exhibit space, and then evacuated through a large duct on the east wall near the ceiling (Fig. 3) and returned to the plant, where it was filtered, dehumidified, and cooled to about 45°F (9°C). For visitor comfort, about 30% outdoor air was included in the conditioned air, which was then redirected into the museum. Onboard the ship an internal air-distribution system, with air exchange of 247,200 ft.^{3}/h (7,000 m^3/h), was adapted from the ducting used during the post-conservation drying. When the museum opened in 1990, specifications of 60% RH and 68°F (20°C) were set for summer months, and 57% RH and 62°F (17°C) in winter to reduce the risk of condensation in the walls of the building.[6] These values corresponded to a target moisture content in the wood of 10 to 12%. Temperature and RH were recorded every 10 minutes through 21 permanently mounted sensors (17 on the exterior and 4 on the interior of the ship) and 10 portable sensors. The basic principle of this system was to distribute conditioned air by convection and thus avoid causing uneven drying of the wood through fan-assisted circulation. The temperature and corresponding RH gradients caused by the building height were accepted as inevitable. In practice, however, the system was under-dimensioned and too often ran at full capacity. The RH targets were frequently exceeded, and data typical of those seen in Figure 4 were regularly recorded.

Clearly one of the major measures in ensuring long-term preservation of the ship, both chemically and structurally, was establishing a stable climate. Complicating matters, however, was the fact that although the Vasa Museum is responsible for the ship, it does not own the building or air-conditioning system. Persuading the landlord, the Swedish National Property Board, that an upgrade was necessary was not an easy task, especially as their sensors, which were located in the ducts providing conditioned air to the exhibit space, showed the target values. Sensors placed by the preservation staff directly on the ship, however, deviated from these readings substantially. Although the landlord had already decided to replace the cooling plants with more efficient units, which would also improve airflow and air quality in the museum, it was the evidence of the salt outbreaks that finally persuaded the authorities in December 2002 that a major and expensive overhaul of the system was needed.

To assist with the planning and design process, the museum hired a heating-and-ventilation company as consultants, and with their assistance a comprehensive evaluation of the existing air-conditioning system was conducted, which continued over the next two years. A gradient of around 10% RH was found between lower decks and underneath the ship and high up in the stern and masts. Large fluctuations were also recorded at the forward starboard hull area near the entrance to the museum shop and the rear starboard area near the restaurant, areas where doors were often left open to improve air circulation and where unconditioned air could enter freely. Public congregation points were also examined, which showed areas of strongly fluctuating RH at the viewing galleries on level six at the stern, areas where stronger lighting

Fig. 6. Specially designed duct heads used to provide efficient distribution of climatized air inside the ship. Photograph by the author.

was also concentrated. Smoke visualization tests showed that the airflow was uneven in the hull interior, especially on the lower decks, where pockets of higher RH were created, and that the ducting was in poor condition and leaking.[7] Much of this information had been reinforced by the evidence of the salt outbreaks, which were more numerous and exhibited lower pH levels in areas exposed to higher or fluctuating RH levels.[8] The design and capacity of the air-conditioning system were also examined, as were the effectiveness of the supply ducts and the location of sensors for controlling and monitoring the climate. Computer simulations using computational fluid dynamics analyzed the effects produced by evening events or banquets and times of maximum load to the system, for example in July and August, when visitor numbers are highest and maximum dehumidification is required.

The New Climate-control System

For the new climate-control system, the preservation staff stipulated a year-round temperature of 18.5 ± 1.5°C (i.e., 62-68°F, 17-20°C) and RH of 55 ± 4% (i.e., 51-59%), a figure comparable to 10% moisture content in wood. Based on the fire regulations of the time, which allowed a maximum of 1,440 visitors in the museum, it was agreed that the system should be slightly over-dimensioned to accommodate 1,500 persons. Moreover, based on the recommendation of the consultant, who had particular experience in designing medical facilities and hospitals, the museum required that a reserve power supply should be installed in case of power failure.

Construction of the new climate-control system took place between 2003 and 2004, during which temporary air-conditioning units were in operation at the museum entrance. The principle of the new system is similar to that of the old but with improvements; the major plant, CA01, circulates conditioned air through the drum-shaped outlets underneath the ship and through ducts inside the hull, providing a protective curtain of conditioned air around the ship. The air is then removed via the large duct in the east wall and returned to the plant in the basement. After advice from the museum consultants to improve airflow inside the ship but also protect the wood from drying too rapidly, the ducts onboard the ship were shortened in some cases and repositioned to allow at least 3 ft. 3 in. (1 m) of free space around them. The specially designed duct openings were retained, since they provide efficient multi-directional distribution of the conditioned air (Fig. 6). With leaks removed, the average airflow is now 409.7 ft.^{3}/h (11.6 m^3/h), compared to 190.7 ft.^{3}/h (5.4 m^3/h) previously, and air exchange is now doubled to about 8 volume changes per hour.

To combat problem areas in the museum, auxiliary systems have also been installed. As visitors tend to congregate to look at the sculptures adorning the stern, a second plant, CA02, delivers conditioned air through small slits located in the walls of the visitor galleries on levels four and six, and ducts high on the south wall of the museum above the stern are connected to plant CA03 (Fig. 7). Controlled by nearby sensors on the ship, these plants are designed to remove extra moisture. Since the ship does not sit at the center of the museum, there is consequently a huge volume of air on the port side. Plans to include air-conditioning in this area were struck from the 1980s designs for reasons of cost, but with the latest upgrade, six columns 11 ft. 6 in. (3.5m) high connected to CA01 have now been installed in this area; they are guided by sensors on the port side of the ship. These columns are capable of distributing conditioned air to a height of 52 ft. 6 in. (16 m) to create a “climate umbrella” around the hull (Fig. 8).

Sensors

Temperature and RH monitoring is done by 42 sensors mounted directly on the ship hull, inside and out. One of these sensors has no permanent placement but has proved useful when other sensor readings need to be checked, as it can be moved around the ship as necessary. A further 15 temperature and RH sensors are used in other components of the system, one of which is placed on the exterior of the building, allowing comparison with external environmental conditions. The sensors, Vaisala HMP 230, have tolerances of ±0.04°F (±0.15°C) and ±1% RH. In order to minimize the number of cables on the ship, cordless sensors were investigated. However, since they can easily be affected by radio traffic, are slower to transfer information, and require more work to replace batteries, hardwired sensors were eventually chosen, each connected to individual display boxes sitting on the ship, which show real-time temperature and RH (Fig. 9). Certain sensors may be chosen to guide the system, and should the average RH readings from these sensors exceed the specified values for more than 10 minutes, automatic alarms sound in the landlord’s and security-personnel offices.

Monitoring the Climate

A shortcoming of the old system was that only a week’s worth of data could be stored on the landlord’s hard drive. Preservation staff received print-outs of the sensor readings a week after they were recorded, by which time it was too late to make adjustments. The advantage of the new system is that data may be accessed by logging onto the landlord’s server, which shows climate data in real time. Also, comparisons can be made over longer periods, up to the previous two years. Diagrams can be

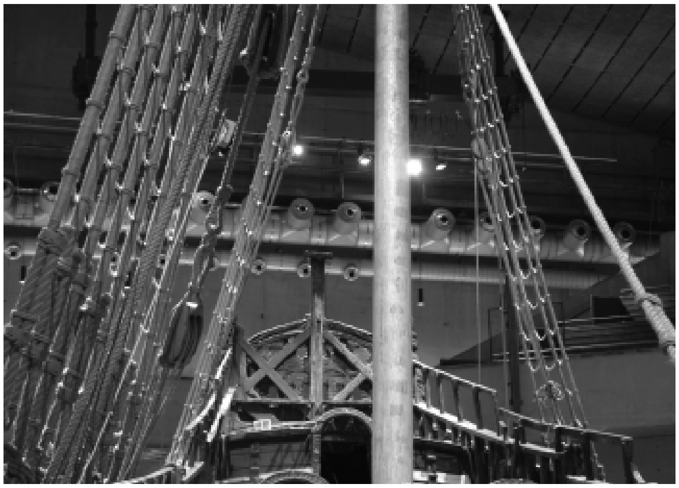

Fig. 7. Ducting at the stern of the ship, part of auxiliary plant CA03. Photograph by the author.

Fig. 8. Auxiliary vertical ducting on the port side of the hull. Photograph by the author.

generated from any combination of sensors and time periods, from hours to years. Past data can be saved as diagrams or generated from the back-up files, which the landlord forwards weekly to museum staff as text files.

Initial Results and Lessons Learned

The new system came on line in May 2004 and was trimmed in July 2004 with visibly effective results (Fig. 10). The almost 10% RH gradient over the height of the ship was halved immediately, and by the end of summer 2004 the data curves appeared to be converging even more, averaging about 52 to 55% RH. Since 2004, efforts have been concentrated on fine-tuning the guidance parameters, both to improve energy efficiency and to achieve the best balance of factors for the ship; for example, adjusting the balance between the humidifiers, de-humidifiers, cooling units, and distribution fans. At first, sensors near the bottom of the ship, where freshly conditioned air emerges, were chosen to guide the main plant; however, a better overall climate has now been achieved by changing two of these primary sensors for two halfway up the hull, which are more sensitive to ambient changes in museum climate. There is still a tendency in summer months for the RH and temperature bands to spread in reaction to higher external temperatures and greater numbers of visitors, but these data still fall within acceptable levels and are appreciably better than in previous summers. Indeed, the system has functioned so well that the average RH for the rest of the year is now 53 ±2% at all parts of the ship. Daily RH fluctuations at any sensor are reduced to around ±2%, helped in 2008 by the introduction of more energy-efficient lighting in the museum.

While preservation staff can view data, any technical adjustments to the system must be done by the landlord, and so it has been necessary — and productive — to develop a smooth working relationship with the technicians. Regular meetings are held to discuss pertinent issues and to fine-tune the system to everyone's benefit. A long-term goal has been to be more proactive than reactive in moderating the climate. A sensor that measures carbon dioxide levels from visitor respiration has always been part of the climate-control system, but since September 2009 the visitor counter at the museum entrance has been incorporated into the control parameters. It is now possible to get advance warning of potential large loads and in theory prepare high-traffic areas, such as the stern galleries, which may need to be dehumidified in advance.

For all the sophistication and success of the new system, however, traditional techniques of measuring RH are still employed. Thanks to regular measurements by preservation staff using an Assmann psychrometer (a type of wet/dry bulb psychrometer), the newly installed RH sensors inside the ship were revealed to be reading 3% too low about 6 months after installation. The manufacturer's theory was that due to the unique chemical composition of wood in the *Vasa*, "unknown substances" were saturating the sensor membranes and distorting the readings. Although air samples and samples of the membrane were sent for analysis, the results were inconclusive, as the manufacturer was unwilling to reveal the full chemical composition of the membrane. This predicament has been solved by investment in a portable sensor with a chemical purge function; that is, the sensor may be heated to 320°F (160°C) for 2 minutes to burn off any built-up deposits on the membrane that might reduce its ability to absorb water molecules and reduce its sensitivity. This portable sensor is sent annually for calibration. Each spring before the peak tourist season, all sensors on the ship are individually adjusted to match the newly calibrated portable sensor, which is chemically purged each morning. The landlord then uses the same sensor to calibrate those in the plant. This solution avoids the impractical and expensive alternative of sending all sensors to the manufacturer for annual calibration.

Costs and Environmental Considerations

The upgrade of this sophisticated system has not been cheap. Installation costs are estimated to be about 50 million SEK, with another 30 million

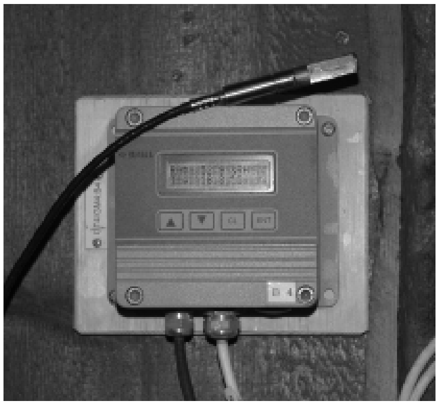

Fig. 9. On-board sensor and display box. Photograph by the author.

SEK in consultant fees, etc. (a total of US$8.8 million or 7 million euros). Financial responsibility has been divided; although the landlord paid for the bulk of the installation costs, the museum purchased the sensors and the back-up generator and hired the consultant, but it is now paying indirectly for some of the landlord's costs through increased rent.

However, significant savings have been made. The operating costs have actually been reduced, helped in large part by the landlord's environmental-policy goals to reduce greenhouse gases and move to cleaner fuels. The oil-burning furnaces have been replaced by cheaper and cleaner electrical-powered heat pumps, and the three cooling units are now cooled by water from the nearby Stockholm harbor, thus eliminating the need for the ozone-degrading substances in the earlier refrigeration units. According to the landlord, annual energy savings of 10-15%, or 400,000 kilowatt-hours, have been achieved.[9] The system still draws in 30% fresh air, but only when it is needed for visitor comfort in the daytime, and so savings can be made after opening hours.

Conclusions

The new climate-control system at the Vasa Museum has proven that a stable climate can be achieved in a huge volume of air — probably one of the largest internal public spaces in the world maintained at this close tolerance — but at a cost that most museums are unlikely to be able to fund. In this regard, the role of the *Vasa* in attracting tourism to Stockholm helps to explain why this enormous financial outlay was approved by the state, which oversees the National Property Board. Costs aside, the resulting stable climate has exceeded the expectations of preservation staff, the technicians, and even the consultants. That the height gradients and daily fluctuations in such a huge volume of air have been minimized is nothing short of remarkable.

One of the clear consequences of a more stable climate has been seen in the salt-outbreak problem on the ship: since 2004 no major new outbreaks have been identified, and the pH of the existing precipitations has stabilized, strongly indicating that major moisture movement has been abated. This is clearly a positive effect for *Vasa*'s wood chemistry and, due to the size of the ship, likely the only practical measure that can be taken in the short term to treat the outbreaks. From a structural viewpoint, the semi-annual geodetic measurement of the hull form has not shown the large seasonal movements exhibited with the older climate system, and less work is required to adjust the wedges between the hull and the support cradle. If structural movement can be minimized, it will assist greatly in the planning of a better support system. The ship continues to dry out, as can be seen from the weight change in the PEG-treated plank in Figure 5, probably due to the increased airflow established with the new system, but since 2007 this effect appears to be stabilizing.

Each year the landlord stages an overnight test of the back-up services by switching off the power supply to the building. The reserves have so far responded automatically, with no detectable changes in the museum climate, but this test is done when the museum is empty, with no respiring visitors to affect the climate. Two unplanned power cuts have also taken place in the last few years during museum operating hours. The reserves started up as expected, with little effect on the museum climate, since these outages were not during peak season. What is a concern, however, is that should a power cut or system failure happen in peak summer months when the museum is full of people, a stable climate cannot be guaranteed, since the reserve systems can provide only 40% of the main plant's capacity. This is why, after five years of use, the first major overhaul of the main plant, CA01, took place overnight in November 2009, historically the month with fewest visitors and when the load on the system is at its lowest.

The popularity of the museum is a mixed blessing. Although valuable income is generated by more visitors, the long queues outside the museum in peak tourist season have put pressure on the museum authorities to increase the number of visitors allowed inside the museum at one time from 1,440 to

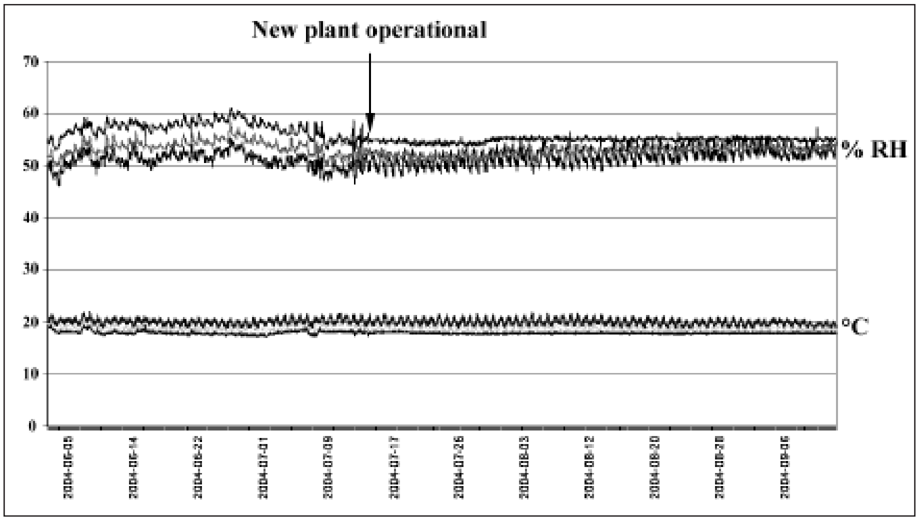

Fig. 10. Temperature and RH readings during summer 2004, when the new climate-control system became operational.

1,600. Since the air-conditioning system is dimensioned for 1,500 visitors, this decision will require that the system be operated at maximum capacity for longer periods, with the risk that if there is failure of any component of the main plant, the carefully maintained stable climate cannot be guaranteed. The difficult decision of whether to close the museum in order to preserve the climate is unlikely to be taken, but failure to take this decision might jeopardize the careful and expensive attempts to preserve the ship.

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Notes

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9. Personal communication with technicians from the National Property Board, Aug. 2009.