

AN UNUSUAL SURFACE CHANGE ON THE VIKING SHIPS EXHIBITED IN ROSKILDE

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Abstract

Five Viking ships, conserved with PEG, have been displayed for over 50 years in an exhibition hall with a large window section. Daylight could reach peak levels of up to 30,000 lux in summer. An unexplained phenomenon of a thin bluish-white layer forming on surfaces has been observed on the ship planks. It is distributed everywhere but most intensely on surfaces facing the windows. Light and UV were suspected to cause this, and the phenomenon was investigated so that a sufficient light level policy can be formulated. Monitoring of light and UV revealed annual light doses between 2 and 8 Mlux-hours. Blue-wool scales faded to step 5 in one year. Color measurements of areas cleaned and then exposed to exhibition light showed a color change (CIELAB1976 Delta E) of about 3 after one year, and about 7 after three years. A UV-filter retarded this change. The phenomenon was imitated on PEG impregnated wood samples by accelerated light and UV exposure tests. It is assumed that the discoloration is due to light and UV-radiation and that UV is at least equally contributing, and probably the main driver of it. An annual light exposure limit of 0.6 Mlux-hours with no UV-content was recommended.

Resumé

Fem 1000 år gamle Vikingskibe, som er blevet konserveret ved imprægnering med PEG, har i over 50 år været udstillet i en udstillingshal med et stort vinduesparti, der tillader dagslys som hovedlyskilde, om sommeren med spidsbelastninger på op til 30.000 lux. Et uforklaret fænomen er blevet observeret på skibenes træplanker, hvor et tyndt hvidt-blåligt lag dannes på overfladerne, fordelt overalt, men mest intenst på områder med retning mod vinduer. Måling af lys og UV viste årlige lysdoser på mellem 2 og 8 Mlux-timer. Blå-uld skalaer faldede til trin 5 på et år. Farvemålinger af afrensede områder, som derefter blev lyseksponeret i udstillingen viste en farveændring (CIELAB1976 Delta E) på omkring 3 efter et år, og omkring 7 efter tre år. Et UV-filter forsinkede denne udvikling. Fænomenet blev eftergjort på PEG-imprægnerede træprøver ved accelererede lys- og UV-eksponeringstest. Det antages, at misfarvningen skyldes lys og UV-stråling, og at UV-andelen mindst er ligeværdigt medvirkende, og sandsynligvis den primære årsag. En årlig grænse for lyseksponering på 0,6 Mlux-timer, for lys uden UV-indhold, blev anbefalet.

Nøgleord:

PEG; lysdosis; UV-stråling; blue-wool standard; dagslys; nedbrydning; præventiv konservering.

Keywords:

PEG; light dose; UV radiation; blue-wool scale; daylight; deterioration; preventive conservation.

Introduction

The Viking Ship Museum in Roskilde houses five 1000-year old wooden ships, which were found and excavated from Roskilde Fjord near Skuldelev in the early 1960s. The ships are among the most well-preserved and complete Viking ship finds in the world. They had been preserved under waterlogged conditions, but since the wood was deteriorated and extremely fragile they were therefore conserved over the next decade mainly by impregnation with polyethylene glycol (PEG) 4000 (Brorson Christensen, 1970; Crumlin-Pedersen & Olsen, 2002; Strætkvern & Hjelm-Petersen, 2021). Since 1972 the ships have been exhibited in a purpose-built exhibition hall located at the water's edge of the Roskilde Fjord. The exhibition hall has a large window section facing north, and smaller windows facing east and west and in the roof, allowing daylight as the main light source (Figure 1). The ships in the exhibition are named Skuldelev 1,2,3, 5 and 6.

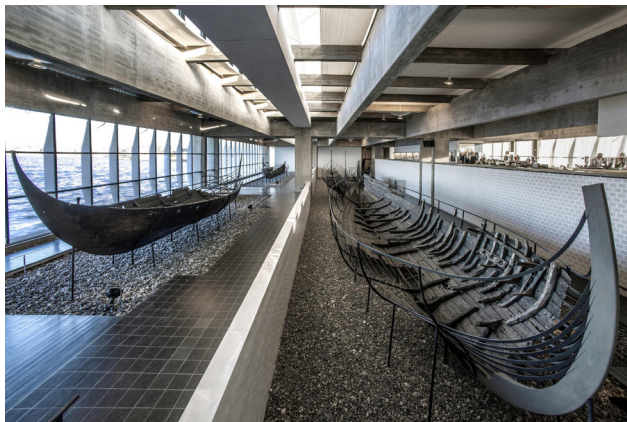


Figure 1. The museum hall with the five Skuldelev ships. To the left the large window section toward the fjord, with the two ships Skuldelev 3 and 5 nearest the windows. Photo: Werner Karasch, Copyright: The Viking Ship Museum in Roskilde.

For several years, an unexplained phenomenon of color shift has been observed on the wooden planks of the ships, primarily on surfaces oriented toward daylight. Already in a newspaper article from 2002 with the title “The Viking ships suffer sunstroke” (translated from Danish) it was reported how the ships suffered from an efflorescence-like surface alteration, and it was speculated if light and ultraviolet (UV) radiation were to blame (s.a., 2002). Since then the white-surface phenomenon has only increased. A very thin but clear bluish white layer forms on the surfaces, distributed everywhere on the ships but most intensely

on parts pointing toward the windows. The layer is easily removed, e.g., by wiping with a cloth wetted by ethanol or simply by stroking it with your hand (Figure 2-3). To our knowledge, this type of deterioration has not been investigated previously. Another efflorescence phenomenon was observed at the Swedish Vasa ship previously (Sandström et al, 2002). However, this was different in appearance and was due to uptake of sulfur compounds from the marine environment where the ship was sunk reacting with high quantities of iron compounds in the wood.

The Viking Ship Museum is planning to change the exhibition into a new, not yet designed exhibition building. This is a major project, which implies demolition of the old building and temporary removal of the ships, until the new building opens in 2030 (Vikingskibsmuseet,



Figure 2. Section of Skuldelev 3 facing the window, with the white-blue surface appearance. Photo: Morten Ryhl-Svendsen.



Figure 3. Close-up of a ship plank with the powdery surface, which easily can be rubbed off. Photo: Morten Ryhl-Svendsen.

2023). In connection with establishing future indoor climate specifications for the museum, conservators at The National Museum of Denmark were asked in 2020 to investigate the problem of the discolored planks. The theory that light was suspected to be the main cause had to be confirmed, and the extent of the problem established, so that a sufficient light level policy can be formulated for the new museum project.

Method

The white-surface phenomenon was investigated on-site in the museum exhibition, and by laboratory tests on wood pieces kept at the sample collection at the Conservation Department of The National Museum of Denmark. Light and indoor climate measurements were carried out at the ships over a one-year period, from February 2020 to March 2021, and with a few extensions continued into January 2023. As light and UV were suspected to be the main causes of the surface alteration, methods were chosen for establishing what was the exposure of light and UV in the exhibition hall, and if the development of the bluish white layer could be observed on cleaned surface areas after light exposure (at natural or accelerated conditions).

Light and UV monitoring

The intensity of light and the relative UV content was monitored with the use of data-logging instruments, recording measurements at 10-minute intervals. All five ships had two instruments attached, one facing the large window facade, and one facing away from the windows (Figure 4). The monitors were by Hanwell Ellab Group Ltd, UK (ML 4000 Lux & UV Datalogger) or Elsec Littlemore Scientific Engineering, UK (764 Environmental Monitor).

In addition to this, two Blue Wool Scale fading cards (type P986-1000, Preservation Equipment Ltd., UK) were placed at the Skuldelev 3 ship, facing the large window facade. One third of each Blue Wool Scale was darkened by metal foil, one third covered by a UV-filtering but light transparent foil (Foil R3114, Edmond Optics, UK), and one third was left fully exposed. The UV-filter foil blocked 98 % of the UV content, and reduced the visual light by about 10% (measured by Elsec monitor).

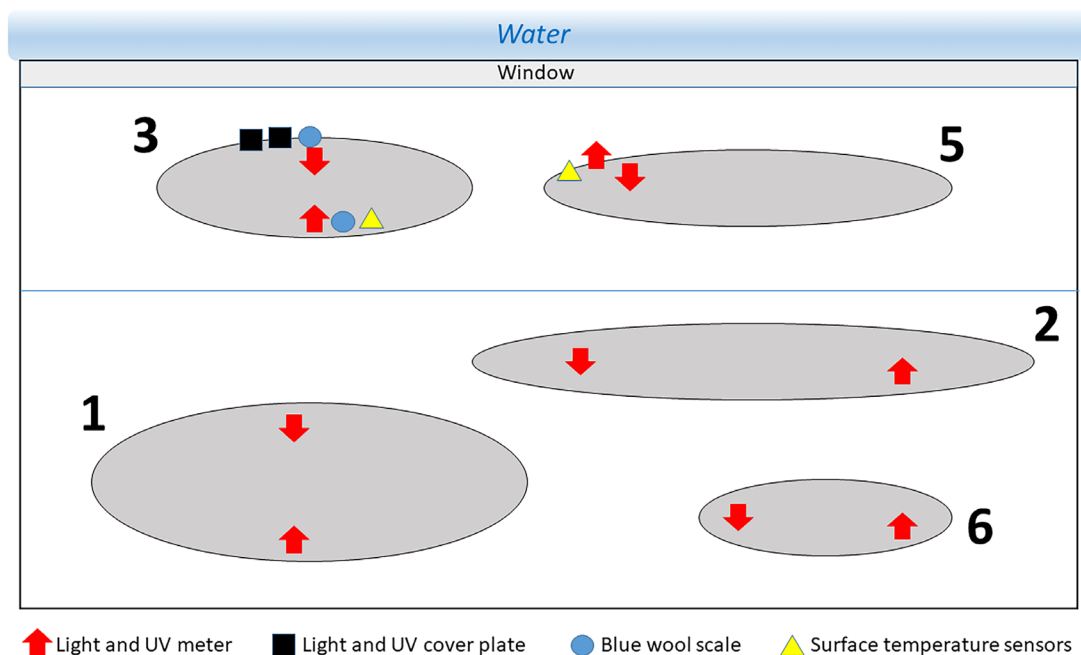


Figure 4. Plan of the distribution of the five Skuldelev ships in the exhibition hall (number refers to ship name), and the location of climate sensors. The arrows on the light and UV meter symbol indicates the direction of the measurements. One light and UV meter at each ship also contained sensors for air temperature and relative humidity (Elsec monitors). Color change measurements were performed at the cover plate locations on Skuldelev 3. Drawing not to scale.

Climate

The Elsec 764 monitors (see above) for light and UV monitoring were also used for room temperature and relative humidity (RH) monitoring (10-minute intervals).

For each of the two ships located closest to the window facade (Skuldelev 3 and 5), the surface temperature of a plank was measured on the side facing the windows and exposed to daylight, and then again directly on the other side facing away from the windows and never exposed to direct daylight (Figure 4). This was done by attaching the tip of a thin thermistor probe to each side of the plank with hot-melt glue. The probe was then connected to a datalogger recording measurements by 10-minute intervals (Tiny Tag Plus 2 TGP 4520 logger with two thermistor probes PB-5009-0M6, Gemini Data Loggers, UK).

Direct light exposure test (exhibition)

Test 1

On Skuldelev 3, a 20 x 30 cm area was wiped clean of any white surface layer with a cloth wetted with ethanol (Figure 4). Half of this cleaned area was covered by UV-filter foil (Foil R3114, Edmond Optics, UK). The foil was attached to the plank by thick adhesive pads in each corner raising the foil to 2-3 mm above the surface. The other half of the cleaned area was left exposed to light and UV. The UV-filter foil was mounted for 412 days after which it was removed and the appearance of the area was evaluated visually, and by color measurements (see below).

Test 2

After the first test, another 20 x 30 cm area of plank, also on Skuldelev 3 (Figure 4), was wiped clean as described above and half covered by UV-filter foil, and half by a black, lightproof plate with a Blue Wool Scale fading card (described above) attached to it (Figure 5). Foil and plate were attached to the plank by thick adhesive pads in the corners, raising the foil and plate to 2-3 mm above the surface. The UV-filter foil and plate were mounted for 258 days, after which they were removed and the appearance of the two areas was evaluated visually.

Color change measurements

Color measurements (CIELAB1976 color space) were conducted on cleaned and non-cleaned areas of ship



Figure 5. A lightproof plate and a UV filter foil mounted on the side of Skuldelev 3, directly facing the window (top). At the bottom the two areas are shown after the covers were removed after 258 days. The white pads indicates the corners of each cover. The plank on which the covers were mounted was newly cleaned, while the bluish planks below were uncleaned. Photo: Morten Ryhl-Svendesen.

planks using a Konica Minolta Spectrophotometer CM-2600d (Minolta Co. Ltd, Japan) with an 8 mm aperture and standard 10° observer and D65 light source. All color measurements were conducted on Skuldelev 3, on planks directly facing the window section. At each location measurements were repeated three times, and the average CIE76 L*, a* and b* coordinates were used for calculating color difference between areas, or color change at the same area over time (delta E). Measurements were conducted about one year after cleaning, however, at one spot up to three years after cleaning.

Accelerated light aging tests (laboratory)

Samples

Two samples of archaeological wood, originating from the same site and treated with the same PEG impregnation as the exhibited five ships, were used in two short term accelerated light aging tests in order

to try to replicate the appearance of the bluish white surface. The samples were from the National Museum's collection of sample materials. They were the same age as the ships, but had not previously been exposed to exhibition light. Both samples were about 12 cm long. Two tests were conducted: Exposure to light and UV in a spectral distribution comparable to daylight through window glass, and another exposure to UV radiation only.

Daylight aging test

The accelerated daylight aging test was performed in Weather-Ometer Ci3000+ test cabinet (Atlas Material Testing Technology, USA), powered by a xenon lamp at about 85,000 lux. The total effect received by the samples was 2.2 kWh/m², of which UV constituted 50 W/m². Conditions were 27 °C air temperature, surface (black panel) temperature was 40 °C, relative humidity was 50% RH, and the samples were examined visually after light doses of 9.5, 15 and 43 Mlux-hours. This relates to accumulated energy doses of about 250, 400, and 1150 kWh/m², respectively, and equals light and UV doses in the exhibition area near the windows of one to five years of exhibition.

UV aging test

The pure UV exposure was conducted by placing a half-covered sample a few cm under two laboratory UV-lamps (model UVP UVGL-58, 254-365 nm, by Analytik Jena, USA), for 118 days at an intensity of 22 W/m² (measured by an ELSEC 764 instrument). This resulted in an energy dose of 62 kWh/m². The surface temperature of the sample was checked several times with a handheld IR thermometer (Testo 830, Germany) and never exceeded 35 °C.

PEG melting point

Samples of surface PEG were scraped from three ships at areas with visible bluish white hue (Skuldelev 2, 3 and 5). Each sample was approximately the size of a match head. Samples were tested for their melting point on a Stuart SMP3 Melting Point Apparatus (Bibby Scientific Ltd., UK), and observed visually through a magnifying glass while the temperature was raised at a rate of 1.0 °C/min until the samples became liquid. The temperature interval from first appearance of melting until the whole sample was liquid was noted. Reference samples of new PEG 4000 and PEG 2000 were also tested (stock of unknown origin from the lab shelf).

Results

Indoor climate and surface temperature

The daily average temperature was almost uniform across the hall; however, it fluctuated more near the large window section, than further inside the room. The annual average air temperature measured in the middle of the hall (near Skuldelev 1) was 21 °C, and with a relative humidity between 50-60%. At Skuldelev 3 and 5 the air temperature typically varied about 2 °C daily, however with up to 9 °C fluctuation during the summer, and with peak temperatures of up to about 30 °C.

The ships' dark surfaces received radiant heat from daylight, which would raise the surface temperature during daytime. This was most evident in summer, where the surface temperature in average was 1-2 °C above the air temperature, while in winter it was typically 0.5-1 °C below the air temperature. During daytime, there was always a temperature difference between the two sides of ship planks near the window section of about 1 °C in during winter and up to 5 °C in the summer. During the month of June, the surface temperatures of planks on Skuldelev 3 and 5 were between 21 - 25 °C daily, but with short-term periods of up to 30 °C on the sides facing the window.

Light and UV

The light intensity varied a lot over the year, depending on the seasons, time of day, and the weather. Light levels at the area near the window (around Skuldelev 3 and 5) were typically between 1,000-5,000 lux during the day, and for many hours (Figure 6). Over a one-year period (8760 hours), the light level was at least 100 lux for about 4250 hours, and within this time above 1000 lux for about 2900 hours, many of which were outside opening hours. For 10 hours, the light level was higher than 10,000 lux, with peak values of about 30,000 lux. Depending on weather and time of day, the relative UV content varied typically between 0.5 and 1.5 mW/lumen.

Table 1 lists the accumulated light dosages for one year (365 days) for each ship. The ships near the window section (Skuldelev 3 and 5) received more than ten times the light than that of Skuldelev 6, which is located furthest away from the window section. Likewise, on Skuldelev 3 and 5 the areas facing the window received about ten times more light than areas on the same ships facing inwards.

Direct light exposure tests

Both Blue Wool Scale fading cards at Skuldelev 3 (Test 1 and Test 2), positioned facing the window facade, faded to step 5 on the un-protected part, and to step 3 on the part covered by UV-filter. The first card (Test 1) was exposed through the months of February to March the following year (2021-22), a total of 412 days. Following this, a new Blue Wool Scale fading card also mounted at Skuldelev 3 (Test 2) for 258 days, was exposed through the months of March to December (2022).

Direct light exposure tests, and color change

Test 1

Over 412 days (13.5 months), the cleaned area of a plank on Skuldelev 3 which was covered by UV-filter foil, experienced a color change of delta E = 0.7. The area without UV-filter had a delta E color change of 3.4. Two years later, after a total of 1075 days the color change of the uncovered area had increased to 7.3. Comparative spot measurements of newly cleaned and uncleaned areas at Skuldelev 3 revealed color differences between 7.2 and 9.4. For all measurements the surface change went toward a more light/white (increased *L value) and more blue (decreasing b* value) appearance.

Test 2

For the second test, the areas covered by the UV-filter or the black plate equally appeared clearly darker and more “fresh” than the surrounding area, when examined visually after 258 days running from the month of March to December (Figure 5).

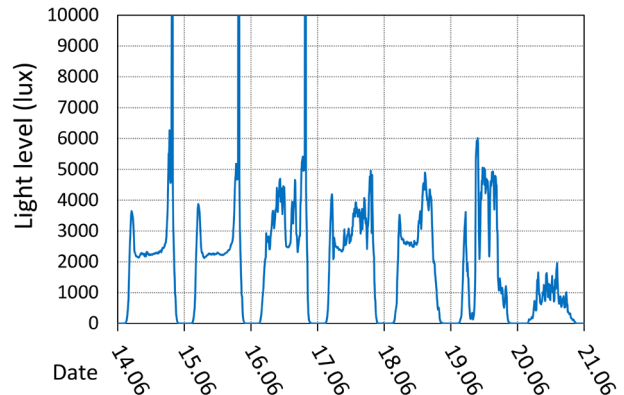


Figure 6. Light level at Skuldelev 5 during one week of June 2020. The evening peaks over the first three days exceeded 30,000 lux.

Accelerated light aging tests (laboratory)

Daylight aging test

On the sample exposed in the Weather-Ometer test cabinet a white surface became apparent after 9.5 Mlux-hours. This continued to increase in intensity with increased light dose (15 Mlux-hours), and after 43 Mlux-hours an almost efflorescence-like layer was formed (Figure 7).

The accelerated light aging doses of 9.5, 15 and 43 Mlux-hours corresponds roughly to about 1, 2 and 5 years of natural light exposure at the location of Skuldelev 5 in the exhibition.

Table 1. The accumulated light dose for one year, measured at each ship facing towards and away from the window section. Skuldelev 3 and 5 are located next to the window, while Skuldelev 1, 2 and 6 are located further inwards in the hall.

Ship	Light dose (Mlux-hour) Measured facing the window facade	Light dose (Mlux-hour) Measured facing away from the window facade
Skuldelev 1	2.2	0.4
Skuldelev 2	1.1	0.4
Skuldelev 3	6.0	0.7
Skuldelev 5	7.9	0.8
Skuldelev 6	0.6	0.3

UV aging test

The laboratory UV-exposure resulted in a slightly white appearance of the uncovered part of the sample (Figure 8). The white surface layer had an almost powdery and very delicate structure, which was easily removed by the touch of a finger. The energy dose by UV delivered during the test (62 kWh/m²) was comparable to what is received by light and UV combined for about one year in the dimmer areas of the exhibition (e.g., around Skuldelev 1 and 2) or by a few months near the window area.

PEG melting point

The samples had a total melting point interval between 55.7 – 60.4 °C, which was lower than that of the new PEG 4000 (range 60.8 – 61.9 °C) and higher than the new PEG 2000 (53.5 – 54.0 °C). The sample with the lowest melting range (55.7 – 57.7 °C) was taken from a plank close to and directly facing the window section (Figure 9).

Discussion and conclusion

The phenomenon of the development of a bluish white surface is clear and ongoing, especially on areas exposed to direct daylight. When an area was covered, entirely blocking out all light or UV radiation, the whitish blooming was retarded to an extent which could not be



Figure 7. The wood sample exposed to the accelerated light aging test: Before exposure (top left); after 9.5 Mlux-hours (top right); after 15 Mlux-hours (bottom left); and after 43 Mlux-hours (bottom right). Photo: Morten Ryhl-Svendsten.

noted visually after a period of about one year (color change was delta E 0.7 under UV filter foil, as compared to 3.4 for an exposed area, which had become clearly whitish). Even when taking into account the difficulties of making precise color measurements on such uneven surfaces as the ship planks, the difference between covered and un-covered areas was significant. This was further substantiated by spot measurements which all showed color differences (delta E) of 7.2 - 9.4 between cleaned and uncleaned areas.



Figure 8. The sample for the UV test, before (left) and after exposure (right). The upper half was exposed during the test and developed a faint white surface, while the lower half was covered by lightproof aluminum foil (see insert upper right). Photo: Morten Ryhl-Svendsten.

The effect of light and UV was successfully imitated by the accelerated light aging tests, with formation of the white surface layer already at light doses equivalent to about one year of natural exposure in the exhibition. Likewise, a faint but visually clear beginning of white formation under UV lamps was obtained at an exposure similar to what is gained over a few summer months near the window section in the exhibition hall. An additional argument for the light and UV being the primary and probably sole cause is that the unexposed parts of the samples did not change color during the accelerated ageing tests.

Temperature is not thought to have a direct impact on the formation of the white surface (cf. the observations on front and back of samples). However, as climate, and especially temperature, have a general influence on chemical reaction rates, it is conceivable that the temperature in the exhibition environment, including solar heating of the planks, is influencing the deterioration rate of the PEG, which has degraded from a molecular length originally of about 4000 to a lower grade. Indirectly this may accelerate the formation of the bluish white film on the surface.

The degradation of the PEG may be reflected in the melting point of surface samples, which all were below new off-the-shelf PEG 4000. Even when taking into account the uneven size and surface of the samples (due to the irregular surface of the planks), and possible impurities (dust, etc.), they still indicate a degradation of the PEG to a grade less than 4000, but higher than

2000. The low melting point was moreover implied by some initial difficulties which were experienced during the accelerated light tests: During a preliminary pilot run at a higher light level (100 klux) the white surface formation did not appear, instead the surface became more black and glossy with a transparent, newly melted surface layer. Due to the high light intensity, the black panel surface temperature rose to about 45 °C, and only by lowering the light level and ventilating the test chamber at a high rate could the black panel surface temperature be kept at max. 40 °C, which then allowed the white surface layer to form without melting and merging again.

In light of the results of our investigation we suggest that the cause of the discoloration of the ships is due to the exposure to light and UV radiation, and that UV is at least equally contributing, if not the main driver of it. An obvious way to retard the process is to lower the light exposure, and especially to remove the UV content from the light. This could be achieved by selecting UV-free light sources and applying UV-filters on the windows. It is noteworthy that a large part of the light exposure takes place outside opening hours, including the peak levels occurring when direct sun falls on the ships during the early summer morning and evening hours (Figure 6). The light monitoring campaign revealed that during one year the light level in the hall was at least 100 lux for 4250 hours; in comparison to this, the museum opening hours were only about 2400 hours. Installing blinds on the windows to block out the daylight entirely outside museum opening hours would make a large difference.

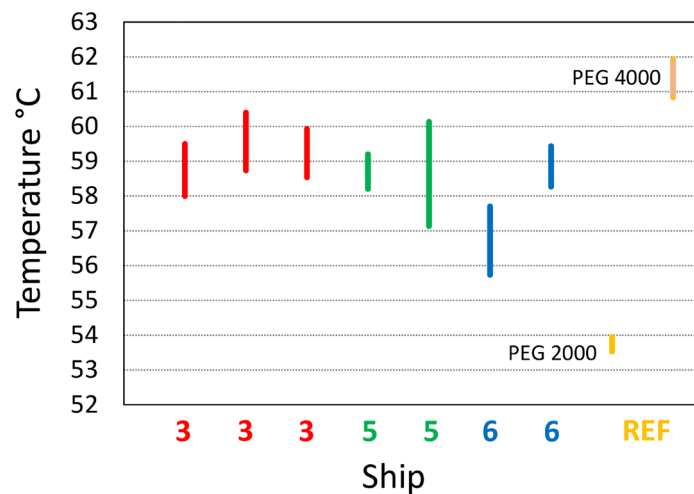


Figure 9. Melting point intervals of PEG samples taken from Skuldelev 3, 5 and 6, together with reference samples of new PEG 2000 and PEG 4000.

Specific exhibition lighting guidelines on this particular type of heritage material are scarce; however, the Danish Agency for Culture and Palaces (SLKS) hosts a set of museum conservation guidelines, in which a maximum of 200 lux is recommended (SLKS, 2022). The International Commission on Illumination (CIE) recommends an annual exposure limit of 0.6 Mlux-hours for the general class of museum objects having a low responsivity to light (CIE 157:2004). This is about the same level to which the ships located furthest away from the windows are currently exposed to (Table 1), however, today's exhibition light is unnecessarily high in UV content. In general, the 0.6 Mlux-hours limit can be obtained with an overall light level of 200 lux for 3000 hours per year, which allows time for cleaning, maintenance, evening events, etc., outside opening hours.

The Viking ships have been exhibited in the current environment for more than 50 years, and for the last 20 years or so they have been cleaned manually several times as the white surface formation has become more and more evident. The accelerated light tests show a clear formation after what equals one year, and a very strong blooming after what equals about five years of exhibition time. The surface formation does not seem in itself to harm the wooden planks, or to alter the structure of the wood. However, as the ships are being cleaned at regular intervals, due to the unaesthetic appearance of the white bloom, this action provides a continuous and strong wear on the ships.

Perspectives

Some questions remain unanswered, and call for more research. We have described the probable cause for the development of the powdery white surface (light and UV), however, the mechanical processes which may be behind the microscopic surface alterations, and which produce this optical change in appearance are not fully understood. Could it be that temperature and relative humidity plays a secondary role in this phenomenon? Furthermore, it would be interesting to investigate further the quality of PEG in the ships' wood. The melting point measurements imply a degraded PEG on the surface, but how is the condition inside the planks? An investigation of polymer length and state of the PEG, sampled from various depths of ship planks would not only reveal if the decay is limited to the surface, but also indicate consequences for the conservation of the ships in the long run.

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Competing interests

The authors declare that they have no competing interests.

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