CONSERVATION OF THE WOOD OF THE SWEDISH WARSHIP VASA OF A.D. 1628

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CONSERVATION OF THE WOOD OF THE SWEDISH WARSHIP VASA OF A.D. 1628

Evaluation of Polyethylene Glycol Conservation Programmes

Birgitta Håfors

UNIVERSITY OF GOTHENBURG
ACTA UNIVERSITATIS GOTHOBURGENSIS

Dissertation for the Degree of Doctor of Philosophy

CONSERVATION OF THE WOOD OF THE SWEDISH WARSHIP VASA OF A.D. 1628

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University of Gothenburg
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UNIVERSITY OF GOTHENBURG
Department of Conservation

Dissertation for the Degree of Doctor of Philosophy

By: Birgitta Håfors, M.Sc.
Supervisor: Professor Emeritus Jan Rosvall, Ph.D.
External mentor: Professor Emeritus Ingvar Johansson

Abstract

The principal aim of this dissertation is to investigate whether or not polyethylene glycol (PEG) has acted as a dimension stabilizing agent of the Vasa wooden material, i.e. whether or not the PEG molecules have penetrated into the secondary cell wall, and in this have been enabled to preserve the capillary system through the drying and continuing maintenance periods.

This dissertation deals with the experimental work made at the Vasa conservation laboratory parallel to the conservation performance, with the aim to gain reasonable knowledge about the conservation parameters to proceed with the treatment, and to adjust the methods to needs observed. The experimental work was mainly performed as immersion treatments and with oak wood material removed from the Vasa hull as test material. The results were used at the surface application on the Vasa hull as well as at the immersion treatment of large loose timbers and wooden objects from the Vasa.

The achievement of an equilibrium between the PEG-concentration of the conservation solution and the PEG absorbed by the wood involved was agreed upon as a basis for the conservation procedure, but it soon became obvious that the equilibrium criteria were difficult to define.

The main conclusion of this dissertation is that the PEG's 4000, 1500 and 600 have acted as dimension stabilizing agents of the Vasa oak wood by an anti-shrink-efficiency (ASE) factor of 60% and higher, with amounts of 30% PEG and higher in the dry matter of the Vasa oak wood-PEG 4000, 1500 and 600 composites respectively.

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Key words: Anti shrink efficiency (ASE), **a**rchaeological wet site, conservation, dimensional stabilisation, osmosis, polyethylene glycol (PEG), PEG conservation programme, immersion treatment, spray treatment, waterlogged archaeological wood, the Swedish warship Vasa of A.D. 1628, the Vasa oak wood-PEG composite.

Editors Preface

This volume of *Gothenburg Studies in Conservation* (GSC No 26) is composed of the doctoral dissertation by *M.Sc. Birgitta Håfors* with its title "*Conservation of the Swedish Warship Vasa of A.D. 1628, Evaluation of Polyethylene Glycol Conservation Programmes"*, due for public presentation and defence on October 18 this year in the Main Building of the University of Gothenburg, for earning her Ph.D. degree. As responsible for this scrutiny, *Dr. Norman Tennent,* Professor in Chemistry of Conservation and Restoration at the University of Amsterdam was appointed as the *Opponent*, by Professor Margareta Hallberg, Deanship of Faculty of Humanities, to pursue the public examination according to the Swedish academic system. An important part of this formal examination procedure is based on the formulation of the ultimate and strict decision on the verdict by the *Examination Committee,* reporting directly to the university through the faculty, in this case in Humanities and its Deanship. These committees are always appointed on an *ad hoc* basis. They are to be equipped with recognised senior members, specially selected to jointly provide the capacity of required special knowledge related directly with the dissertation and its author, as well as to represent adequately formulated and well developed general experience of assessing principal values of academic performance. In the case of deciding on the verdict of Birgitta Håfors´ printed dissertation and her oral public defence, the committee was appointed with following three members: *Professor Kristian Kristiansen, Ph.D., Professor Britt-Marie Steenari, Ph.D., Associate Professor Charlotte Gjelstrup Björdal, and Associate Professor Johnny Bjurman Ph.D.* as their substitute.

The publication is composed of two parts: the printed dissertation proper, accompanied by a CD with the title *"Conservation of the Swedish Warship Vasa from 1628"* (inserted as an appendix inside the back cover). A full *e-version* also is available of this volume (**http://hdl.handle.net/2077/23215**). While the present dissertation is designed according to established academic criteria in Sweden for the preparation of Ph.D. dissertations, this CD is a new edition of the documentation report — *"Conservation of the Swedish Warship Vasa from 1628"*— earlier prepared by Birgitta Håfors, and originally published by The Vasa Museum. The CD enclosed provides the comprehensive basis for the transparent scientific information structure about the huge Vasa conservation project, all since its inception in the early

1960's. This compound of data has been collected systematically and continuously under leadership of Håfors during the decades of the operative Vasa project organization, for continuing use in the progressing conservation process. Further this information has been carefully organized to be prepared as a data base and support for future preservation use. During the actual research situation and beyond, this has offered optimum utility as a necessary overall reference system for the needs of the progressing dissertation project, eventually leading to this publication.

As a research specimen for earning her Ph.D. degree, this dissertation entirely is the product of the enduring ambitions, efforts and achievements of Birgitta Håfors, though in continuing collaboration with and support from many advisors, colleagues, professionals and researchers at related museums, universities and elsewhere in many countries, besides the University of Gothenburg and the Vasa Museum.

It is a standard procedure in the academic sphere, that doctoral projects like this one requires continuing support from a responsible senior supervisor, generally a professor in the discipline of concern, preferably supported by additional mentoring by auxiliary advice on special issues of importance. In this case, this editor of GSC has accepted to serve, in his long enduring capacity as responsible professor, also since being appointed an Emeritus professor after his retirement in the conservation discipline, from his initial promotion of Birgitta Håfors for Ph.D. studies in the early 1990's, and as her mentoring supervisor during the decades to come until final delivery of this dissertation. Already in an early phase, I recognised the need of some adequate co-mentoring, and asked my close colleague *Associate Professor Stig Aleby* who was at that time senior lecturer in conservation science, to support Håfors, which he generously offered, ending with his retirement. His successor *Associate Professor Jonny Bjurman* continued this valuable mentoring likewise in a substantial way, to the benefit of Birgitta Håfors and her developing project. Later on it was further deemed preferable to gain direct support from *Dr. Ingvar Johansson, Professor in Wood Technology and former Head of Wood Material Research at the Swedish Institute of Wood Technology,* for continuation of his long-lasting supervision of the Vasa conservation project, in his capacity as Chairman of the Conservation Council.

For understanding the development of this specific Ph.D. project, it has to be viewed within the context of its actual and accessible academic framework of relevance for desirable research and postgraduate education, during the period concerned. At the time of the initial phase of the Vasa conservation project, and for a long period to follow, conservation still was not installed in Sweden nor in most other countries – though with a very few and restricted exceptions. This became evident, neither as an established university discipline concerning basic academic education (at Bachelor and Master levels), nor as a postgraduate structure being internationally calibrated with Ph.D. programs and senior professorships instigated at respected universities, such as the case in generally established "normal science" disciplines, like in chemistry, art history and technology etc.

During the period when the Vasa project was developing, Birgitta Håfors gradually was establishing the aims of its intended research, preparing the first attempts to design the needed analytical approach of the conservation process. The Vasa conservation project was favoured by serious and highly competent external support from well established experts in relevant fields of competence, on behalf of its Scientific advisory board (The Conservation Council) within the museum ambience. However, it still obviously was not possible to identify an adequate scholarly-scientific academic institution, where the Vasa project would find reasonable continuing support for Håfors' potential doctoral ambitions.

Meanwhile, preparations for establishing professional conservation education and research were accelerating at various levels in Sweden, from the mid-1970´s significantly in a set of devoted departments at University of Gothenburg - in art history, anthropology, design and crafts, chemistry as well as with the decisive support from a group of successive Vice Chancellors and Deans. Consequently these sides were actively involved in continuing and accelerating cooperation with important museums and heritage bodies in Western Sweden and Gothenburg, as well as nationwide, including national museums mainly in Stockholm, and jointly coordinated by decisions on behalf of Government and Parliament of Sweden. These multifaceted efforts, originally non-univocal for natural reasons, ultimately were concluded in a unanimous and comprehensive decision by the responsible parties. The conservation supportive sides ranged from Parliament and governmental offices to various local and regional bodies. The actions successively taking place, were heading principally according to a voluminous set of well prepared background documents and their supportive opinions among experts of concern. Continuously they were coordinated, together with efforts also in other institutions and public agencies, by this author as the promoting and responsible actor.

Those involved, partly from the national decision-makers and partly from representatives of the carefully prepared organizational design from University of Gothenburg - concerning how to have organized and financed a brand-new multi-dimensional university discipline with its complex and complicated needs of many components, concerning – among other things - the main scholarly-scientific theoretical discourse to be established, needed faculty, and mobilizing available external competences, laboratories demanded, as well as implications in required curricula at main course levels anticipated, with very specific entrance requirements of testing models for student applicants, ranging from pure science and humanities, communication abilities, to practical research capacity and also ambi-dextrous abilities of coming students. The model established, and its realization was well underpinned by a local committee and linked to a multi-faceted international network with relevant and critically-supportive conservation contact partners in the museum world, heritage bodies, private enterprising and academic institutions, around in Europe and North America.

The planning phase was concluded by starting in 1985 this new comprehensive and integrated bachelor´s program for coming professionally educated conservators. This was furnished with adequately and well equipped laboratories, expanding library resources and other institutional facilities. As from 1986, this was located in the city centre, in an appropriately rehabilitated edifice of architectural dignity of considerable dimensions, and according to the firmly established master-plan, successively enlarged, revised and enhanced in many respects. The conservators' program was operating with a number of carefully selected conservation sub-branches and based on a common comprehensive curriculum formula at international top level, designed in conformity and jointly settled with many of the most respected experts in this professional field.

At this time when the *conservators' program* was instigated and beginning its regular and continuing operations, it was immediately incorporated in the *department for conservation studies*, mainly composed until then of the likewise comprehensive bachelors program for *integrated conservation of built environment*, established a decade earlier. Over-bridging cooperation between these two programs was anticipated and was generating an expansive development already from start, within appropriate areas. When this initial program was launched in the 1970's, it was already at the start firmly proposed from the initiators´ side, to organise a linked postgraduate program in fields of great theoretical and professional concern for the undergraduate level, to facilitate necessary inter- and trans-disciplinary epistemological competence formation, otherwise non-existent at universities or elsewhere. After much preparatory considerations at all decision-making levels, this internationally relatively unique initiative was accepted in 1991 by Dean of Humanities, professor Jan Ling, later Vice Chancellor, for a first phase of feasibility testing, before ultimately being endorsed for decision at national level by Government and Parliament in 1993, when the general and comprehensive discipline of conservation was delivered for instigation at University of Gothenburg, as a permanent contribution to the Swedish university system and beyond, internationally.

In my capacity as responsible for this initiative and its implementation, it was understood that I would need to have promoted all appropriate decisions necessary to be taken by responsible governmental and administrative bodies, for the allocation of financial and other kinds of resources required for a totally new postgraduate program. In the first phase of this expansion from an undergraduate structure, there was a firm need immediately to organise a feasibility plan for an academic structure still totally lacking resources for senior positions as full professors, grants for scholarly-scientific research at academic level, and linked postgraduate education with a Ph.D. program and stipends for doctoral candidates to be accepted and involved. This process had started already with a few candidates that were accepted in other disciplines, but mainly this phase in the early 1990´s resulted in promotion – as traditionally organised - of a few devoted members of the staff of the own department, strongly prepared individually to pursue their Ph.D. studies in the fresh program in conservation *per se* (*e.g. Bosse Lagerquist*, see GSC No 4). In addition a number of museum institutions, heritage planning offices and conservation laboratories were beginning to line up for finding adequate forms of cooperation. The idea was to support, like in the industry, their staff members that were granted salaried positions for doctoral studies. The other side of this concept was to have supported the organisation for operating research of their priorities, to be performed with academic calibre (initial partner was the *Conservation laboratory of National Museum of Denmark, promoting senior conservator Jesper Stub Johnsen, see* GSC No 5; and professor *Stephen L.Williams, at Baylor University in Texas*; see No 6).

Simultaneously this kind of interest was beginning to grow also in Sweden. A considerable number of employees in museums and in the heritage sector were consulting for possibilities to pursue their postgraduate education and research in the conservation discipline. In this way a number of highly competent conservators were addressing their interests to enrol and affiliate with the Ph.D. studies in Göteborg. Some of these professionals were granted stipends from various research supporting organisations, but some of them were able to make agreements with their employers, to perform their doctoral research within the time frames of their normal work-load, and stretched over longer periods. In addition, travel grants, costs for specialised laboratory facilities and other kinds of expenditures were covered for the special needs of their research projects. In these cases, agreements on behalf of doctoral candidates were established between the Department of conservation, and those organisations concerned, being responsible for the expenditures for the students and their vocational mentoring in their work places. At the other hand, the university would organise and cover expensive individual costs for time-consuming academic supervision, mentoring, course management and examination processing for students involved. This model for cost-sharing and establishment of joint responsibilities for development of research and competence enhancement was rewarding for both sides, as well as for the heritage sector at large. In fact, this arrangement can be considered as a good example of creative and dynamic support of knowledge development enhancing critical mass.

The situation presented above, has to be understood as important background factors, when Birgitta Håfors and her principals of the Vasa Museum in the 1990's, were approaching Department of conservation for accepting her research project, and the considerable experiences of conservation of the Vasa ship, as topic for a Ph.D. dissertation. After various normal considerations on both sides, her project was accepted for the preparation of a coming dissertation, and to be supported by necessary postgraduate studies in addition to her already massive achievements of various kinds.

Consequently Birgitta Håfors embarked as a mature and internationally well respected researcher and senior staff member of the Vasa organisation, to be integrated together with the other doctoral candidates in conservation, with widely ranging ages, backgrounds and competences. This kind of groupings have been profoundly supportive for the enhancement of individuals, as well as for the collective critical mind and the general understanding of research processes, comprising all kinds of issues involved - from theoretical discourse development to practical experimental approaches, related to different categories of objects, and to various kinds of problem complexes.

As for the other participants of the on-going postgraduate activities, comprising freshmen researchers, as well as profoundly experienced senior professional conservationists in various fields of specialisation, Birgitta Håfors was presenting her important experiences and research modelling, to mutual benefits for herself and for all the others involved. Much was gained since her project in many respects is quite unique (as also other projects), but many common concerns were possible to observe and to be aware about for the colloquium participants, independent of formal position. This obviously is one of the great benefits of the academic system for collective scrutiny, where Håfors and "her" Vasa project contributed to the enhancement of the critical minds of the conservation researchers involved.

For natural reasons, these achievements have been refined and enlarged through Håfors´ many visits at, and contacts with relevant partner institutions world-wide, primarily at maritime museums, conservation laboratories for handling waterlogged wood, as well as at various university departments specialising in the kinds of problems identified in the Vasa ship and its ambience. This background is well reflected in her printed dissertation, but has certainly also been a vivid component of all continuing mentoring conversations and oral examinations, from the sides of involved colleagues invited to colloquies, on behalf of the postgraduate structure in conservation.

For me it has been a privilege to learn to know Birgitta Håfors as a profoundly critical-minded and never surrendering conservation scientist in a complex and complicated field of research like this. Her capacity to endure the entire initial one-generation-long conservation and research cycle of this huge complex, will certainly find its benefitting rewards not just in the presently available dissertation, but even more in the long-term, according to the well established formula of qualified conservation.

Among all those colleagues and friends that I find have had crucial importance for Birgitta Håfors and her dissertation, and therefore also for me, I especially want to address my cordial thanks to *Dr. Stig Aleby, Professor in Conservation science*, *Dr. Jonny Bjurman, Professor in Conservation science*, *Dr. Ingvar Johansson, Professor in Wood Technology and former Head of Wood Material Research at the Swedish Institute of Wood Technology, and Dr. Lars-Ivar Elding,* *Professor Emeritus in Chemistry and Coordinator of the Preserve the Vasa Project*. For the final scrutiny of the dissertation before printing, I also want to direct my sincere thanks to *Dr. Elizabeth Peacock, Professor in Conservation science*, for most valuable and supportive contributions. In this context it is also a delight for me to present my appreciation for the enduring support of this project from the side of *Dr. Ola Wetterberg, Professor in conservation*, and my successor as *Head of the Department of conservation.*

Ultimately, it is with much of personal admiration that I am now saluting Birgitta Håfors, for her never ending and overwhelming efforts during five decades of loyal service, of highest quality of her professional and scholarly-scientific endeavours fulfilling demands of long-lasting sustainable and ethical conservation performance, with her focus at Vasa.

Birgitta, let me deliver my sincere congratulations!

Göteborg, September 11, 2010-09-11

Jan Rosvall Ph.D.
Professor emeritus in Conservation

GMV Centre for Environment and sustainability
Chalmers University of Technology & University of Gothenburg

Editor, GSC *Gothenburg Studies in Conservation,* AUG *Acta Universitatis Gothoburgensis*

Authors Foreword

When visiting my parents in Lund on 28 April 1961, I cast a glance at the black-and-white TV screen and saw the Vasa wreck being salvaged. At that moment I could not imagine what impact that wreck would have on my future. In 1961 I was concluding my studies at the university of Stockholm and I was convinced that afterwards a carrier as a teacher was waiting for me. However, if something more exciting might turn up I would not hesitate to try it.

I was looking for a temporary job during the summer, and by the employment office I was recommended to contact the Swedish National Heritage Board that was looking for a chemist. As my professional experience at that time was with the central laboratory of the Swedish Dairies Association I was looking for laboratory work. However, it had not occurred to me that chemical laboratories existed at such an institution as the Swedish National Heritage Board.

To obtain some information about what the chemist was expected to do I paid a visit to the technical department of the National Heritage Board where I was received by the head of the department, *Dr. Arne Strömberg*. I presented my CV and I learned that the position had been created for the conservation of the Vasa.

The Vasa happened to emerge and I happened to get involved.

Täby, September 6, 2010

Birgitta Håfors

Acknowledgements

One of my first working-days at the Technical department of the National Heritage Board and the Swedish National historical museum my principal, *Dr. Arne Strömberg* invited me to accompany himself to visit the newly appointed Head of the Vasa Conservation Department, *Civil engineer Lars Barkman*, who was looking for staff for the Vasa Conservation Department. A couple of months later I became temporarily employed as a chemist. The conservation of the Vasa hull and loose material was expected to need about seven years. It soon became obvious that this was not time enough. I had the opportunity to take part in the Vasa conservation project during the whole of my working career. I chose conservation of the waterlogged archaeological wood as my field of professional specialization, which gave me the opportunity to develop the research and analytical laboratory of the Vasa conservation project and also provided me with a core position in the conservation processing of the hull and loose wooden findings of the Vasa. This has enabled me to accomplish this dissertation. However, I had not been able to do it on my own. Many persons have given me their support.

First and foremost I would like to express my gratitude to *Professor Emeritus Jan Rosvall, Ph.D.*, who invited me to perform this work under his supervision and who has guided me with patience through to the completion of this dissertation.

I would also like to express my gratitude to:

Professor Emeritus Ingvar Johansson who has thoroughly scrutinized my text and made comments from a wood science point of view, although always notifying that my dissertation deals with the discipline of Conservation.

Professor Elizabeth Peacock, who twice has acted as chairperson of seminars on my dissertation manuscript and who has given me very useful advice on structuring this.

Professor Emeritus Lars Ivar Elding, scientific coordinator of the *Preserve the Vasa Project*, who has read and thoroughly commented on my manuscript.

Professor Ola Wetterberg, head of the Department of Conservation, who has taken great interest in the progress of this dissertation.

I would like also to mention with gratitude:

Annika Nicklasson, Ph.D., Per Meiling, Ph.D., Christer Gustafsson, Ph.D. and Erika Johansson, Ph.D. who have guided me with useful information when I have stumbled over some troubles with the computer programmes and other kinds of trouble.

This dissertation would never have been able to be accomplished without the digitalizing of a substantial part of the catalogue material of the Vasa finds made by *Andrea Filyo, M.Sc.* in the mid 1980´s and by *Ms Motoko Kinushita* in the mid 1990´s.

The importance for the development of my work has depended on the staff members of the archive and the library of the Maritime Museum of Stockholm:

Librarians Helena Franzén, Inga-Lill Ankarström and Hans Orstadius, and archivist Malin Joakimson.

The conservation of the Vasa was a teamwork. I want to express my gratitude to:

My own team of the research and analytical laboratory, the team that under the leadership of *engineers Arne Stolt, Sture Bruce and Ulf Bjälrud* have kept the spraying system operating and reported regularly from its performance, and the team of the conservation of the large wooden loose material under the leadership of *Conservator Bo Lundvall* with whom I had a stimulating collaboration concerning the development of the conservation programme.

My gratitude also goes to *Conservator Sven Bengtsson* who along his work with the sails and the leather of the Vasa was responsible for monitoring the museum climate.

My gratitude goes also to my husband, *Arne Håfors* who has helped me in several ways and who has never complained about having his holidays in connection with some Conservation Conference.

I would also like to express my gratitude to:

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Wilhelm och Martina Lundgrens Fonder
The Faculty of Humanities at the University of Gothenburg

for financial support of the printing of this dissertation and other expenditures.

Täby, September 9, 2010

Birgitta Håfors

APPENDIX
Attached as a CD, enclosed inside the back cover

BIRGITTA HÅFORS:
CONSERVATION OF THE SWEDISH WARSHIP VASA FROM 1628
Printed Report published by the Vasa Museum
Stockholm 2001, 185 pp

I. Introduction

The Vasa hull broke the water surface on 24 April 1961. This was a proud moment for engineer Anders Franzén who in 1956 had relocated the Swedish warship Vasa which capsized in the harbour of Stockholm on 10 August 1628 on her maiden voyage. How the huge wet archaeological wooden object would be preserved was not clear at that time. Franzén commented on the conservation issue in the following way, in his report about the Vasa-find dated on the last of December 1956:[1]

> "… it will be best to raise the Vasa hull in steps above the water surface so that there will be time for the preliminary conservation work to be done on the gradually exposed timbers, because, otherwise there is a risk that these will be damaged. Conservation of the wood basically means cleaning by rinsing and spraying with an appropriate conservation liquid."

The excavation of the Vasa hull in 1961 provided a huge amount of wooden objects.[2] Since nearly all bolts and nails in the Vasa had rusted away during the 333 year period at the seabed in the Stockholm harbour both sculptures and some large timbers had disconnected from the hull and was salvaged separately from the Vasa underwater site. These salvage operations took place mainly during the years 1964 – 1967.

There had not been much interest in conservation matters before 1959 concerning the Vasa material. This year, the newly established Board of the Vasa took over responsibility for the conservation project. Then the conservation matter came up as an important issue.

When a preservative for dimension stabilising the Vasa wood was to be selected, little was published on the effect on archaeological wet wood of polyethylene glycols (PEG). Information found was about treatment of small items such as a bucket or a spoon and most times there was no information available about from what species of wood the item was

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[1] Franzén, 1956.

[2] Håfors, 2001, pp 4-5.

made.[3] Despite this, PEG was selected as dimension stabilising substance in competition only with carboxy-methyl cellulose.

When the Vasa hull was newly raised it was in a materially delicate situation. Taking care of the large amounts of wood was the main concern at that time. The immediate task was to keep everything as wet as possible. For the hull this was performed by a system that was continuously sprinkling water on the surfaces inside the hull and by spraying the outside of the hull intermittently by hand with a fire-hose.[4]

The material excavated from the hull was transferred to tanks containing normal tap-water. The tanks used for the more delicate material were placed in a rock shelter with a temperature above the freezing point while the tanks with categories of material that were considered less delicate were placed outside in the yard of the conservation laboratory. The water of these tanks did freeze to ice in winter periods. This was considered not to be too harmful as long as the wooden material was completely submerged into the water.

There was no more space available in the yard and therefore some large pieces of construction material that were salvaged during the diving operations were stored along the keel of the Vasa hull. The idea was that the dripping of PEG-solution from the hull would keep the stored wood from drying and that the PEG that might penetrate into it would be of benefit to the conservation process during the succeeding immersion conservation. However, this would be disclosed to be a misjudgement.

While storing wet wooden material in the high humidity of the pontoon superstructure was required by circumstances, some years, a number of not preserved wooden sculptures were put on exhibition in the pontoon superstructure during the summer months, to attract visitors. The sculptures were surface treated with PEG solution a couple of times every day which placed them in the same position towards the succeeding immersion conservation as the above mentioned construction material.

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[3] Mo & Domsjö AB, Technical Information No. 64, pp 9-12, figures 6-9.
[4] Håfors, 2001, pp 17-19.

1. History of Conservation of Wooden Finds removed from Wet Archaeological Sites

Archaeological excavations were exclusively land-based at the beginning of the establishment of the discipline. Many of the excavation sites were burial-mounds. These often contained ceramics and metal objects, but organic materials such as wood and textile, to which the metal often had been attached, were gradually decomposed and had disappeared.[5] However, in 1880, a burial-mound, situated at Gokstad in Vestfold region in Norway, was investigated and disclosed a wooden ship in seemingly good condition.[6] This was equipped with a special burial chamber made of timber, and a large number of wooden artefacts of various sizes, ranging from bowls and spoons to sleighs that had been placed in the grave. Some twenty years later, in 1903-04 another large burial-mound, situated at Oseberg, also in Vestfold in Norway, was investigated. This investigation showed a similar ship as the one at Gokstad. Both of these graves also contained textiles.[7]

The fact that the organic materials found in a wet condition apparently were in a good state of preservation indicated a burial situation which had detained the degradation processes. One conclusion drawn from the description of the burial circumstances of the Oseberg ship is, that as the ship at the time of the burial had been placed with its bottom about three quarters of a metre down into a clay layer, these parts had been protected from the outside atmosphere.[8] Above this level the ship was covered with c. 70 m^3 of stones.[9] This stone packing was meticulously covered with a layer of peat, which made the burial chamber airtight. This may have prevented oxygen from the surrounding atmosphere to gain access to the burial chamber thus retarding the biological deterioration processes. The excavation of these two burial-mounds made obvious the difficulties in preserving water-containing organic materials.

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[5] Burenhult, 1982, pp 22 - 23.

[6] Blindheim, pp 84 – 85.

[7] Brøgger I, 1917, pp 27 - 28, Hins and Blindheim, p 103.

[8] Brøgger I, 1917, p 93.

[9] Brøgger I, 1917, p 187.

Apart from the spectacular finds of these two burial ships in Norway, objects made of wood were rare in excavations at that time. However, it sometimes happened that log-boats were found in peat-bogs during peat-harvesting or in ditched lakes during agricultural work. Those log-boats, despite their robust making, often got cracks, and lost their shape when drying. This made it obvious that something had to be done to preserve them once they were removed from their burial circumstances. Often the measure chosen for the conservation was the traditional treatment of small wooden boats, namely to apply linseed oil, as a painted surface coating. This was not very effective in reducing shrinkage of the wood when drying, and for this reason research into the matter was performed by the National Museum of Denmark.[10] This research led to the introduction of alum as a dimension stabilizing agent for wood from archaeological wet sites. The alum then was used for about one hundred years, from the 1850's to the 1950's as a dimension preserving agent for wooden objects from archaeological wet sites of sizes that made possible boiling them in a tank.

In the lake Nemi, close to Rome a couple of large galleys, intended for, and used as entertainment palaces had been constructed by the Roman emperor Caligula, in the 1st century A.D. The vessels were c. 70 m long and 20 m wide. It has been said that after a while they were dismantled, and abandoned, and left to sink in the lake. Attempts were made to recover the ships and in 1450 the architect and writer Leon Battista Alberti was involved in an archaeological operation in order to raise the ships.[11] The project, however, was not successful. With the purpose of accomplishing the salvage of the two Roman galleys the Italian authorities in 1928-30 had the lake drained, leaving the galleys on dry land. A museum was built for the vessels and the objects that were found. This, however, was destroyed by fire in 1944, thus leaving no information as to how the wood might have responded to prolonged drying.[12]

In Holland the polder project for reclaiming land, which meant draining a large part of the "Zuiderzee" was started in 1918. During the operation, diked-in parts of the bay were pumped free of water, which made a large amount of wooden ships from many centuries of seafaring come to light. This made the Dutch archaeologists the most experienced about what

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[10] Bill and Mühlethaler, p 101.
[11] Jokilehto, 1986, volume 1, p 14.
[12] Hanell, 1951, Sloan, 2000 and Åkesson, 2008.

happens to historic, wooden wrecks from wet sites when they dry. Accordingly, this challenged conservators who often also were archaeologists, to consider means to prevent the deteriorated wood from shrinking, at least to some extent. During this period carboxy-methyl-cellulose (CMC) came into use as a dimension stabilizing and drying regulating substance.

Next to Caligula's galleys, the Swedish warship Vasa is the largest of this kind of cultural heritage objects that has been brought onto dry land. The Vasa was salvaged in 1961 with conventional salvage methods.[13] The Vasa salvage was planned in detail to minimize drying of the wood during the procedures anticipated.[14] As early as possible a construction was built covering the hull of the Vasa. In this "climate shelter" conservation treatments of the hull have been executed by spraying technique.[15] The wooden finds from the excavation of the interior of the hull, that was accomplished during the summer period in 1961, and the disconnected finds brought to the surface by the divers before and after the hull was lifted were kept in water in large tanks and were later preserved by immersion treatment.

In 1962, five ships and boats from the Viking age were found in the Roskilde fjord at Skuldelev located in mid-Själland, Denmark. They had been deliberately sunk to form a lock in a shallow part of the fjord. To accomplish an archaeological excavation of the Viking ships the site was surrounded by iron sheets forced into the bottom sediments of the fjord, thus creating a dock for the whole site. This dock was kept dry by pumping during the excavation period. Inside the dock the excavation was performed in the same way as in land-based excavations. The wooden material was found in an advanced state of deterioration, and fastenings between planks and other constructional parts had disappeared which made dismantling an obvious choice. The planks and other shipbuilding timbers were kept in water tanks. These timbers were later preserved by immersion treatment with PEG 4000. As an outcome of this project a special museum building was erected at Roskilde for the Viking ships, where they were exhibited after reconstruction.

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[13] Claus, 1986, pp 113 - 123.

[14] Håfors, 2001, pp 17-19.

[15] Håfors, 2001, pp 23-25.

In 1962 a cog was found, in river Weser close to the North Sea, in the harbour area of the town Bremerhaven in Germany. This vessel had been embedded in the river bank and was found meanwhile dredging to deepen the harbour. The cog was excavated, and saved in pieces which were stored in tanks with water.[16] When the new German National Maritime Museum was under construction in Bremerhaven, the 25 m long, more than seven m high and six and a half m wide hull was reassembled in the centre of the planned exhibition hall, in the place chosen for its permanent exhibition. The reassembling work lasted for five years and was performed between 1972 and 1979. Then, following the contour of the hull a tank was constructed. In this purpose-built tank conservation was accomplished by immersion treatment. After the treatment period the tank surrounding the cog was removed and the cog was put on exhibition in May 2000.[17]

Another project started in 1962 when construction timbers were brought up during a diving expedition at the Great Barrier Reef off the coast of Australia. These timbers were parts of the Dutch merchant ship Batavia which had stranded on the reef in 1627. The wooden material was preserved by immersion treatment with PEG and was pieced together and put on exhibition in the Western Australian Maritime Museum at Fremantle.

In 1980 another Swedish warship by the name "Kronan" was located at island Öland in the south of the Baltic by the finder of the Vasa, Anders Franzén and his team.[18] This ship has been excavated from 1981 by diving archaeologists who have brought disconnected findings to the surface. These have been preserved and are exhibited in the Kalmar Regional Museum. The hull however, still is remaining at the seabed.

In 1980 the hull of Mary Rose was salvaged outside Portsmouth, in South England. The salvage operation was made after the hull had been excavated under water. This hull had been lying with one side buried in clay that had saved it from being consumed by shipworm *(Teredo navalis)*. The still existing side of the hull was encased by a metal bar construction. This device was lifted from the seabed by crane. The Mary Rose then was placed on her keel in a roofed dry dock at Portsmouth.

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[16] Fliedner und Pohl-Weber.

[17] Kiedel and Schnall, 2000.

[18] Einarsson, 2001.

1. HISTORY OF CONSERVATION OF WOODEN FINDS REMOVED FROM WET ARCHAEOLOGICAL SITES

This housing is planned to be used temporarily for the conservation treatments.

The hull of the Pandora wreck, located at the coast of New Zeeland, maybe in future, will be salvaged and placed in a museum exhibition. New techniques, however, have made their way into the museum world. Nowadays it is possible with the aid of computer technology to pay a visit to a museum object that is located on the bottom of the sea. Maybe this can provide a better contact with the material remains of this kind of cultural heritage, and constitute an alternative to physical salvage and material conservation of large wooden wrecks.

However, there are many objects of this kind, that for different reasons have been or in future will be brought out of watery sites, onto dry land. So it is a firm belief of this author that the experiences from the conservation and the assessment of the long-term conservation of the Swedish warship Vasa will be of value to future projects caring for large wooden structures from archaeological wet sites.

2. The Dissertation

In the early 1970's, when the main body of experimental work for developing conservation methods for the conservation of the Vasa wood was finished, the author of this dissertation contacted the Department of Polymer Technology at the Royal Institute of Technology in Stockholm to find out if such studies would be possible to prepare for a doctoral dissertation. This made a chain of contacts to happen that eventually ended with the Head of the Department of Organic Chemistry at the Royal Institute of Technology, professor Torbjörn Norin. After discussion jointly with senior lecturer in wood chemistry Dr. Joseph Gierer, professor Norin replied that they had reached the conclusion, that the conservation experiments prepared for development of the conservation method for the Vasa would be a suitable basis for a doctoral dissertation in the field of wood chemistry.[19]

This, however, did not come to be executed at that time and when the author of this dissertation in 1985 contacted the institution again the reply was not as positive as it had been a decade earlier.

In the 1990´s when the Institute of Conservation at the University of Gothenburg had established its Ph.D. programme, and obtained authority to enrol doctoral students, the author of this dissertation was invited by professor Jan Rosvall as a doctoral student with the experimental research done mainly in the 1960's as empiric research material for the dissertation.

2.1. Background to dissertation

The main problems of wooden objects from archaeological wet sites like peat-bogs are their shrinkage, distortion or even collapse when drying. This problem seemed to have been solved at the National Museum of Denmark in Copenhagen in the 1850's, when museum director Christian Fredrik Herbst,[20] proposed alum as dimension-stabilizing substance for archaeological wood from wet sites. The "alum method" was further

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[19] Letter of 8 August 1974.

[20] Bricka, C.F., Danskt biografiskt lexikon: Christian Fredrik Herbst, b. 1818, Inspektør ved det Kgl. Museum for de nordiske Oldsager.

developed by conservator Georg Rosenberg,[21] and became the standard method at the National Museum for a period of more than a century from the 1850's. It was stated by Jakob Bill and Bruno Mühlethaler,[22] in "*Zum derzeitigen Stand der Nassholzkonservierung. Diskussion der Grundlagen und Resultate eines von Fachlaboratorien 1976 – 1978 durchgefürten Methodenvergleiches*", that

> "... In den fünfziger Jahren des letzten Jahrhunderts [1850's, author's remark] wurde im Nationalmuseum in Kopenhagen zum erstenmal mit Erfolg versucht, das Wasser zu ersetzen und die Holzporen zu schliessen. C.F. Herbst hat Nassholz in einer konzentrierten Alaunlösung während einiger Stunden gekocht; nach völliger Austrocknung wurden die Objekte mit Leinöl getränkt, um Luft und Feuchtigkeit möglichst fernzuhalten ..."

Alum was used as a dimension stabilizing substance at the Oseberg excavation in Norway for some of the wooden finds that were small enough to be handled in a liquid-tank. Large wooden objects, that could not be handled in a liquid-tank instead were brushed on the surface with linseed oil or wood tar.[23] For a long period alum treatment seemed to work well but later brittleness and even pulverising was reported from wooden objects preserved with that substance. Alum was finally abolished in 1962 as preservative for waterlogged wooden finds at the National Museum of Denmark.[24] When wooden finds from the Vasa began to emerge in 1958, evidently there was no tested and experienced conservation method on which to rely. However, as polyethylene glycol (PEG) had been introduced as dimension stabilising agent for wet archaeological wood that substance was chosen for the newly salvaged wooden material of delicate nature.[25] Later PEG was chosen even for the hull and large loose wooden findings.

2.2. Definitions

In 1993 the generic term "hydro-archaeology" was proposed by Valerie Fenwick in the editorial of *International Journal of Nautical Archaeology*

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[21] http:www.natmus.dk/cons/x/ww/rosenbrg.htm.

[22] Bill and Mühlethaler, 1979, p 101.

[23] Egenberg, 2003.

[24] Brorson Christensen, 1971, p 27.

[25] Håfors, 2001, p 44.

(IJNA) for all aspects of archaeology connected to water.[26] As a matter of fact the term "hydro-archaeology" had been suggested by John E. Rexine for underwater archaeology already in 1968.[27] Under-water archaeologists, however, did not adopt the term. When analysing the idea, Alison Gale stated that hydro-archaeology also might provide a "subject framework" for all kinds of archaeology connected with water that, until then had been denoted marine, maritime, shipwreck, underwater etc.[28] Gale derived the definition of "hydro-archaeology" from a definition of "archaeology" suggested by Keith Branigan:[29]

> "It embraces the discovery, recording, conservation (where possible) and interpretation of all traces of man and the world in which he lived before present."

From this statement Gale derived three components that embrace the whole of archaeology:

1. The *Subject of Study* – man and his world;
2. The *Source for the Study* – all traces of man;
3. The *Process of Study* – discovery through to interpretation.

These three components have been represented by Gale as a three-dimensional figure, with three interlocking planes forming 90° angles with each other. All of the constituent planes identified in the three-dimensional figure for archaeology as a whole can be used in *Hydroarchaeology*. However, according to Gale:[30]

> "…. some of the techniques into which they divide are exclusive to the investigation of the archaeological resource in the *Wet Environment*. These are the specific preserve of *Hydroarchaeology*: for example, the use of diving for field survey and excavation, or seismic survey equipment specific to the marine environment, or techniques for recovering and conserving waterlogged wood."

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[26] Fenwick, 1993, IJNA 22.1, Editorial.
[27] Rexine, 1968.
[28] Gale, 1993.
[29] Branigan, 1973.
[30] Gale, 1993, p 214.

In this context the term "waterlogged" was introduced without explanation. R. James Barbour states that he has used the term "waterlogged", introduced by Christen Skarr,[31] with the meaning, wood "at or near its maximum water content".[32] Charlotte G. Björdal has given the same signification to the word "waterlogged", and the same definition will be used in this dissertation.[33] This excludes from the terminology wood of lower degrees of water content. If needed, that might be overcome by using the term "wood from hydro-archaeological sites", and specifying the water content of the wood.

It seems reasonable to derive a description or definition of a vessel recovered from the seabed, using the three main components of hydro-archaeology as proposed by Gale. However, since the word "*hydro-archaeology*" has not been adopted by the discipline of archaeology the expression to be used in this dissertation will be "*wet site archaeology*".

Under the first heading "The *Subject of Study*" Gale identifies six "*Uses of Water*" with "Transport" as the fifth item. This leads to "Vessels" and further on to "Rescue and Recovery", e.g. of vessels. Under the second heading, "The *Source for the Study*" Gale divides into "The *Data Environment*" and "The *Physical Environment*", respectively - of which the latter one is further divided into dry and wet environments. The wet environment is divided into six different types of wet habitats, among these "the seabed". The third heading, "The *Process of Study*" comprises the many techniques employed by archaeologists to extract and manipulate information from the archaeological records which are the sources for the study. "Conservation" is listed among these techniques, but the term "conservation", has not been specified by Gale.

Feilden has proposed a definition of conservation as follows: [34]

> " Conservation deals directly with cultural property, its object is to keep it in the same state. Damage and destruction caused by humidity, chemical agents and all types of pests and micro-organisms which have infested cultural property must be stopped in order to preserve the object or structure."

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[31] Skarr, 1972, p 84.
[32] Barbour, 1982, p 209.
[33] Björdal, 2000, p 28.
[34] Feilden, 1991, chapter 3, p 16.

This indicates that situations may arise when special actions have to be taken to achieve keeping an object in the same state as when found.

Concerning the field of natural science collections, Waller points out:[35]

> "… the term "conservation", in addition to its conservation-related meaning has a second meaning related to the act of physically, and/or chemically, rendering a lasting specimen from a living or recently killed organism."

In the same sense, conservation, in the field of archaeology and, especially concerning wooden finds from archaeological wet sites, beside the meaning of measures taken for long term maintenance of the finds as museum objects, has the meaning of immediately taken measures in order to physically, and/or chemically stabilize the material for keeping and handling in adequate museum atmosphere.

2.3. Delimitations

This dissertation is focused on the initial phase of preliminary storage and stabilizing a large wooden wet archaeological object, namely the Swedish warship Vasa of AD 1628. This initial phase lasted from the salvage of the Vasa fore mast in 1956, the few finds that were taken ashore during the investigation of the hull in 1957 to 1961, the salvage and excavation of the hull in 1961 and the salvage of additional finds during the concluding diving operations that were finished in 1967, until 1979 when the spraying of the Vasa hull with conservation solution as well as the immersion treatment of the loose wooden finds were terminated. The stabilizing phase was paralleled by refitting work and display of not preserved sculptures that were hand-sprayed with conservation solution twice a day and night period during the exhibition period.

The initial phase was succeeded by a drying and surface treatment phase which was terminated when the Vasa ship was moved into its permanent museum building in 1988. The phase starting in 1988 within the newly constructed permanent museum building was a bridging phase consisting of building-up the moisture content of the museum

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[35] Waller, 2003, p 6-7.

atmosphere and the artefact's physical/chemical adjustment to its surrounding atmosphere. This phase continued until salt precipitations were discovered on the timbers of the Vasa hull during the winter 2000–01.[36] The former part of this phase will be given some attention in this dissertation.

The phase starting with the discovery of the salt precipitations on the Vasa hull has started a research project on ways to deal with the new situation. The results from work in this project until the present situation (autumn 2010), have brought about that a new air-conditioning equipment has been installed in the Vasa museum and that new climatic parameters have been decided for the Vasa museum atmosphere.[37]

Neither the latter part of the bridging phase nor the present research and adjustment phase will be dealt with in this dissertation.

2.4. Problems

Feilden's proposal that "Conservation deals directly with cultural property, its object is to keep it in the same state …" may not be what is wanted where wet archaeological wood is concerned. Conservator Børje Brorson Christensen at the National Museum of Denmark wrote in 1971:

"As far as I am aware, all works on the conservation of waterlogged wood take it for granted that the ideal is to preserve and stabilize waterlogged wooden artefacts in the size and shape they have when found. This cannot be quite correct. Any piece of wood that gets soaked in water will swell, and even totally green wood will swell a little. In the case of an artefact made of air-dried wood the swelling may be much more pronounced than is perhaps realized by many archaeologists. It is the opinion of the author that an artefact excavated in the true "waterlogged" state should – if possible – be stabilized in the size and shape it had when dropped into the water, …"[38]

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[36] Sandström T., *et al.*, 2002, and Sandström, M. *et al.*, 2003.
[37] Hall Roth *et al.*, 2005, p 173.
[38] Christensen, 1971, p 32.

Hoffmann states that the cell walls of archaeological wood might be found in a swollen condition, "… which means they contain a greater amount of wider capillaries than fresh wood."[39]

This may have been the cause of the fact that the sum of the measurements of the widths of nine deck planks of the upper gun deck of the Vasa hull was too high for the planks to be able to get into place on their proper deck beam, according to a measurement taken between the nail-holes for the first and the ninth deck-plank on the beam. This was a clear indication of swelling of the planks during the submersion period. The extent of additional space needed to put the nine planks down on the measured section was calculated by the conservator of the Swedish Maritime Museum, sea captain Sam Svensson in January 1963 to be a little more than 0.5%. To allow for some caulking, the swelling of the deck planks was estimated to be c. 1%.[40]

Since the original size and shape can not be established with certainty, the size and shape of the newly excavated waterlogged wooden object must be the scale of measurements of changes in size and shape of that object.

2.5. Aims and objectives

The overall intent of this study is to link the results of dimension stabilization with PEG's of large wet archaeological wooden finds intended to be permanent museum exhibits with criteria of shape and dimensions of newly excavated finds, and further to discuss how these criteria of newly excavated finds might be related to those of the original wooden objects, before being submitted to a wet archaeological site.

Another major aim is to present the results of the completed laboratory research programme at the Vasa conservation laboratory, for improving the immersion impregnation technique using polyethylene glycol, for wet archaeological wood.

A more specific objective is to compare the management actions that were taken in the Vasa conservation project, with the management

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[39] Hoffmann, 1982, p 76.

[40] Svensson, 3. 1. 1963, Barkman, 1965, p 5.

actions to be advisable from the results of the feed-back of the longitudinal study, and from the results of the laboratory research.

2.6. Assumptions

The comprehensive assumption of this dissertation is that *polyethylene glycols* (PEG's) *are capable as dimension stabilizing agents of wet archaeological wood, meaning that these* (PEG's) *prevent or reduce shrinkage during the drying procedure of a* PEG *preserved piece of archaeological wood brought from a wet site, compared to an untreated sample of the same piece of wood.*

This statement is strictly opposed to a declaration by S. Muñoz Viñas concerning some preservatives, including polyethylene glycols:[41]

> "… conservation processes can, at best, slow down alterations, but in many cases, conservation has accelerated the alterations of the objects it has been performed upon: the use of cellulose nitrates and acetates in paper conservation, the use of polyethylene glycols in archaeological conservation or the use of adhesive tapes on documents are some examples of stabilizing processes that did not achieve their goals, but unfortunately even had negative effects on the objects they were intended to conserve."

This distrust in conservation work expressed by Muñoz Viñas is not an unknown kind of reaction, even among museum officials at all levels. Controversies as to the effects of treatments also exist between conservators. It seems to indicate lack of knowledge about the materials and the methods of conservation work of concern, and may have been the result of insufficient research and documentation in the field of conservation. Perhaps also that uncritical myth-building may have caused misunderstandings of this kind.

2.7. Theoretical framework

There are tangible as well as intangible dimensions characterizing "cultural heritage". Tangible items, like e.g. historic monuments and

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[41] Muños Viñas, 2005, p 16.

museum objects, are considered to be carriers of some special messages between the past and the present. The contemporary in its turn is supposed to pass on special messages by passing on tangible items. Modern philosophers have formulated three “value parameters” characterising the tangible items that may be selected to pass on cultural heritage. These value parameters are “ethno-historical meaning”, “social meaning”, and “sentimental meaning”. Mũnoz Viñas distinguishes three categories of social meanings namely, hi-cult,[42] group-identification and ideological meanings.[43]

These three value parameters are organized as axes in the “conservation space”, as defined by Michalsky. An object that has high values on the three axes has the potential of becoming a “conservation object”. No rule exists, however, concerning specific objects conditions for how to become “conservation objects”.[44]

Finds from archaeological sites obviously have a high potential of scientific value. Even social value, especially group-identification value, e.g. at national level may be present or may be developed. Recently, the salvage of huge ship’s hulls from the sea-floor has been made possible and several projects were launched in the 1960’s.[45]

2.7.1. Conservation theory

The definition of conservation most widely adopted, has been formulated by Sir Bernard Feilden, who states that “conservation is the dynamic management of change to reduce the rate of decay”.[46]

Rosvall proposed “models for communication of material culture based on conservation concerns”, with the purpose of:

> “Focusing on the material culture, the aim of the research is to study complex relations between events in the past, objects and meanings linked to such events and present activities within the field of conservation where knowledge is generated and presented.

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[42] Mũnoz Viñas, 2005, p 38.
[43] Mũnoz Viñas, 2005, p 55.
[44] Mũnoz Viñas, 2005, p 63-64.
[45] This dissertation, chapter 1.
[46] Feilden, 1979.

> In this context it is clear that the initial interpretation and structuring of historical data is of central importance for the conservation process and for future use and conservation of cultural resources, as well as for 'normal' disciplines active in research connected with or based on cultural objects as source material. This field of research area is also closely connected with museological perspectives."[47]

Mũnoz Viñas has formulated "the reasons for conservation" as follows:

> "Understanding why an activity is performed comes very close to understanding the activity itself. It may reveal its goals and, by doing so, how to better fulfil them, which rules to abide by, and why they should be followed. Acknowledging that conservation objects have communicative effects is useful to this end."[48]

From this concept Mũnoz Viñas has developed his contemporary theory of conservation which he describes as functional and value-led conservation. This conservation concept would be guided by "meaning" instead of by "truth". Scientific conservation aims at revealing an object's "true integrity". This latter was the concept, that was predominant during the 1950's when the Vasa was recovered. Since the working methods of this concept were quite normal to the people trained in natural sciences who were employed to perform the conservation treatment of different material groups of the Vasa, the scientific conservation concept generally was accepted by them without any discussion.

Even the "conservation science" concept was accepted as a tool for the development of conservation methods for the large categories of different materials that were excavated from the Vasa hull. However, some philosophers have pointed out that the definition of conservation science is vague and not directly connected to any benefit to the conservation practise. A more narrow view on natural science investigations has been proposed, signifying that only those natural science investigations would be accepted as conservation science that can be proven to directly have helped the practise of conservation.[49] This

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[47] Rosvall *et al.*, 1995, p 11.
[48] Muñoz Viñas, 2005, p 171.
[49] Muñoz Viñas, 2005, pp 77-78.

narrow way of looking at natural science investigations from the conservation point of view, however, does not coincide with requirements from the side of the conservation of wet archaeological material. Knowledge about the material might un-expectedly be of value in unpredictable situations during often occurring very extended periods of conservation interventions.

"Truth-based conservation" claims objectivity and that "… the main purpose of conservation is to maintain or reveal an object's true nature or integrity".

Integrity factors of truth-based conservation have been listed by Clavir as follows:[50]

- Physical, refers to the material components of the object
- Aesthetic, describes the ability of the object to produce aesthetic sensations upon the observer
- Historical, describes the evidence that history has imprinted upon the object – its own, particular history

Muñoz Viñas suggested the following integrity factors for classical conservation theories:[51]

- its material components
- its perceivable features
- the producer's intent
- its original function

The pre-historic objects excavated at archaeological sites seldom produce easily observable aesthetic sensations, and they are mostly excavated for their value as ethno-historical evidence. Their integrity fits excellently with Muñoz Viñas four integrity factors. A truth-based conservation like scientific conservation would be suitable. This is founded on a "material theory of conservation" which claims as its most important principle, "… to preserve or restore the true nature of objects.[52]

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[50] Clavir, 2002.
[51] Muñoz Viñas, 2003.
[52] Muñoz Viñas, 2005, p 90.

What, however, was the true nature of an object like the Vasa? Bertil Thunell, wood expert of the Vasa Conservation Council, that had been established in September 1960, suggested that the criteria for recent seasoned wood for outdoor service be considered as the "true nature" of the Vasa wood. As wood for outdoor service was seasoned to a moisture content of c. 12%, made this moisture content the goal of the drying process of the preserved Vasa wood.[53] The fact that a moisture content of 12% would be maintained in recent wood by a RH of c. 65% made this value important for the RH parameter of the drying programme.[54]

However, the salvage of material of much later date from underwater sites excavated in the middle of the twentieth century became a new branch of archaeology, where objects with aesthetic integrity and social symbolism were recovered. The Vasa being a national symbol belongs to this category.

2.7.2. Natural science backbone

Since this dissertation deals with a huge wooden object, wood is the most important material to be considered. Wood is generally described as a porous and hygroscopic material. The hygroscopicity makes the wood take up and give off water, related to changes of the RH of the surrounding atmosphere. This process normally causes a piece of wood to swell and to shrink, respectively. The swelling and shrinking movements of a piece of wood are not uniform, but may be described in relation with the three spatial directions of the wood. These are the tangential, the radial, and the axial directions, meaning the directions along the growth-rings, perpendicular to the growth-rings and along the fibre axis, respectively. The "normal" use of wood includes the felling of a tree and the drying of the wood to a suitable water content. During the procedure the wood looses water and normally shrinks. To the users of wood, the shrinkage of wood is of greater interest than the swelling. Therefore a shrinkage-anisotropy-coefficient has been introduced. This coefficient is calculated as a quotient between the shrinkage in the tangential direction and the shrinkage in the radial direction, respectively. The values of the shrinkage-anisotropy-coefficient for fresh oak is 2 and for fresh pine 1.9, when dried from the high water content of newly

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[53] Thunell, 1952, p 38.

[54] Thunell, 1952, p 37, fig. 33.

felled “green” timber, to 0% water content of oven-dried wood.[55] This means that wood shrinks about twice as much in the tangential direction compared to the radial direction.

The capacity of absorption and de-sorption is exercised by a system of capillaries in the secondary cell-walls of the wood. This system makes up c. 40% of the volume of the cell-wall and has an inner surface of 100-200 m^2 per each cubic centimetre of cell-wall.[56]

Wood may be grouped into conifer woods that are called softwoods, and wood from deciduous trees that are called hardwoods. Softwood and hardwood trees differ mainly in their systems of water transport in the stems. The water transport system of softwoods is constructed from fibre cells with ring-pores, while the water transport system of hardwoods display a variety of cells forming ducts of considerable width through the length of the wooden stem. Pine wood belongs to the softwood group, while oak wood belongs to the hardwood group.[57]

The Vasa hull is built mainly of oak, with only a few constructional parts included, that are made of pine. Oak and pine are also the most common of wood-species even among the loose wooden objects found onboard the Vasa. This makes oak and pine the two wood-species of interest to be investigated in this dissertation.

Wood from archaeological wet sites

Any piece of wood found in wet surroundings may be found to be in a waterlogged state. However, wood that lacks the special features of archaeological wood, i.e. marks of cultural activity, will be difficult to define as to original shape and material state at the time before being submerged into a wet environment.

During the period submerged in water, the wood has been subjected to deterioration forces of physical, chemical and biological origin. Even seemingly well preserved wooden objects may show unexpected shrinkage and distortion when dried. This indicates that some change in the wooden material may have occurred. To a great extent this change

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[55] Esping, 1992, pp 170-172.
[56] Hoffmann, 1982, p 75.
[57] Esping, 1992, p 25.

might be attributed to bacterial activity, where erosion bacteria have been shown to play a major role.[58] Although these micro-organisms are oxygen-dependent, they may be active at very low oxygen levels and thus be able to degrade wood to substantial depths from the surface.[59] The bacterial activity may increase the internal surface of the wood, and thus enhance the velocity of chemical reactions between the wood polymers and components of the surrounding medium.

Deterioration may cause wood from archaeological wet sites to start shrinking at a higher water content than what is the case where recent wood is concerned.

Polyethylene glycol

Since the main problem with waterlogged archaeological finds made of wood is change of shape and dimensions during the drying procedure, there is a need for preventing this to happen. The method considered in this dissertation is the bulking method, with polyethylene glycol (PEG) as bulking agent.

PEG is a straight chain polymer built from ethylene oxide units, $HO-(CH_2-CH_2-O)_n-H$. It is manufactured in different chain lengths, giving products of various molecular weights. The PEG's used in the conservation work range from an average molecular weight of 200 to 4000. Since the chemical properties emanate partly from the ether oxygen of the chain, and partly from the alcoholic end groups, the various PEG's have many chemical properties in common. The physical properties, i.e. viscosity and melting point vary with the chain lengths. The higher molecular weight PEG's used in conservation work are solid substances of waxy character, while the lower molecular weight PEG's are viscous liquids at room temperature.

2.7.3. Selection of objects for protection

The first question to be asked is, why a particular archaeological object has been selected to become a museum exhibit. Has the archaeological

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[58] Björdal, 2000, pp 31-35.
[59] Björdal, 2000, p 40.

part of the cultural heritage been appreciated? Have the known objects been valued from a museological viewpoint as representatives of culture and history? Does there exist a plan for the retrieval of objects from archaeological wet sites? If so, will this be suitable or even possible to follow up, meaning rejecting possible objects and instead waiting for those that have been given a higher cultural value but for the time being not possible to be recovered by available technology? Whatever the reasons are for recovering an object from wet archaeological surroundings, the possibilities of stabilizing the object in museum surroundings should be thoroughly surveyed.

The fact that an object has been collected in order to become a museum exhibit also makes important a close museological analysis of the significance of the object. Depending on that a wet archaeological object usually needs some treatment to become evidenced as a museum exhibit, and since such treatment will need some time, and maybe also will change the object's material substance, shape and appearance, the museological analysis will have to be repeated during the treatment period and together with knowledge about the status of the material, to create a basis for decisions about the object, for its expected future.

The Vasa was not noted in any list of proposed archaeological finds to be salvaged.[60] In fact, before the wreck of the Vasa was relocated the possibility of salvaging such a huge object for the purpose of a museum exhibition, was never considered, and therefore not even proposed. Franzén, who relocated the Vasa carried out his search of personal curiosity. Inspired by his knowledge that the shipworm, *Teredo navalis*, did not exist in the Baltic he judged the wooden hulls in this surrounding to be in a good condition. The strength of the wood was also a requirement for the salvage operation. In practice, the condition of a particular object always has to be weighed into the decision to add it to a museum collection.

Thus, an object may be chosen for maintenance for a number of reasons. Once the selection is made, the object chosen becomes a "conservation object", in accordance with the definition proposed by Muñoz Viñas.[61]

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[60] Håfors, 2001, pp 2-3.

[61] Muñoz Viñas, 2005, pp 62-64.

2.7.4. Conservation performance

The most important competence of the conservator of wet archaeological finds is knowledge about handling material and processes of transforming an unstable wet wooden object into a stable exhibit under museum conditions.

There are three main ways of stabilizing a waterlogged wooden object.[62] The first one is to keep it in the waterlogged state, which might be done by using a water-tank. This possibility is limited by the size of the object and involves complications that make this way of exhibiting difficult to maintain for a longer period. However, there will be no dimensional change of the wooden material with this kind of processing.

The second way is to dry the waterlogged wooden object with certain precautions, to prevent shrinkage. The most well known way of doing this is freeze-drying. The size of the freeze-drying chamber, however, is a limiting factor. For some boats,[63] slow drying, has been chosen, performed by covering the ship with sand for an extended period.

The third way is making the waterlogged wood absorb a substance, which by entering the wood has the effect of preserving its dimensions. Polyethylene glycols (PEG's) belong to the substances with such capacity.

Arne Strömberg, member of the Vasa Committee and Head of conservation at the Swedish National Board of Antiquities listed treatments designed to eliminate, or at least reduce, shrinkage of wet archaeological wood on drying that might be taken under consideration as follows:

- Slow drying at high humidity,
- Freezing and air-drying,
- Limited drying by adding to the wood a hygroscopic substance like glycol or glycerol,

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[62] Håfors, 1995, pp 65-66.
[63] Jenssen, V. and Murdock, L., 1982.

- Substituting the water in the wood by a water soluble substance e.g. alum, water glass, or polyethylene glycol, and
- Extraction of the water by organic solvents.[64]

The preservative, PEG, discussed in this dissertation, is supposed to enter the wood structure by diffusion. Hunt and Garratt, referring to diffusion processes in wood conservation, have indicated that "… there are a number of methods of treating timber (in addition to the steeping process) in which penetration is dependent upon the gradual diffusion of preservative into the wood from a concentrated source of supply". In a footnote to the term "diffusion" the authors stated that "… the term diffusion, as used here, is not limited to the strictly physical-chemical meaning of the movement of individual particles, but includes also the mass movement of solution. Some so-called diffusion processes include both these kinds of movement".[65] This might be true for the PEG conservation process of waterlogged wood, both within the immersion process and when surface application is used. The wood to be preserved in the process referred to by Hunt and Garratt has to be recently felled timbers with a high water content, that, however, never had been dried, and therefore could not be compared to waterlogged wood. The preservatives used were salt solutions and the process got a few weeks to work. In the case of the Vasa the PEG macro-molecules were given a long time to move into the wood. How long this period of time would have to be, however, was not foreseen.

In this dissertation parameters for diffusion and mass movement of solution have been investigated both by immersion treatment, and by spray treatments with PEG solutions.

2.8. Methods

The author has applied the qualitative scientific method of "*participating observation*",[66] as overall approach to the different fields of investigation into the conservation of the Vasa wood. The basis for this is a profound personal involvement in the experimental and conservation work during

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[64] Claus, 1986, p 271.
[65] Hunt and Garratt, 1953, p 184.
[66] Patton, 1987, pp 74-75.

the author's employment at the Vasa project and the Vasa museum as head of the research and analysis laboratory during the period 1961–78 and as head of the Vasa conservation department 1978–99

2.9. Material

The materials of this dissertation are the Vasa hull and loose timbers and other wooden items. During the period 1961–78 experimental work was performed to gain reasonable knowledge about the conservation parameters to proceed with the treatment, and to adjust methods. The experimental work was mainly done as immersion experiments, where various parameters of the conservation solution were tested. To widen the perspective, PEG of various molecular weights were tried in experiments. Most of the experimental work was done with oak removed from the Vasa hull as test material.

Beside the experiments, extensive monitoring was performed of the Vasa hull and the immersion conservation. This provided a resource for feed-back from the conservation of the Vasa hull by surface application of PEG-solution, as well as from the immersion conservation, that would have been difficult to obtain by laboratory experiments. The PEG concentration of the conservation solutions of the immersion conservation was monitored by measurement of the density at regular intervals that provided information about divergence from the PEG concentration of the conservation programme. The water-ratio and the PEG-ratio of a number of items removed for core sampling before the start of the conservation programme and after the programme was finished provide information about the results of the conservation treatment.

Since pine from the Vasa was difficult to procure for laboratory experiment, the feed-back from the conservation treatment provided an opportunity to learn about the differences between the oak and the pine that together constitute the main body of the Vasa wooden material.

II. Development of the PEG Conservation Programmes

Depending on that there had never been such a conservation project earlier, there was no knowledge available about the problems to deal with, like how to stabilize the wood or what time it would take for the salvaged hull to reach the state of museum exhibit. There was not even a definition available of what material state that was intended in the end for the exhibit. In 1960, before the hull was raised, an opinion had been launched that it would be an impossible task to stabilize the dimensions of the timbers. This meant that the idea to keep the shape and tightness of the hull would have to be abandoned. The only thing that was understood to be possible, was to give the hull some treatment against rotting fungi and mould, and therefore some contacts were made to solve that problem.[67]

It was, however, decided that the wooden sculptures - which, although some of them were rather large, could be treated in a tank - were to have dimension-stabilizing treatment. This had been started on a small scale with polyethylene glycol (PEG), in the autumn of 1958 with small wooden objects that were brought up from the Vasa wreck by the divers. In the autumn of 1959 a glass-fibre reinforced plastic tank, holding c. 8 m^3 had been supplied free of charge by a private company.[68] In this tank, that was placed in a not heated warehouse space, the large figure-head lion that had been brought up from the Vasa wreck site was immersed into a not heated 30% PEG 4000 water-solution for nine months.[69]

The situation, when in 1961 the newly established Vasa conservation laboratory stood before the gigantic task of taking care of the Vasa hull, that was raised in April that year and the many disconnected wooden items that filled a great number of tanks in the naval dockyard, was challenging. No one could foresee the length of time the conservation would take. The laboratory building that was constructed for the purpose of housing the conservation of the disconnected and loose material was

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[67] Claus, 1986, p 281.
[68] The Swedish company AGA.
[69] Claus, 1986, p 14 and p 276.

estimated to be needed for a period of 5-7 years and the temporary housing that was constructed around the hull was expected to be replaced by a permanent museum building after c. 6-7 years.[70]

To deal with the situation, experimental work was started with PEG as the selected substance for dimension stabilising conservation. A fungicide was also sought out that had to be adequate for the task but not to be harmful neither to those who handled the conservation solution, nor to museum visitors.

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[70] Claus, 1986, p 287.

3. Development of the Surface Application Procedure

In May 1961 the Board of the Vasa had managed to dispose of financial means to employ a full time conservation manager.[71] This situation stressed the importance of the conservation issue. In June 1961 a letter arrived from Gerrit van der Heide, director of the Wieringermeer, at Shokland in the Netherlands. He was involved in the "polder project" in the Netherlands and had a long time experience of handling large wooden objects from archaeological wet sites. This letter was a reply to an invitation to a meeting about conservation methods, which he had not been able to attend. Instead, in his letter he presented some views on conservation of large wet wooden objects. One of these was stressing the importance of that the conservation agent penetrates all through the wood, and the other was that to achieve such a penetration the wood must be kept "as wet as possible" during the entire conservation period.[72] This letter restarted the discussion about conservation of the Vasa hull.

Immersion treatment would only be possible if the hull was to be dismantled. This, however, was considered to be too risky because there was no guarantee that the separate wooden members would not shrink or become distorted, a fact that would make later reassembling of the hull difficult. Therefore it was decided to keep the hull as a unit and go for surface treatment with a conservation solution.

Two experiments were designed to achieve information on the conservation procedure. One was a laboratory-scale experiment that would provide information for the decision on conservation substance. The other experiment was designed to be a large-scale test on surface application and drying large timbers.

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[71] Håfors, 2001, p 11.
[72] Håfors, 2001, p 47.

3.1. Methods and material

Material

Oak constitutes the main body of the Vasa hull, and was therefore chosen as test material. A deck-batten from under the lower gun-deck of the Vasa was removed to provide test material for the laboratory scale experiment.

For the large-scale experiment timbers of large dimensions were needed. These were obtained from another wreck of about the same age as the Vasa and were brought up by divers from the wreck site.

Conservation performance

The test specimens of the laboratory scale experiment were treated by brushing the conservation solution on to the surface. The test panels were treated by using a spraying equipment.

Conditioning procedure

Half of the number of test specimens of the laboratory scale experiment were kept in a climatic chamber during the treatment period while the other half of the number of specimens were kept in the laboratory atmosphere during the treatment period. Drying of the test specimens was performed in the laboratory atmosphere.

The test panels were conditioned individually during the treatment and the drying periods.

3.2. Testing surface treatment of oak wood from the 17th century Swedish warship Vasa with various conservation formulae

With the arrival of the letter from the Netherlands two suggestions were presented for dimension stabilizing substances to be considered in the Vasa conservation project. Oak constitutes the main body of the Vasa hull, and therefore, it was decided to test both suggested substances,

3. DEVELOPMENT OF THE SURFACE APPLICATION PROCEDURE

PEG 4000 and carboxy-methyl-cellulose (CMC), in an experiment using pieces of oak specimens from the Vasa hull as test material, in order to form a basis for evaluating their dimension stabilizing effect on this particular object. In April 1962, a deck-batten with a cross-section of c. 9 x 9 cm was removed from under the lower gun-deck of the Vasa. The deck-batten was crosscut into test blocks, each one with a length of c. 15 cm. Each block was marked at equal distance from the same transverse end surface. At this mark two sides perpendicular to each other of each test block was going to be measured from edge to edge with a vernier calliper to enable calculation of the transverse area at the mark of each test block. Each block weighed c. 1100 g in wet condition. To slow down evaporation of water the two large transverse surfaces of each test block were painted with an adhesive (Araldite) that cures under moist conditions.

van der Heide had stressed the importance of keeping the wood moist during treatment, so it was decided to set up an experiment in order to elucidate this phenomenon. Two RH-levels were chosen as far apart from each other as would be feasible even for full scale realization; one was a climatic chamber with c. 90% RH, and the other was normal indoor ambient RH of the laboratory. Both test climates had the same indoor ambient temperature of the season. The test blocks were grouped into two series: one was to be treated in the climatic chamber and the other in the laboratory. Both series contained specimens that were to be treated with each of the suggested dimension-stabilizing substances: CMC, and PEG 4000. Each of the series also contained untreated specimens and specimens treated with combinations of PEG 800, PEG 4000 and a boron formula, respectively.

Since handling organic solvents involves risk of fire and health hazards, only water was allowed as a solvent for these preservatives. It was possible to mix both CMC and PEG 4000 could be mixed with water to viscous liquids. These liquids, however, differed much in concentration. To be usable, the CMC conservation liquid could be prepared only with 3% CMC while an equally practicable PEG 4000 conservation solution contained 30% PEG 4000.

The experiment was started on 18 April 1962 by a team composed of responsible conservation manager Lars Barkman and this author, at that time in charge of the research and analysis laboratory at the Vasa conservation department. The treatment programme involved surface application of conservation solution with a brush once a day, on weekdays during a treatment period that lasted for

five weeks. This meant 30 brushings of conservation solution on to each test block. The test blocks were weighed before and after each treatment, to enable calculation of the amount of conservation solution added each time. From these daily amounts the total amount of conservation solution added to each test block was calculated. Despite the differences in preservative concentration the two conservation liquids were adsorbed by the wooden blocks to roughly similar extent at each of the chosen RH programmes (table 3-I).

Conservation solution	Conservation solution added at c. 90% RH atmosphere (g)	Conservation solution added at indoor seasonal ambient RH (g)
30% PEG 4000 in water	156	281
3% CMC in water	210	301

Table 3-I. Total amount of conservation solution added to the test blocks.

The main difference was observed between the two RH atmospheres. Generally, a larger amount of conservation solution had been adsorbed by the specimens treated in the laboratory than by those treated in the climatic chamber. The table (table 3-I) shows that about as much as 80% more PEG 4000 solution had been adsorbed by the surface of the block in the ambient climate compared to the block that had been kept at c. 90% RH while the amount adsorbed CMC-water mixture by the block in the ambient climate was c. 40% larger than the amount adsorbed by the block that was kept at c. 90% RH. Thus, the adsorbed amounts of the two conservation liquids seem to be of comparable magnitude in both climates. However, as the concentration of CMC was only one tenth of the concentration of PEG 4000 the adsorbed amount of CMC was only one tenth of the adsorbed amount of PEG 4000.

The conservation treatment was followed by eight months drying in ambient laboratory climate. During this period the test blocks were weighed twice a month. From these weights and their calculated dry weights the water-ratio of each block was calculated (figures 3-1, 3-2).

The diagrams show that the c. 90 % RH atmosphere had almost prevented drying during the treatment period, while the blocks in the ambient atmosphere had lost about half their amount of water during the treatment period. The water-ratios at the end of the drying period were low for both groups of test blocks in both climates.

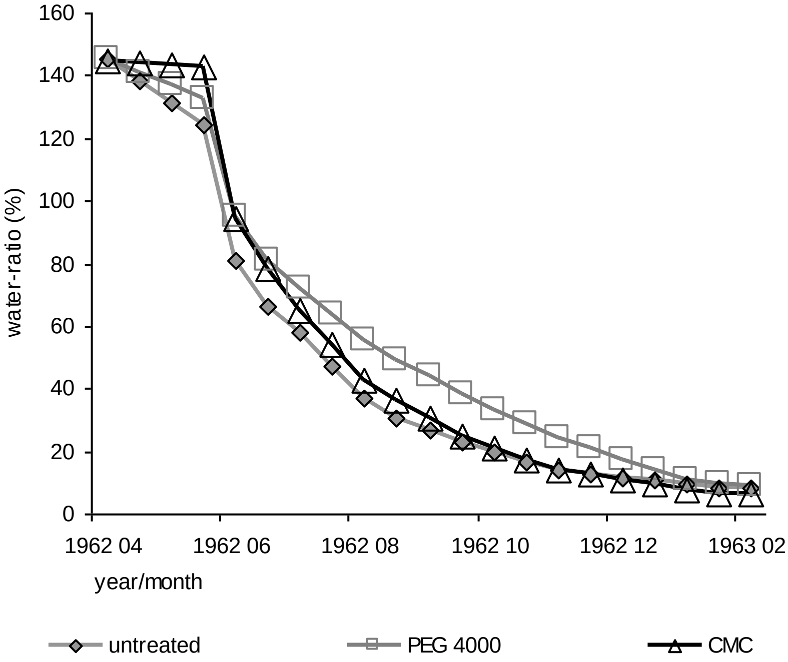

Figure 3-1. Water-ratios during treatment and drying periods. Conservation treatment at c. 90% RH atmosphere.

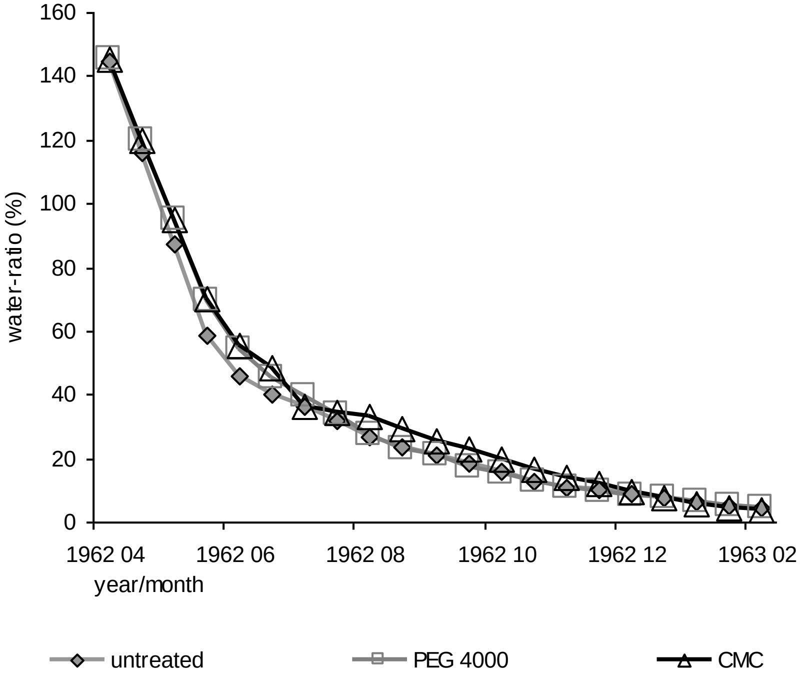

Figure 3-2. Water-ratios during treatment and drying periods.
Conservation treatment at indoor ambient atmosphere of the season.

Before treatment and twice a month during the drying period when the blocks were weighed each block was measured and the transverse area was calculated. Thus, the shrinkage of the differently treated test blocks and the untreated references could be followed during the drying period (figures 3-3, 3-4).

As extracted from the drying diagrams the block treated in ambient atmosphere and the untreated block in that group had shrunk more (4 - 8 %) during the treatment period than the blocks that were treated at c. 90% RH. In the latter group the untreated and the CMC treated blocks respectively, had shrunk 1% while the PEG 4000 treated block had not shrunk at all during the treatment period.

At the end of the drying period the shrinkage of the transverse area of the block that had been treated with PEG 4000 at c. 90% RH was 14%, and the one that had been treated at indoor ambient atmosphere had shrunk 16%. The transverse shrinkage of the CMC treated blocks was 17% in both c. 90% RH and indoor ambient atmosphere. The PEG 4000 treatment at c. 90% RH also seemed to slow down the velocity of shrinkage during the early phases of the drying period compared to both untreated and CMC treated blocks (figure 3-3). The transverse shrinkage of the untreated blocks that had accompanied the blocks treated at c. 90% RH and the blocks treated at indoor ambient atmosphere were 15% and 18%, respectively.

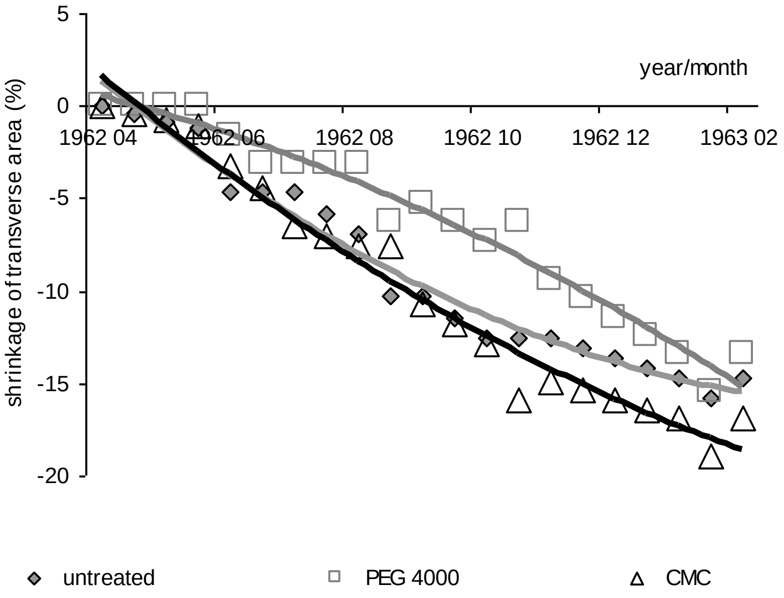

Figure 3-3. Shrinkage of transverse area during treatment and drying periods. Conservation treatment at c. 90% RH atmosphere. Trend-lines; least square fittings.

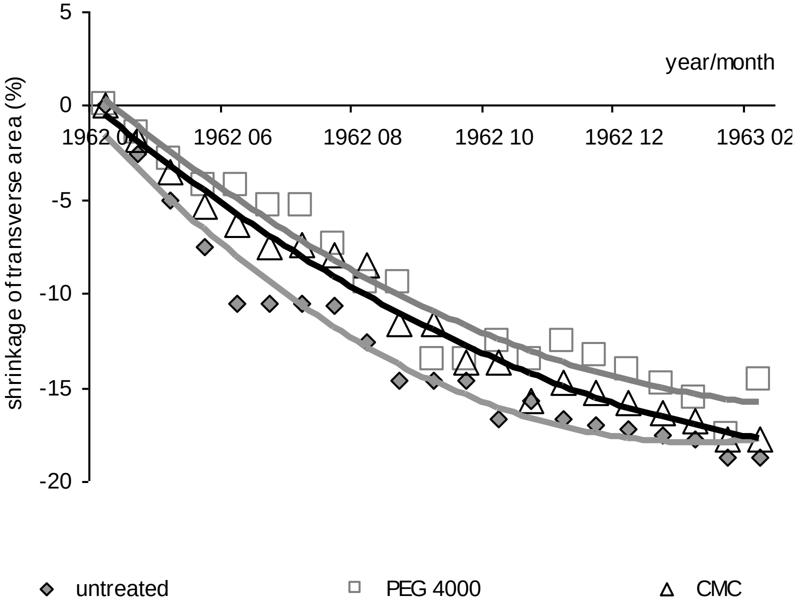

Figure 3-4. Shrinkage of transverse area during treatment and drying periods. Conservation treatment at indoor ambient atmosphere of the season. Trend-lines; least square fittings.

Conclusion

This investigation thus provided no grounds for using CMC, and the CMC therefore was abandoned from the Vasa project. However, the experiment supports the hypotheses by van der Heide that, to achieve penetration of preservatives the wood must be kept “as wet as possible” during the conservation period and that the conservation period should be extended.

3.3. The test panels

In order to create a basis for designing a conservation programme a large-scale test was made before the treatment of the Vasa started. To perform a proper test, it was necessary to use wood with characteristics that resembled those of the Vasa wood. The parameters to be tested made it important to use identical material for a number of parallel treatments. Thus, it was necessary to obtain a large amount of such material.

Fortunately, there are other wrecks of about the same age as the Vasa, with known geodetic positions at the sea bottom. As there had been no plan proposed to salvage these vessels, some timbers had already been removed and used for private purposes from another "man-of-war" at an under-water site just outside the Stockholm harbour. From this already damaged ship divers brought some oak boards and planks in September 1961.

With this oak wood material, four panels were constructed, c. 1.5 by 1.5 m.[73] During the construction period and until the experiment was started at the beginning of July 1962 the panels were kept wet by water spraying.

The PEG's 4000 and 1500 were chosen as dimension stabilizing substances in the experiment. They were both made up as solutions in water of 30% PEG. Both solutions contained 8% of boric acid and borax mixture (7:3) as a fungicide. This was the conservation solution formula composed by the research and analysis laboratory.[74] However, as the boric acid/borax mixture was judged not to be potent enough if surface moulds such as *blue stain* would make an attack, a water solution of sodium-pentachloro-phenol (NaPCP) was also prepared for the test.

The aim of the experiment was to test again the hypotheses by van der Heide that, to achieve penetration of preservatives the wood has to be kept "as wet as possible" during the conservation period and that the conservation period should be extended. In order to get an idea of what "as wet as possible" meant in practice one of the panels (panel B) was designed to be covered by a plastic sheet from the beginning of and during the entire experimental period to slow down evaporation while the other three panels would be kept at the laboratory climate without any protection. When the treatment of panels C and D had been performed for some weeks the conservation solution, however, seemed to dry rather quickly on the wood surface. To slow down the drying

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[73] Håfors, 2001, pp 51-54; Barkman, 1975, pp 83-84.
[74] Håfors, 2001, pp 56-57.

process those panels too were covered with plastic sheets after six weeks and for the rest of the treatment period. Panel A, that was designed as a blank test, remained uncovered.

Since panel A was chosen as blank test it was not treated with preservatives. The other three panels (panels B, C and D) were sprayed daily with a NaPCP-solution during the first week of the experiment. During the second and third weeks panel C was sprayed with the solution with PEG 4000 while the other two were sprayed with the solution based on PEG 1500. From the fourth week through the rest of the conservation period all three panels were sprayed with the solution based on PEG 4000. This created two panels, panel B and panel D with the same treatment programme but with different conditions during the treatment and drying periods. The treatment with PEG solution was performed twice daily and was continued until no absorption of conservation solution was observed. This happened after six months of treatment.

The experiment was monitored by analysing wood samples to determine the conservation and drying status and by measuring shrinkage at a number of measuring points with a strain gauge equipment.

The oak material salvaged for the experiment and the oak timbers of the Vasa held about the same maximum water ratio (u_{max}), c. 150%. The first check on the water-ratio of the wood of the panels took place 16 weeks after the treatment had been started. At that time all four panels had dried but showed varying water-ratios. Panel A had a mean water-ratio of 88% despite being uncovered, panel B had a mean water-ratio of 94% and panels C and D had mean water-ratios of 72 and 68 % respectively.[75] Wood samples were also taken from the panels half a year after the treatment had been finished. At that time the panels A, C and D presented the same mean water-ratio, while the mean water-ratio of panel B was higher by 6 percentage units of water-ratio (table 3-II). Looking at the 10 mm thick surface layer and even the c. 30 mm thick layer, from the surface through to the centre of the planks, the difference in water-ratio between panel B and the other treated panels was of the order of 10-12 percentage units of water-ratio. The final wood samples were taken after 1½ years of drying. During the year in the not controlled climate of the laboratory, the untreated panel A had lost 4

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[75] Barkman, 1975, p 84.

percentage units of water-ratio while the panels C and D had gained some water. Panel B which still was covered by a plastic sheet had lost a mean of 6 percentage units of water-ratio and the surface layer of 10 mm and also the c. 30 mm layer through to the centre of the planks had lost as much as c. 10 percentage units water-ratio during the year.

Panel	½ a year of drying			1½ years of drying		
	surface layer (0-10 mm)	to the centre of the plank (0-30 mm)	through the plank	surface layer (0-10 mm)	to the centre of the plank (0-30 mm)	through the plank
A	19	18	18	16	16	14
B	34	31	25	22	22	19
C	24	21	18	29	18	23
D	22	20	18	24	20	19

Table 3-II. Mean values (%) of water-ratio of panels A, B, C and D, respectively: in the surface layer (0-10 mm); to the centre of the plank (0-30 mm); and through the plank, respectively.

The PEG-ratio in the wood was measured by analyses of the same core samples as had been analysed for water-ratio. As in the previously described experiment (3.2.) the treatment at higher RH (panel B) resulted in lower PEG concentration in the wood than the treatments at lower RH (table 3-III). This might be considered a disadvantage, but after 1½ years of slow drying there seems to have been a continuing migration of PEG into the wood (panel B),[76] while in contrary, PEG seems to have migrated towards the surface of the wood in the situations of faster drying (panels C and D).

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[76] De Jong, 1981, p 58.

Panel	½ a year of drying			1½ years of drying		
	surface layer (0-10 mm)	to the centre of the plank (0-30 mm)	through the plank	surface layer (0-10 mm)	to the centre of the plank (0-30 mm)	through the plank
A	-	-	-	-	-	-
B	22	7.8	4.4	15	13	8.9
C	46	28	11	27	8.1	9.6
D	41	20	16	22	7.5	9.3

Table 3-III. Mean values (%) of PEG-ratio of panels A, B, C and D, respectively: in the surface layer (0-10 mm); to the centre of the plank (0-30 mm); and through the plank, respectively.

Depending on the hypothesis that PEG is a dimension stabilizing substance for wet archaeological wood measurements would be a proper way of monitoring to indicate the treatment and drying programme that had given the best result. All the planks of the panels were measured once a week.[77] From these measurements those that matched the core samplings at the end of the treatment period have been chosen and the mean shrinkage of each panel has been calculated (figure 3-5).

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[77] Barkman, 1975, pp 85-88.

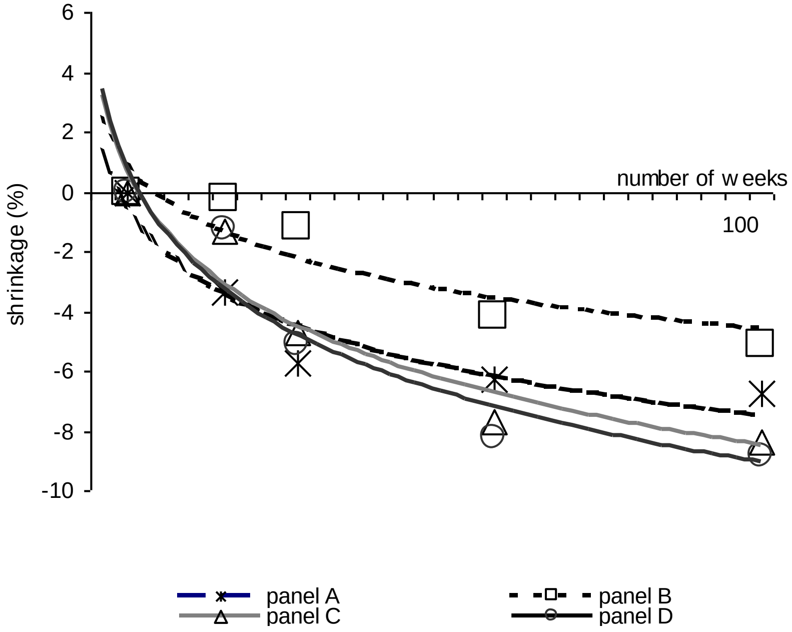

Figure 3-5. Mean shrinkage of the planks of the panels A, B, C, and D, during the treatment and drying periods. Trend-lines; least square fittings.

Panel B clearly shows the most favourable shrinkage pattern despite the lower PEG concentrations in the wood at the end of the treatment period. The indications of the previous experiment were verified and the hypotheses by van der Heide were strengthened again, indicating that, to achieve penetration of preservatives the wood must be kept "as wet as possible" during the conservation period, and that the conservation period should be extended.

3.4. Development of the surface application procedure; conclusions:

Two substances were mentioned as possible to be used as preservative for the wet archaeological wood. These were carboxy-methyl cellulose (CMC) that had been used by Gerrit van der Heide who was working with the "polder project" in the Netherlands and polyethylene glycol (PEG) that had been in use for conservation of wet wood only for a shorter time. PEG had, however, been used for treatment of small wooden objects in the Vasa project. Both substances were tested in a laboratory experiment. The test worked out in favour of PEG that was chosen as preservative for the Vasa wood.

However, the hypotheses by van der Heide, that, to achieve penetration of preservatives the wood must be kept "as wet as possible" during the conservation period, and that the conservation period should be extended was accepted as a basis for the planning of the treatment of the hull.

4. Development of the Immersion Treatment Procedure

The immersion treatment with PEG of the small wooden objects from the Vasa, that were found before the salvage of the hull,[78] followed the programme protected by the patent held by Morén and Centerwall.[79] A test treatment of an assortment of objects from the Vasa made of different kinds of wood had also been accomplished, in a 5 m^3 tank with a modification of the Morén and Centerwall programme.[80] To investigate what modifications, that would be to the benefit of the immersion treatment programme of the Vasa wooden material, laboratory scale experiments would be more adequate.

The difference established by the test treatment, between the reaction of oak and pine material from the Vasa towards a common conservation programme, indicated that separate conservation programmes would be required for these two wood species that were the main constituents of the Vasa wooden material, Therefore, it would be of great importance to the Vasa conservation project to establish the characteristics of difference of reaction towards a specified treatment programme of these two wood species.[81]

The Morén & Centerwall programme was used to identify the parameters of importance to the immersion process. These were then selected as a basis for a series of laboratory scale PEG impregnation experiments.[82] The parameters of importance to the immersion process were identified as follows:

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[78] Håfors, 2001, p 44.
[79] Claus, 1986, p 273.
[80] Håfors, 1990 pp 202 – 203.
[81] Håfors, 1990, p 203.
[82] Håfors, 1993.

1. Temperature, where either a constant temperature level, or a temperature raising programme may be applied.

2. Concentration of PEG in the immersion bath, where either a constant concentration level, or a concentration raising programme may be applied.

3. Duration of the conservation period, which either may be established as a fixed parameter or be the result of the concentration programme applied.

The characteristics of the wooden object to be preserved ought to be taken into consideration. Wood species,[83] the degree of degradation of the wood,[84] and the proportion of transversely cut grain to longitudinal grain may be considered. The size of the object may be crucial for the choice of conservation method and programme.

When a concentration raising programme is chosen, the start and end concentrations of PEG will become parameters that may be furnished with various numerical values. Likewise, various numerical values may be attached to the size of the PEG increments and the time intervals at which the increments would be charged into the conservation solution. When a steady concentration level is chosen, the duration of the conservation period will become a parameter for which a variation of values may be chosen.

Another circumstance, that might have been important was the question whether various wood species reacted similarly or differently to the same conservation programme. Among the small number of reports about PEG treatment that had been published at the beginning of the 1960's only few mention the species of wood of the preserved objects. It was, however, common knowledge among commercial wood conservation specialists that impregnation of oak wood was especially hard to achieve. Their experience was, however, based on fresh wood.

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[83] De Jong, 1981, p 62.

[84] De Jong, 1981, pp 61-64; Morén and Centerwall, 1960, pp 180 and 186.

4. DEVELOPMENT OF THE IMMERSION TREATMENT PROCEDURE

4.1. Methods and material

In order to gain information on how to conduct the immersion conservation treatment laboratory scale experiments were performed with some PEG's during the period 1962 - 1972.

Since the laboratory experiments aimed directly at improving the conservation methods for the Vasa material, all of these but the initial experiment of the immersion treatment have been performed with authentic test material removed from the Vasa hull. In order to obtain relevant test material, three or four deck-battens were removed from under the lower gun-deck of the Vasa. The removal of material from the Vasa hull had to be authorized by the museum director, and therefore, the oak and pine test material that was utilized in the initial laboratory experiment of immersion treatment was recovered from pieces of detached oak and pine material that were found on board the Vasa, but with unknown location concerning where they would have originally been attached to the hull.

The conservation experiments were performed in thermostatic baths, in accordance with detailed description given in connection to each experiment. When the conservation programmes were terminated the test specimens were seasoned in a conditioning procedure.

The conditioning procedures for the test specimens were performed in a succession of closed chambers with controlled interior atmospheres of different RH levels. One of the climatic chambers was charged with distilled water, and the others were charged with saturated salt solutions in contact with an excess amount of solid phase of the salt, that had precipitated from the saturated solution of the respective climatic chamber. The salts utilised were: sodium-carbonate ($Na_2CO_3 \cdot 10\ H_2O$), ammonium-sulphate ($(NH_4)_2SO_4$), sodium-chloride ($NaCl$), sodium-nitrite ($NaNO_2$), and calcium-nitrate ($Ca(NO_3)_2$), producing 91, 81, 76, 66, and 55% RH respectively at 20°C.[85] The conditioning procedure was monitored by weighing of all of the test specimens. These were removed from the conditioning chambers and transported in desiccators with the same RH as the chambers to the balance for weighing, in order to disturb the conditioning procedure as little as possible. A rather long

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[85] Lange, 1961, p 1420.

period of time was needed to reach equilibrium, since the conditioning procedure relied solely on diffusion of water molecules that had built up a gradient at the surface of the test specimen, and which only was disturbed at the weighing occasions. This conditioning procedure was continued until stable weights had been obtained, during a period of at least one month. The shortest conditioning period utilized actually was 3 months.

Desiccators charged with saturated salt solutions, in immediate contact with an excess of precipitated salt, were also used for conditioning of small size test materials and PEG´s.

Since the climatic chambers were kept in a part of the laboratory that was sheltered from incoming sun - but was not temperature conditioned - they may have been influenced by temperature fluctuations of the ambient laboratory atmosphere.

Drying of test specimens as well as of the wood-cores that had been drilled for analytical purpose, has been performed at ambient room temperature in a desiccator, connected to a vacuum-pump and charged with silica gel as desiccant.[86]

4.2. Laboratory testing of the Morén and Centervall conservation programme

This experiment was the first in a sequence of laboratory experiments that were performed at the Vasa Conservation Laboratory to establish optimal numerical values of the parameters of immersion conservation treatment with PEG of wood from archaeological wet sites. It is to be considered a preliminary experiment, and was planned to provide an orientation about the impact of the different parameters of the PEG 4000 conservation solution on the conservation of wet archaeological wood. The PEG conservation procedure created by Morén and Centerwall was used as a model for identification of the conservation parameters and for testing specific numerical values for these parameters.[87]

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[86] Håfors, 2001, p 129, figure 7-2.

[87] Morén and Centerwall, 1960.

4. DEVELOPMENT OF THE IMMERSION TREATMENT PROCEDURE

The immediate task at the Vasa conservation laboratory was to start immersion conservation of wooden material that had been disconnected from the Vasa hull and was found separately at the site under water and wooden material excavated from the hull. This meant that numerical values of the parameters, initial temperature and PEG concentration of the conservation solution had urgently to be determined.

Morén & Centerwall had created a temperature raising programme linked to specific PEG concentration levels in the conservation bath starting at 30°C and ending at 70°C. The ultimate stage which would be a PEG-melt might even include "a brief period" of heat treatment at 90°C.[88] Consequently, a temperature raising programme was created for the intended experiment. In accordance with Morén & Centerwall the final stage of the PEG concentration raising programme was planned to be a PEG 4000-melt. This meant that a temperature above the melting temperature of PEG 4000 had to be chosen for the later stages of the conservation process. There was to be taken into consideration, however, also a risk of decomposition of the PEG molecule at high temperature, that made it important not to choose an unnecessarily high temperature level. As the melting temperature of PEG 4000 is 56°C it seemed that 65°C would provide a margin to keep the PEG 4000 a melt, and as it was 5°C below the temperature recommended by Morén & Centerwall, who had not reported any sign of decomposition of the PEG 4000 molecules, it would be safe in that respect. On these grounds it was decided to choose 65°C for the final stages of the temperature programme. The initial temperature of the programme was defined as "room temperature ", i.e. 25°C.

To enable evaluation of the effect of raising the temperature during the conservation process a parallel conservation programme at a constant temperature level was set up as reference. Consequently, 65°C was chosen as temperature level for this programme.

Another objective was to investigate the effect on wood from an archaeological wet site of different initial PEG concentration of the conservation solution at immersion conservation. Morén & Centerwall recommended either 10% or 30% PEG 4000 as initial concentration, [89] depending on the state of degradation of the wood, so it seemed logical

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[88] Morén and Centerwall, 1960, p 183.

[89] Morén Centerwall, 1960.

to embrace these values. As experimental arrangements could be made for four different concentration programmes at each temperature programme the four initial concentrations of PEG 4000 chosen were 5%, 10%, 20% and 40%.

Morén & Centerwall used replacement of evaporated water with a 10% PEG 4000 solution to raise the PEG concentration of the conservation solution which meant that they did not specify the size of PEG increments or the length of time intervals for charging PEG into the solution. Thus, values had to be chosen for those parameters, and as the experiment had to be of limited duration to provide the desired information within reasonable time it was considered suitable to raise the PEG 4000 concentration by 5% per week.

In accordance with the recommendations from Morén & Centerwall 100% PEG 4000 was chosen as ultimate concentration for all four programmes. This resulted in a conservation period of maximum 20 weeks duration. The experiment also gave an opportunity to test the reactions of the wet archaeological oak and pine respectively, to the same conservation programme. One oak and one pine specimen were chosen for each of the conservation programmes at each of the temperature programmes. The specimens of oak and pine respectively, should be of similar degree of deterioration, as each of these two species of wood fitted into the Vasa hull.

As there were restrictions for removing material from the Vasa hull, there was a shortage of relevant testing material for experimental work. This had to be sought among the detached wood strips that were found on board the Vasa hull, however with unknown location concerning where they would be fitted into the hull. As the oak and pine strips among the detached material represented different constructional parts of the hull it was difficult to find strips of them both, that were similar in size. One strip of oak and one of pine were sought from the detached material. The oak strip had a transverse section of 5 by 5 cm and was cut into eight test blocks, each 7 cm of length.

4. DEVELOPMENT OF THE IMMERSION TREATMENT PROCEDURE

The transverse section of the pine strip was 3 by 1 cm and it was likewise cut into eight test blocks each 8 cm of length. As with the test blocks previously mentioned,[90] all transverse surfaces were painted with Araldite. The maximum water content (u_{max}) was used as a parameter to characterize the state of deterioration of the test specimens. The u_{max}-value, ranging between 143 - 146 % for the oak specimens was the same as the u_{max}-value for the previously mentioned deck-batten that was taken from under the lower gun-deck of the Vasa. The u_{max}-value for the pine specimens was around 300%. This, as it would appear, was higher by more than 30 % compared to the pine that was fitted into the Vasa hull. However, it may possibly represent some of the detached findings of panels and sculptures.

To accomplish the experiment, two 12 l glass tanks were chosen as vessels for thermostatic baths. Each tank was equipped with a lid made from sheet aluminium. In these lids four holes were cut out for the 800 ml beakers that contained the different PEG 4000 conservation solutions. The lids also had a hole cut out for a thermostat-regulated heating and stirring device that would keep the water in the tank at the chosen temperature (figure 4-1).

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[90] This dissertation, section 2.1.1.

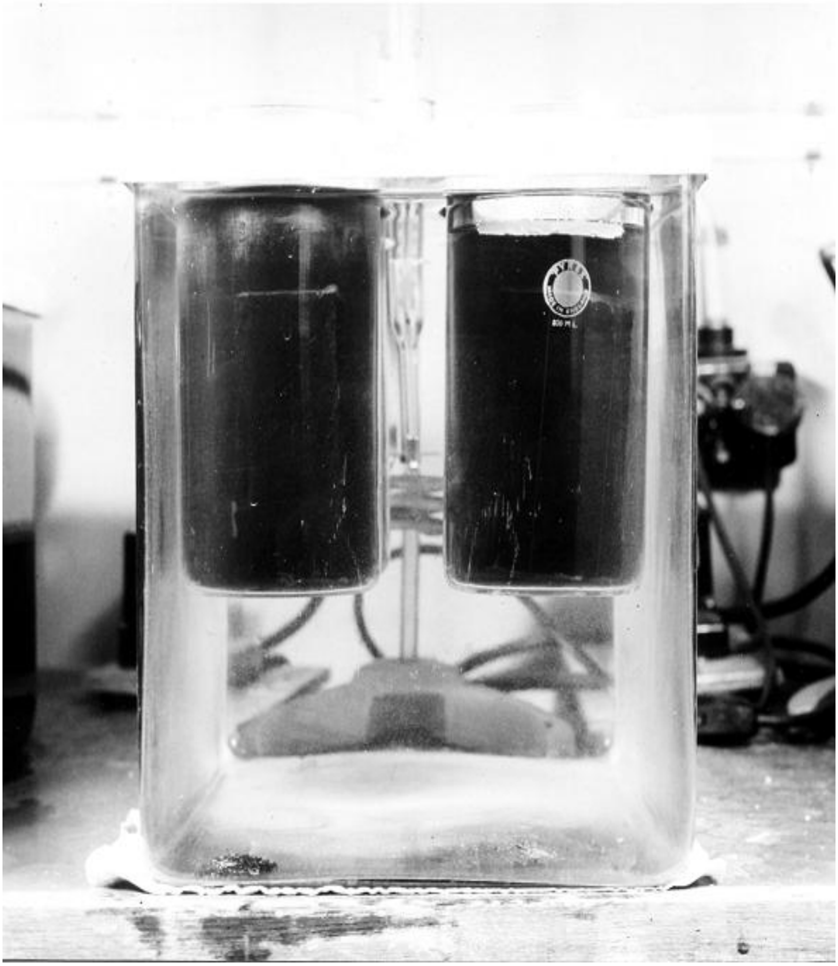

Figure 4-1. Experimental arrangement of thermostatic bath with four beakers and heating- and stirring-device.

In the thermostatic bath chosen for the temperature raising programme the thermostat was initially set at 25°C. This temperature was maintained for three weeks, and during the next period of four weeks the temperature was raised by steps of 10°C, until the 65°C level was reached. The thermostat in the steady temperature level thermostatic bath was permanently set at 65°C.

Each of the beakers was charged with its pre-determined concentration of PEG 4000. Successively the PEG concentration was raised every week by moving the specimens to new, clean PEG 4000-solutions of 5% higher PEG-concentration than those of the previous week. Each conservation solution was brought to its pre-determined temperature before the test specimens were put in.

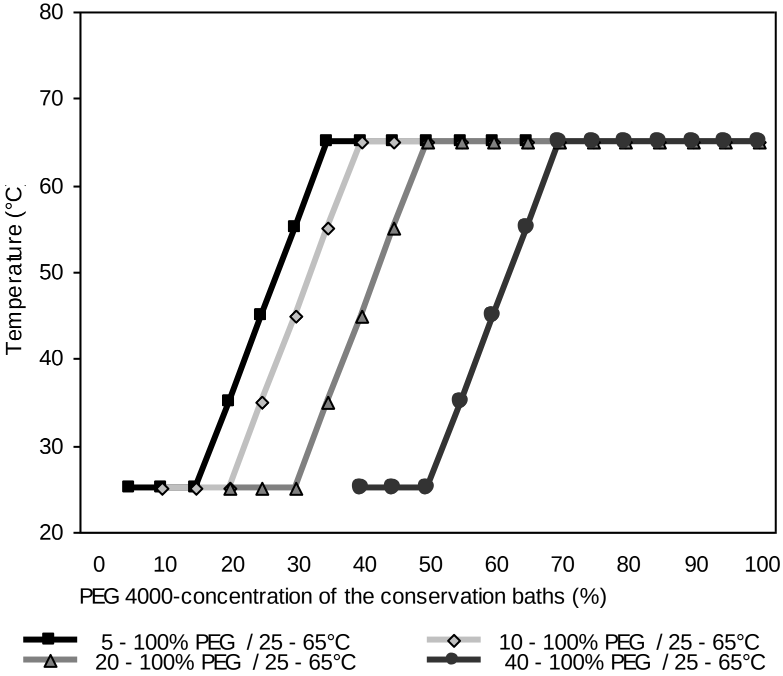

Figure 4-2. Temperature and PEG 4000 concentration raising programmes.

The experimental circumstances created individual conservation programmes respectively for the conservation baths that were placed in the thermostatic bath with a temperature raising programme. The conservation programme with an initial concentration of 5% PEG 4000 had reached a concentration of only 35% PEG when the temperature level in the thermostatic bath had been raised to 65°C, while the ones with initial PEG concentrations of 10%, 20% and 40% PEG had reached 40%, 50% and 70% PEG respectively at the endpoint of the temperature raising programme (figure 4-2). The conservation baths at the temperature raising programme were labelled bath1, bath2, bath3 and bath4 respectively, in the sequence of increasing initial PEG concentration.

Contrary to the conservation baths that were placed in the thermostatic bath in which a temperature raising programme was applied, the ones that were placed in the thermostatic bath that was kept at a constant temperature level may be considered to have formed a series with the PEG concentration as the only changing parameter. These conservation baths were labelled bath5, bath6, bath7 and bath8 respectively, in the sequence of increasing initial PEG concentration.

Bath5, bath6, bath7 and bath8 were kept at 65°C during the whole duration of the conservation period. In accordance with bath1, bath2, bath3 and bath4 these were charged with 5%, 10%, 20% and 40% PEG 4000 respectively, and the PEG concentration was raised in steps of 5% every week ending with the last step, which was a PEG 4000 melt. The oak and pine specimens placed in each of the conservation baths were consequently labelled oak1, oak2, oak3, oak4, oak5, oak6, oak7, and oak8 respectively, and pine1, pine2, pine3, pine4, pine5, pine6, pine7, and pine8 respectively.

Each test specimen was weighed before the experiment was started and — assuming that the wood fibres of the specimens were completely filled with water — the fibre weight of each specimen was calculated from these weights and the u_{max}-value for the wooden test material. At each change of impregnation solution (i.e. each week) the test specimens were weighed again. The sum of water and PEG of each test specimen was calculated at each weighing, by subtracting the fibre weight which had been calculated at the start. A ratio was calculated between this sum of water and PEG and the fibre weight of the test specimen. These ratios provided a means of continuously monitoring the processes.

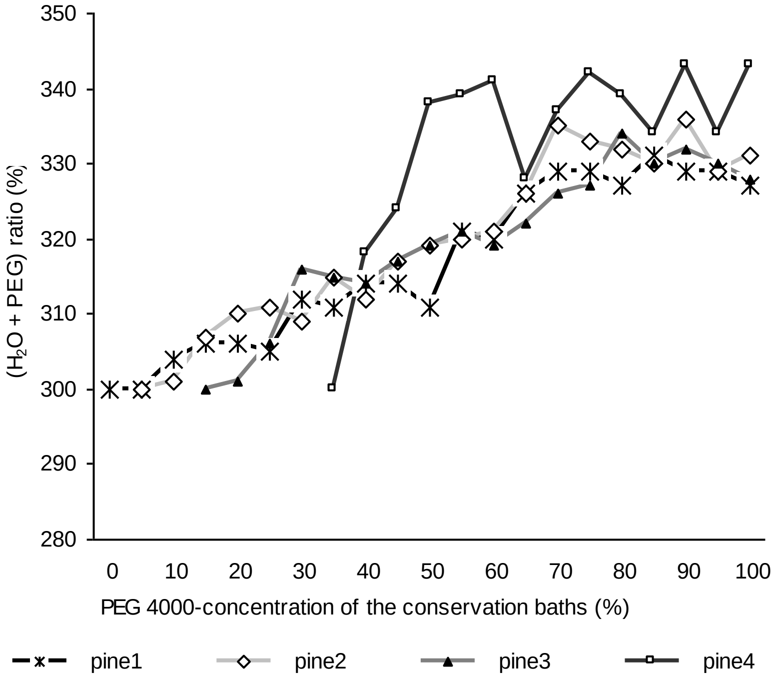

Figure 4-3. (PEG and water)-ratio of pine1, pine2, pine3 and pine4 from the conservation programmes at the temperature raising programme.

The (H_2O+PEG)-ratios calculated for the specimens at each step of the conservation procedure were represented in diagrams with the increasing PEG 4000-concentration of the conservation baths as x-axis. Four diagrams were composed each with four graphs representing the oak and pine specimens at the two different temperature programmes respectively (figures 4-3, 4-4, 4-5 and 4-6).[91]

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[91] Barkman, 1975, pp 74-77.

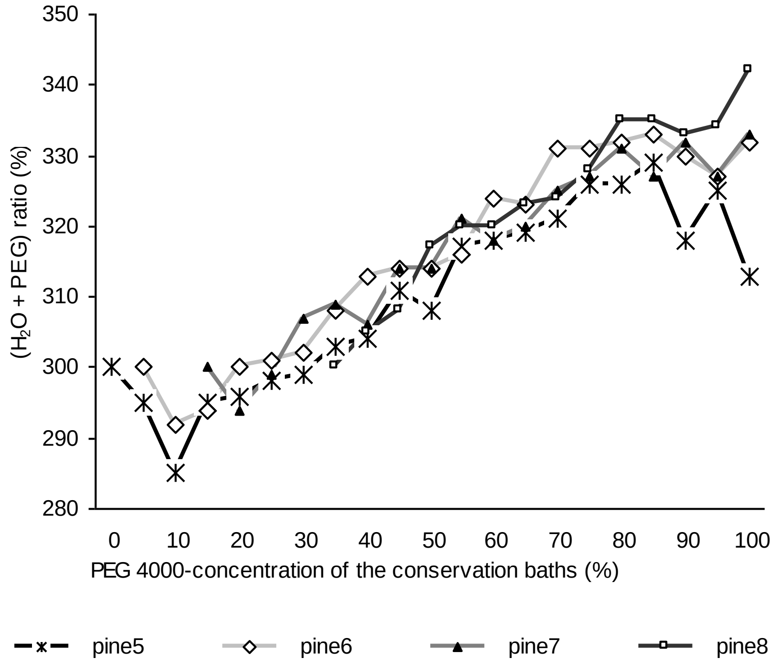

Figure 4-4. (PEG and water)-ratio of pine5, pine6, pine7 and pine8 from the conservation programmes at the constant temperature level.

The diagrams of the pine specimens (figures 4-3 and 4-4) show overall growing (H_2O+PEG)-ratios during the conservation period while the diagrams of the oak specimens, except for one specimen show declining values as an overall result (figures 4-5 and 4-6). This clearly indicates that there is a differing between the reaction to the conservation procedures of the oak and of the pine specimens respectively, used in the experiment.

The oak specimens show, with only one exception, declining (H_2O+PEG)-ratios during the conservation treatment. The diagrams of the (H_2O+PEG)-ratios in the two different temperature situations, however, show substantial divergences (figures 4-5 and 4-6).

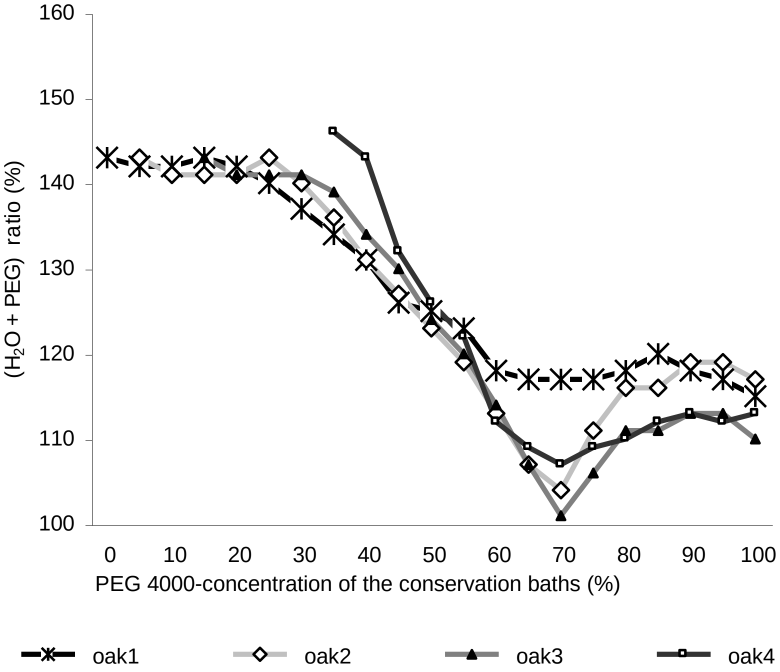

Figure 4-5. (PEG and water)-ratio of oak1, oak2, oak3 and oak4 from the conservation programmes at the temperature raising programme.

The temperature raising programme (figure 4-5) seems to have created a more homogeneous reaction where all four specimens were loosing weight during the conservation process. Three out of the four test specimens show about the same minimum value, 101 - 107% (H_2O+PEG)-ratios at 70% PEG-concentration in the conservation solutions, and then a raise by between 6 and 15 units (H_2O+PEG)-ratio when the PEG-concentration was further raised, despite the fact that their respective PEG-concentration programmes combine differently with the temperature raising programme. The fourth specimen, which is the one that was started at 5% PEG-concentration in the conservation solution, at first showed declining (H_2O+PEG)-ratios until a concentration of 60% PEG had been reached in the conservation solution. At that point a steady (H_2O+PEG)-ratio of about 118 % was maintained during the rest of the conservation period.

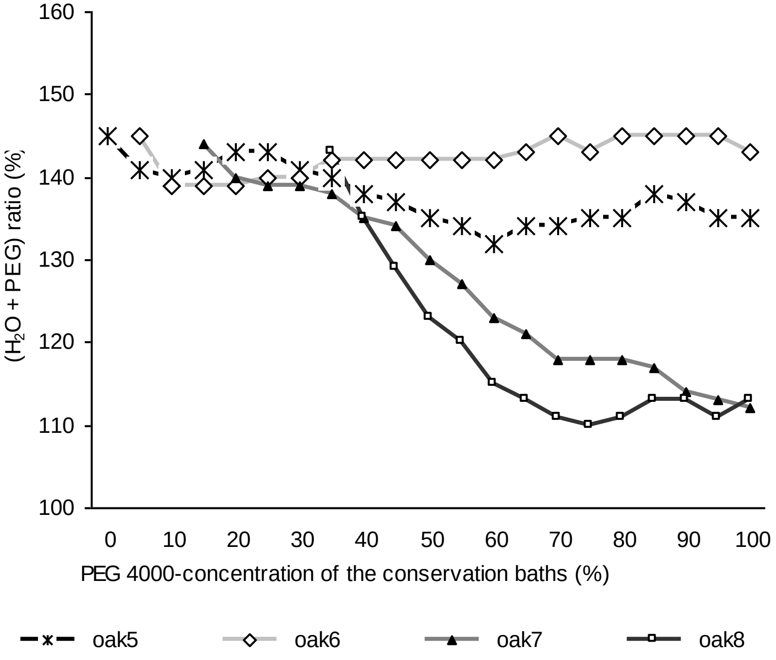

Figure 4-6. (PEG and water)-ratio of oak5, oak6, oak7 and oak8 from the conservation programmes at the constant temperature level.

The (H_2O+PEG)-ratios of the specimens which were conserved at the constant temperature level do not demonstrate such a homogeneous representation as those treated at the temperature raising programme (figure 4-6). Only the specimen that started at 40% PEG-concentration in the conservation solution showed a weak (H_2O+PEG)-ratio minimum of 110% at 75% PEG-concentration in the conservation solution, after which a small elevation by a few percentage units (H_2O+PEG)-ratio occurred. The specimen that started at 20% presented declining (H_2O+PEG)-ratio values that eventually ended up at the same (H_2O+PEG)-ratio value as the previously mentioned specimen while the two specimens that started at 5 and 10% PEG-concentration in their conservation solutions showed practically no weight loss during the entire conservation process.

4. DEVELOPMENT OF THE IMMERSION TREATMENT PROCEDURE

The weight loss during the conservation process indicates that water molecules diffused out of the wood into the surrounding PEG-solution faster than PEG molecules diffused into the wood. This weight loss was considered by this author, who was conducting the experiment, to put unnecessary strain to the wood, especially when followed by weight gain. The weight gain in turn might be explained by liquid transport of PEG-solution into the wood. The driving force for this transportation might be that the diffusion of water from the wood created a negative pressure inside the wood.[92]

The phenomenon brought about by making contact in the immersion situation between the conservation solution and the water, or the more dilute PEG solution inside the wood, is identified as "osmosis". Osmosis is defined as the process of diffusion through a membrane or permeable septum of the molecules of the solvent and the solute respectively. If the molecules of the solvent and the molecules of the solute move by different rates a hydrostatic pressure called the osmotic pressure is built up in one of the solutions separated by the membrane.[93] If, as is the case when a waterlogged piece of wood is placed in a PEG 4000-solution in water, the water molecules move faster than the PEG molecules, an under-pressure is produced in the wood. Since the wood is permeable to both of the water and PEG molecules, the under-pressure is not permanent but when it will have reached a certain extent it will be equalised by the solution being forced into the wood structure.

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[92] Barkman, 1975, p 72.

[93] Findlay, 1953, pp 179-183.

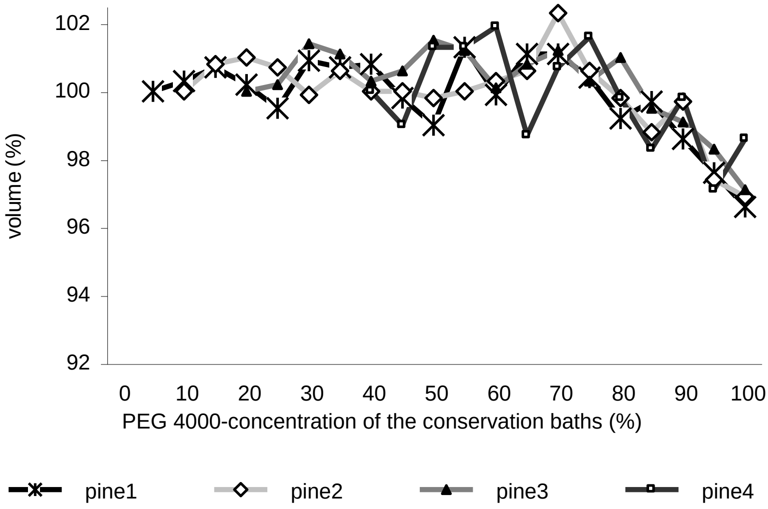

Figure 4-7. Volume change of pine1, pine2, pine3 and pine4 from the conservation programmes at the temperature raising programme.

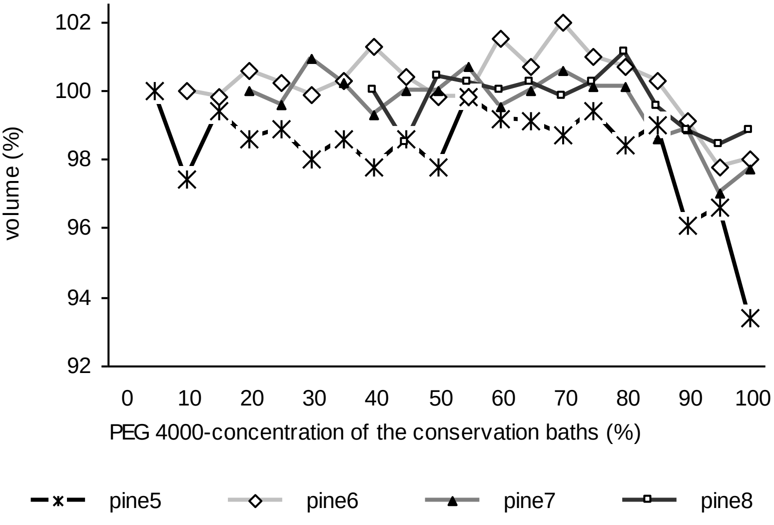

Figure 4-8. Volume change of pine5, pine6, pine7 and pine8 from the conservation programmes at the constant temperature level.

Apart from differences of solute concentration, also temperature differences of the solutions on the two sides of the membrane, may influence the velocity of the diffusion of the solvent and solute molecules differently. This situation is obtained in the present experiment every time a specimen is moved from a solution of lower temperature to a solution of higher temperature.

The other parameter for monitoring the conservation process of the test specimens was shrinkage. In order to monitor this the volumes of all specimens in this experiment have been calculated from weighing each of them at each change of PEG-solution both submerged into the solution, with a spring-balance and taken out of the solution, on a laboratory balance. From those weights and the density of each conservation solution the volume of each specimen at each change of solution was calculated.[94] From the diagrams (figures 4-7 – 4-10) was deduced that all the specimens had shrunk during the conservation period. The oak specimens had shrunk more and at an earlier stage of the conservation process than the pine specimens. Even when shrinkage is concerned the oak specimen that started at 10% PEG-concentration at the constant temperature level (figure 4-10, oak6) diverged by showing less shrinkage at the end of the conservation period than any of the other oak specimens.

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[94] Archimedes' principle.

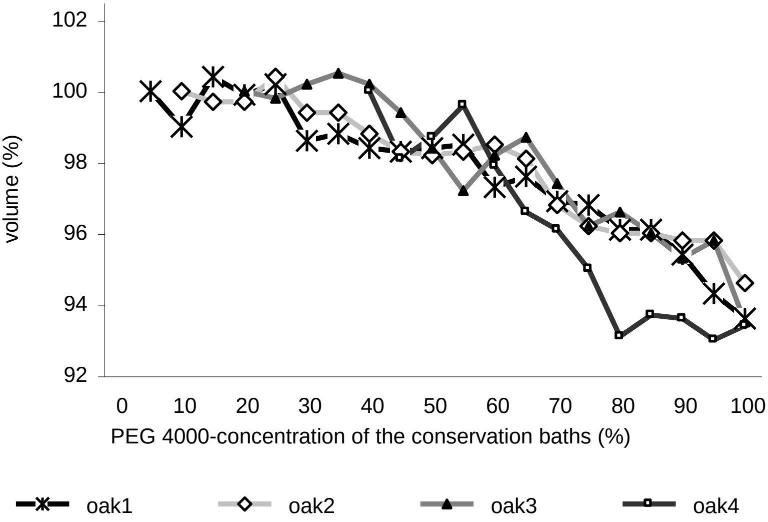

Figure 4-9. Volume change of oak1, oak2, oak3 and oak4 from the conservation programmes at the temperature raising programme.

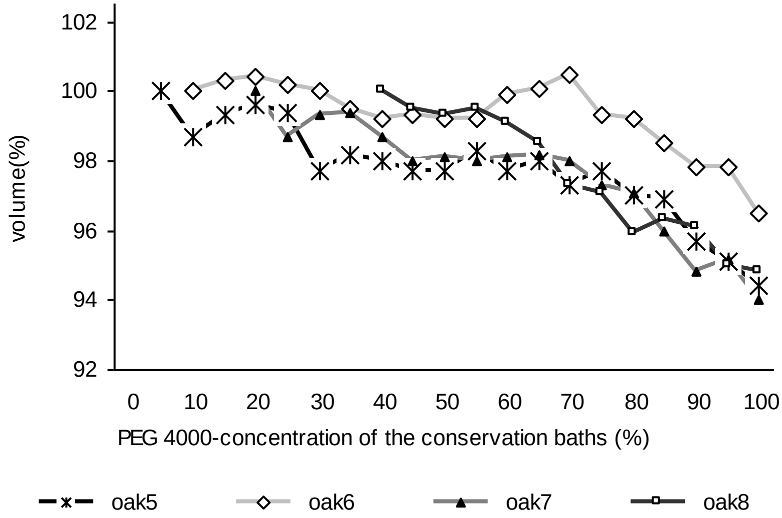

Figure 4-10. Volume change of oak5, oak6, oak7 and oak8 from the conservation programmes at the constant temperature level.

Finally, an important criterion of a successful PEG conservation process is the amount of PEG that has been absorbed by the preserved wood specimen. In the present experiment all specimens show very high mean PEG-ratios at the end of the conservation period. The pine specimens had even absorbed PEG to a c. 10% higher ratio than their initial water ratio. This may be interpreted as 100% absorption of the PEG 4000 since the density of that substance is 1.1g/cm^3. The two oak specimens that had been treated at constant temperature level, in the conservation solutions with initial PEG concentrations of 5 and 10% had absorbed PEG to c. 88 and 94% of their initial water ratio respectively. The PEG absorbed by the rest of the specimens of this experiment was c. 70% of their respective initial water ratio (table 4-I).

specimen	temperature raising programme				constant temperature level			
	PEG raising programme				PEG raising programme			
	5%-PEG-melt	10%-PEG-melt	20%-PEG-melt	40%-PEG-melt	5%-PEG-melt	10%-PEG-melt	20%-PEG-melt	40%-PEG-melt
oak	106	107	103	101	128	136	103	99
pine	321	322	327	335	310	318	341	324

Table 4-I. PEG-ratios (%) of the test specimens at the end of the conservation period.

Conclusion

The overall information gained from this experiment supports the assumption that a conservation process performed at a constant temperature level and with a low initial concentration of PEG will produce higher PEG concentration in the preserved wood and less shrinkage of the specimens during the conservation procedure. The diverging result with 10% PEG 4000 as initial concentration can, however, not be explained in this kind of context, why that was considered a random coincidence.

Thus, this experiment did not support the recommendation of the Morén & Centerwall report, that the conservation programme for wet archaeological wood with u_{max} < 400% should start at a PEG 4000 concentration of 30%.[95]

The experiment also contradicted the application of a temperature raising programme.

The differences in behaviour observed during this experiment of wet archaeological oak and pine specimens respectively, treated at the same conservation programme, may be attributed to differences of size of the specimens and differences of degree of deterioration of the two wood species used for the experiment.

Thus, no definite conclusion might be drawn from this experiment about conceivable differences of reaction of different species of wet archaeological wood towards a specific PEG conservation programme.

4.3. Further development of the PEG immersion conservation programme

From the testing of the Morén & Centerwall conservation programme (4.2.) the question was raised about methods to prevent the unexpected and unwanted weight loss during the conservation process. The explanation adopted was that water molecules were diffusing from the wood structure into the surrounding PEG conservation solution. This direction of the diffusion might be due to the circumstance that a rather steep gradient of PEG-concentration had been formed by a rapid increase of the PEG-concentration of the conservation solution. In the case of the temperature raising programme there might be an added effect by the temperature gradient, formed when a specimen was moved to a conservation solution of a higher PEG-concentration and also at a higher temperature. This explanation was accepted by the Vasa Conservation Council, and therefore the temperature raising programme was abandoned in favour of a constant temperature level. The temperature level chosen for the experiments, 65°C, was the same as had been used as reference in the previous experiment (4.2.).

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[95] Morén, R., and Centerwall, B., 1960, p 186.

4. DEVELOPMENT OF THE IMMERSION TREATMENT PROCEDURE

Since the recommendation by Morén & Centerwall, to use a high initial PEG-concentration when starting a conservation programme with wood of u_{max} < 400 %, was not supported by the previous experiment (4.2.), it was decided to repeat the experiment as far as the four initial concentrations were concerned. To avoid weight loss during the conservation period a slower raise of the PEG concentration was chosen based on a duration of the conservation period of one year at the most.

This would mean a raise of 5/3 % per week of the PEG-concentration in the conservation solution. Moreover, increments were to be added daily on working days instead of only once weekly. This would give a more continuous concentration raise. The end concentration of PEG of the experiment was to be 100%, and in order to map the PEG uptake into the wood during the conservation process several identical specimens were to be placed in each of the baths. The specimens were to be removed successively from the baths at pre-determined PEG-concentrations; these were 15, 30, 45, 60, 80, and 100%.

As the test material of the previous experiment (4.2.) had actually not been removed from the Vasa hull there was some uncertainty about its authenticity. Therefore it was decided that the experiment would be repeated with oak specimens cut from a deck-batten removed from the Vasa hull. This was the same type of timber as was used for the surface treatment experiment mentioned earlier.[96] Twenty-two specimens with the dimensions 4.5 x 4.5 x 10 cm and five specimens with the measurements 4.5 x 4.5 x 7 cm were cut from the deck-batten. The deteriorated 3 to 5 mm thick surface layer of the deck-batten was preserved on two, adjoining longitudinal surfaces of each specimen. The other two longitudinal surfaces and the transverse surfaces were newly sawn. As at the previous experiment (4.2.) all transverse surfaces were painted with Araldite.

Twenty-one specimens were needed for the experiment. However, as discussions about an automatic spray system for the Vasa hull had been started and as such a system might not be able to handle a PEG 4000 solution depending on its viscosity, there was a question raised as to the

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[96] This dissertation 2.1.1.

possibility to change this for PEG 1500. This was discussed at the meeting of the Conservation Council on 14 September 1964.[97]

The proposal to change the PEG 4000 for PEG 1500 made it important to get PEG 4000 paralleled by PEG 1500 in the experiment. It would be possible to do this by shortening the conservation period of the already planned experiment to be ended at 80% instead of proceeding to a PEG-melt ,and by redistribution of the full size test specimens. As the idea to raise the PEG concentration to a melt already had been questioned, as a result of the first experimental conservation of selected Vasa objects made in 1962, it would have been the next parameter to be changed of the laboratory experiments.[98]

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[97] Håfors, 2001, pp 64-65.
[98] Håfors, 1990, p 203.

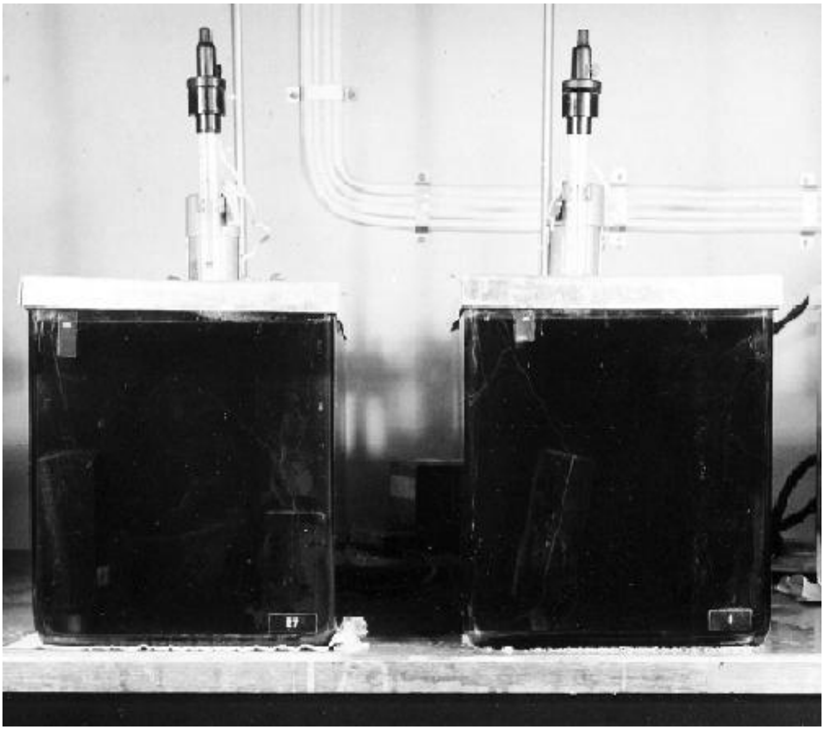

Figure 4-11. Experimental arrangement of thermostatic conservation baths in 12 l glass tanks.

To accomplish the experiment, five 12 l glass-tanks were equipped with heating and stirring devices (figure 4-11). Four of the glass-tanks were charged with the same pre-determined initial concentrations 5, 10, 20 and 40% respectively, of PEG 4000 as was used in the previous experiment (4.2.). These tanks were labelled bath1, bath2, bath3 and bath4. The fifth tank that was introduced after the preparations for the experiment had been started, in order to perform a conservation programme in parallel with PEG 1500, was labelled bath27. For this PEG 1500 conservation programme an initial PEG-concentration of 5% was chosen (figure 4-12). The volume of conservation solution of each tank was 11000 ml. This volume was maintained by adding water daily after the PEG increment had been administered.

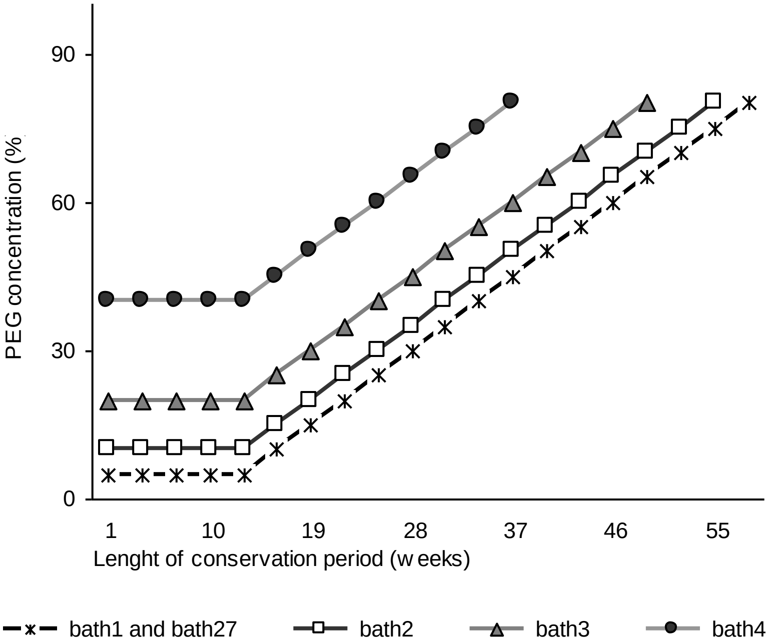

Figure 4-12. Concentration programmes of the conservation baths.

The specimens placed in *bath1* were labelled oak1, oak5, oak9, oak13, oak17, and oak20; those placed in *bath2* were labelled oak2, oak6, oak10, oak14, oak18 and oak21; those placed in *bath3* were labelled oak3, oak7, oak11, oak15 and oak19; those placed in *bath4* were labelled oak4, oak8, oak12 and oak16; and finally the specimens placed in *bath27* were labelled oak22, oak23, oak24, oak25, oak26 and oak27.

The specimens labelled oak1, oak2, oak3, oak4 and oak27 were cut shorter in the longitudinal direction than the other ones, why they have been excluded from the following discussion.

Since the specimens were placed in PEG-solutions where the PEG-concentration was continuously raised instead of transferring them to new solutions of known PEG concentrations there might be a discrepancy between the PEG-concentration presumed from the added amount of PEG and the actual PEG-concentration of the conservation baths. There might be various reasons for this discrepancy. One reason might be that PEG molecules leave the conservation solution and move into the wood structure of the specimens. Another source of discrepancy in the present experimental set-up was that there was no adjustment for the volume of the specimens, so there was a calculable lowering of the PEG-concentration at the removal of specimens as the volume of the solution had been compensated by adding water. Another factor was the long period of heating that might have caused some sort of change to the PEG molecule so that it no longer was recognizable as such.

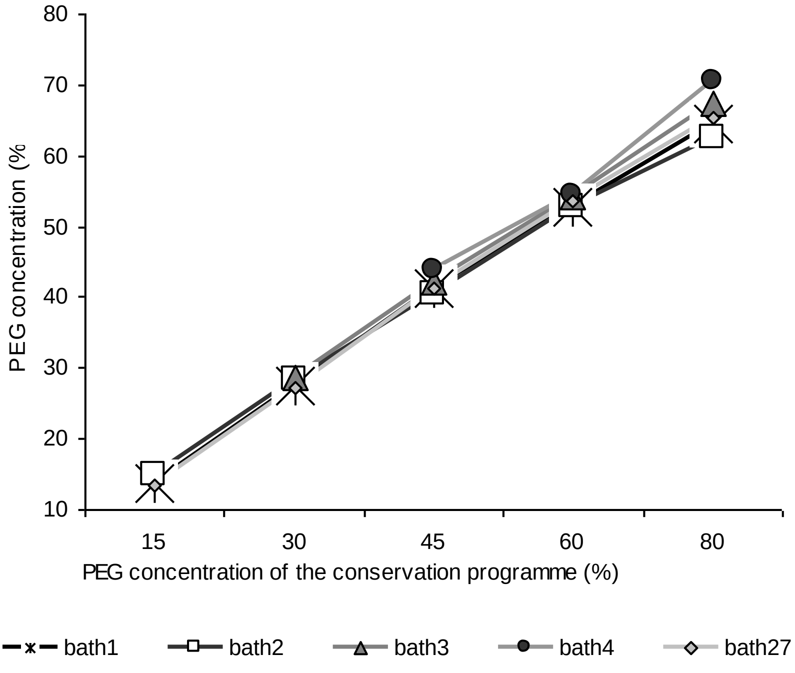

Figure 4-13. End concentrations of PEG in the conservation baths at removal of the specimens from their respective conservation solutions.

To monitor the PEG-concentration samples were taken from the conservation solutions during the conservation period. The diagram (figure 4-13) presents the raise of the PEG-concentration in all five tanks as rectilinearly proportional to the added amount of PEG arriving at end-points between 62% and 71%. As the PEG absorbed by the specimens at their respective removal from the conservation solution was calculated to equal 1.32% or less of the total amount of PEG added to the conservation baths, there was a loss not accounted for from the PEG solutions of between 525 and 895 g of PEG. Considering the fact that the PEG increments were administrated from a measuring glass as a 50% PEG solution and that the filling volume might not have been the same as the volume emptied from the measuring glass especially when a liquid of high viscosity was at hand, it would not be adequate to draw any conclusions from this missing amount of PEG.

The experiment was started by slowly heating the test specimens in water from 20 to 65°C during a period of three weeks. At the beginning and at the end of this heating period the specimens were weighed, and then they were moved to their respective PEG solution that had been pre-heated to 65°C. In order to allow the specimens to establish an equilibrium with their respective conservation solution, the PEG concentrations were kept at the initial levels for a period of three months before the concentration raising programme was started. At this point the test specimens were taken out of their conservation baths and were weighed on a balance in the atmosphere of the laboratory.

This weighing of all test specimens from each conservation bath was repeated every time a particular specimen was removed from the solution. From those weights and the calculated fibre weight of each specimen the ratio of the sum of PEG and water inside the wood of each specimen was calculated (figures 4-14 – 4-18).

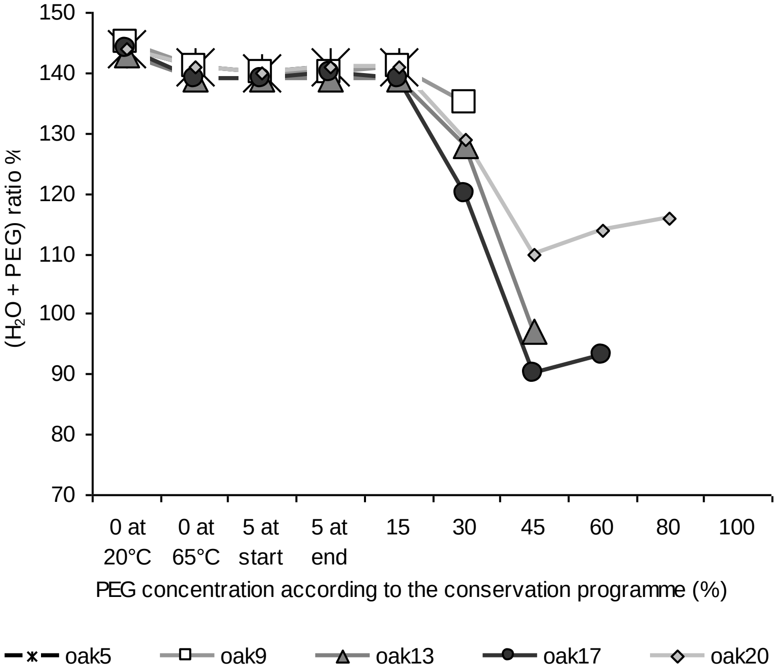

Figure 4-14. (PEG and water)-ratio of oak5 (PEG 4000, 5 – 15%), oak9 (PEG 4000, 5 – 30%), oak13 (PEG 4000, 5 – 45%), oak17 (PEG 4000, 5 – 60%), and oak20 (PEG 4000, 5 – 80%) during the conservation period.

The five specimens of the experimental conservation with initial PEG 4000 concentration of 5% did not show any weight loss before 15% PEG concentration was reached in the conservation solution (figure 4-14). During the increase from 15 to 30% PEG concentration in the solution weight losses of the specimens equalling five to twenty percentage units (PEG + water) ratio were registered. In the concentration interval between 30 to 45% PEG 4000 additional weight loss equalling 20 to 35 percentage units (PEG + water) ratio were registered. During the increase from 45 to 60 and further to 80% PEG concentration the two remaining specimens gained weight equalling two to six percentage units (PEG + water) ratio.

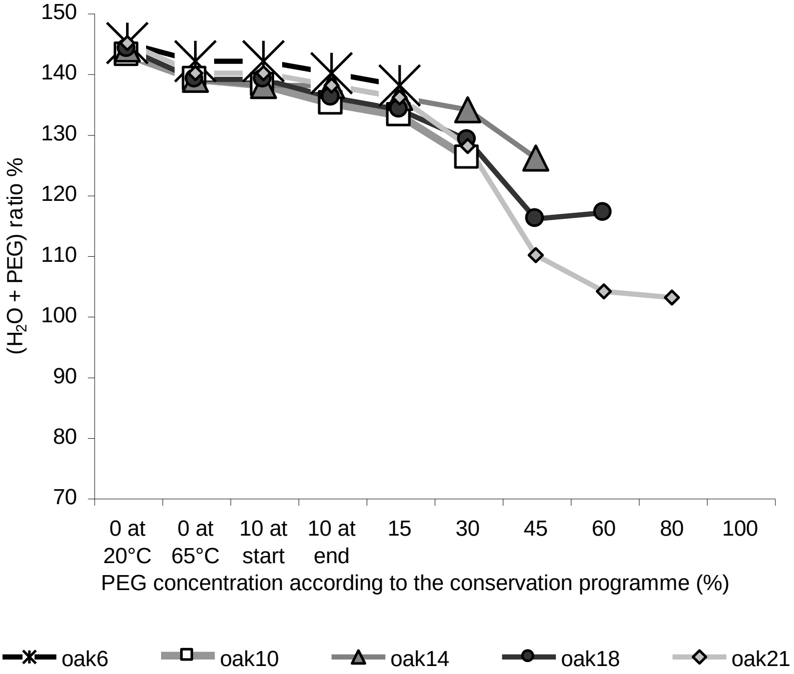

Figure 4-15. (PEG and water)-ratio of oak6 (PEG 4000, 10 – 15%), oak10 (PEG 4000, 10 – 30%), oak14 (PEG 4000, 10 – 45%), oak18 (PEG 4000, 10– 60%), and oak21 (PEG 4000, 10 – 80%) during the conservation period.

The five specimens that were transferred to the 10% PEG 4000 solution showed no immediate reaction, but during their three months' stay at the initial PEG concentration each of them lost c. five percentage units (PEG + water) ratio (figure 4-15). When the PEG concentration of the solution according to the conservation programme had reached 15% the specimens had lost weight equalling another five, and at 30% PEG concentration still another weight loss equalling 5 - 10 percentage units (PEG + water) ratio had occurred. At 45% PEG concentration of the conservation solution the weight losses of the three remaining specimens ranged between 20 and 35% percentage units (PEG + water) ratios and at 60% PEG concentration the particular specimen that was removed from the solution was unchanged, while the other one had lost c. 7 percentage units (PEG + water) ratio. The weight loss of this last specimen in the solution was insignificant during the 60 to 80% step of the conservation programme.

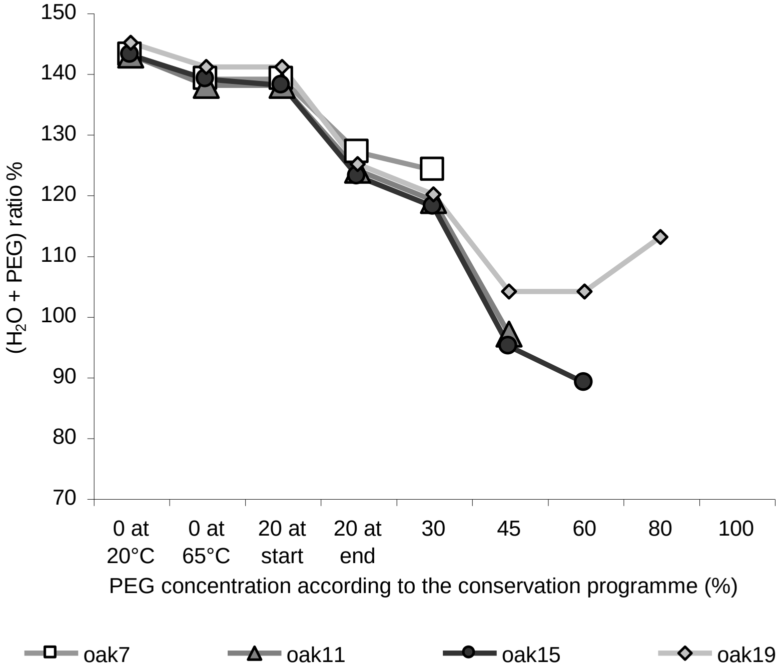

Figure 4-16. (PEG and water)-ratio of oak7 (PEG 4000, 20 – 30%), oak11 (PEG 4000, 20 – 45%), oak15 (PEG 4000, 20– 60%), and oak19 (PEG 4000, 20 – 80%), during the conservation period.

The four specimens that were transferred to the 20% PEG 4000 solution did not react immediately to this but at the end of the three months' period all of them had lost c. 15 percentage units (PEG + water) ratio (figure 4-16). Then there was a slight additional weight loss when the PEG concentration of the conservation solution had reached 30% and a larger one at 45% PEG concentration at which point of the conservation programme the total weight loss calculated as percentage units (PEG +

water) ratio ranged between 40 and 50%. At 60% PEG concentration of the solution there was none or only a slight weight loss respectively of the two specimens still in the conservation bath and the one that stayed in the 80% PEG solution showed a weight gain of c. 10 percentage units (PEG + water) ratio.

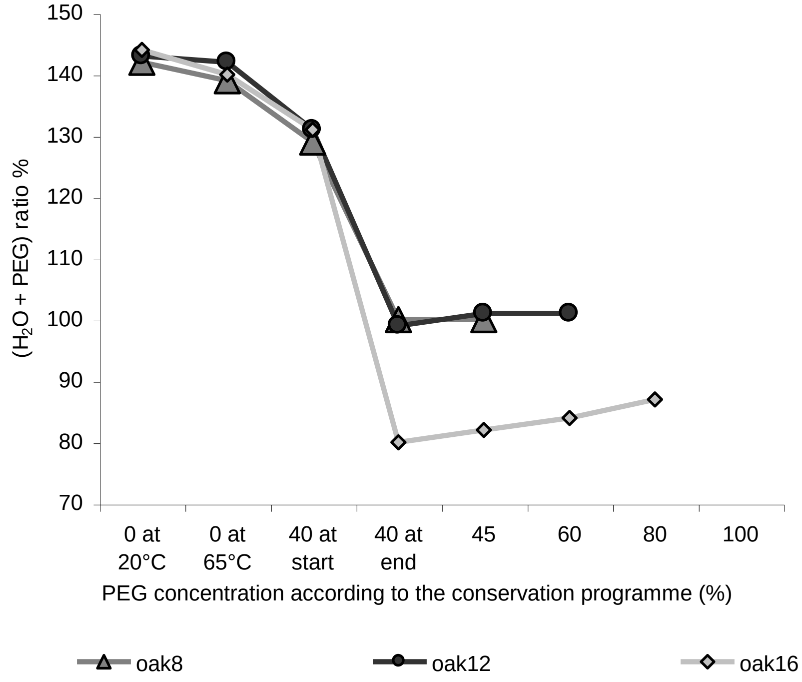

Figure 4-17. (PEG and water)-ratio of oak8 (PEG 4000, 40 – 45%), oak12 (PEG 4000, 40– 60%), and oak16 (PEG 4000, 40 – 80%), during the conservation period.

As the specimens were weighed after being heated in water and again the next day after they had been transferred to their respective PEG solution, it was noted that this caused an immediate weight loss of the specimens at the 40% initial PEG concentration (figure 4-17). This immediate weight loss was of the magnitude of 10 percentage units (PEG + water) ratio and was equally large for all three specimens in this conservation solution. The weight loss continued during the three months period at constant PEG concentration. At the end of the period two specimens had lost another 30 and the third one had lost as much as 50 percentage units (PEG + water) ratio in the 40% PEG 4000 conservation solution. This meant a total loss of 40 and 60 percentage units (PEG + water) ratio respectively. From this point on all three specimens showed slight weight gains.

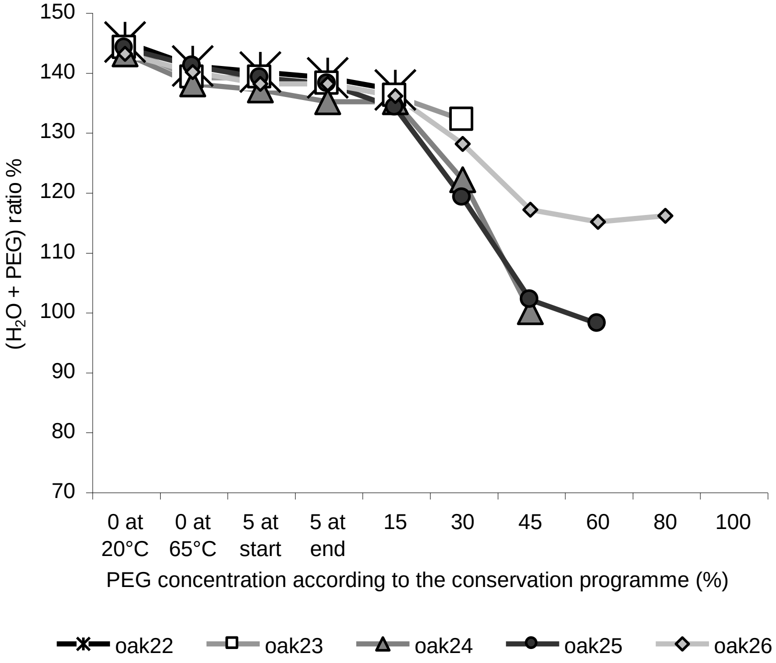

Figure 4-18. (PEG and water)-ratio of oak22 (PEG 1500, 5 – 15%), oak23 (PEG 1500, 5 – 30%), oak24 (PE 1500, 5 – 45%), oak25 (PEG 1500, 5 – 60%), and oak26 (PEG 1500, 5 – 80%), during the conservation period.

The five specimens of the experimental conservation with initial PEG 1500 concentration of 5% reacted with about equal weight losses as the specimens in the PEG 4000 solution of the initial concentration of 10%, until a reading value of 15% PEG concentration had been obtained (figure 4-18). During the increase from 15 to 30% there were further weight losses equalling five to fifteen percentage units (PEG + water) ratio. At further increase of the PEG concentration to 45% PEG 1500 two of the three specimens still kept in the solution showed weight losses equalling 20 percentage units (PEG + water) ratio respectively, while the third specimen only lost weight equalling ten percentage units (PEG + water) ratio. During the interval from 45 to 60% PEG 1500 concentration the weight loss of the two specimens still kept in the solution slowed down, and the specimen that stayed until the 80% PEG 1500 concentration of the conservation programme showed a slight weight gain.

In order to monitor more closely the reaction to the conservation programme, all test specimens were weighed three times a week with a spring-balance, submerged into their respective conservation solution. The weights of the specimens in air and their weights submerged into their respective solutions together with the density of the solution provide a basis for calculating the volume of each specimen (figures 4-19 – 4-23).[99]

The five specimens oak5, oak9, oak13, oak17 and oak20 that were placed in the 5% PEG 4000 conservation solution did not shrink at all until the PEG concentration raising interval between 30 and 45% was reached (figure 4-19). That meant that two specimens were removed before any shrinkage occurred. The specimen that was removed at 45% PEG concentration had shrunk 3.5% and the specimen that was removed at 60% PEG concentration had shrunk 5.5% at their respective points of removal from the conservation programme. The specimen that remained in the conservation bath until the end of the conservation programme did not start shrinking until the PEG concentration programme had reached 45%. During the interval from 45 to 60% this specimen shrank 1%, and during the succeeding 60 to 80% PEG concentration raising interval showed no further shrinkage. Thus, the total shrinkage of this specimen amounted only to 1%. Unexpectedly this specimen had suffered a weight loss equalling a decrease of more than 30 percentage units of (PEG + water)-ratio during the PEG concentration raising interval between 15 and 45%. From the 45% to the 80% PEG 4000 concentration point of the conservation programme this specimen gained weight (figure 4-14).

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[99] Archimedes' principle.

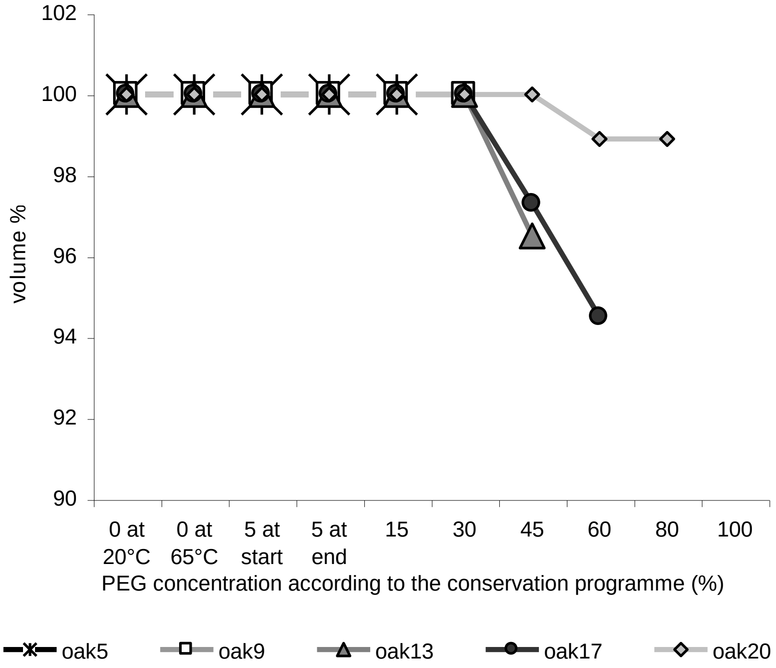

Figure 4-19. Volume shrinkage of the specimens, oak5 (PEG 4000, 5 – 15%), oak9 (PEG 4000, 5 – 30%), oak13 (PEG 4000, 5 – 45%), oak17 (PEG 4000, 5 – 60%), and oak20 (PEG 4000, 5 – 80%), during the conservation period.

The five specimens oak6, oak10, oak14, oak18 and oak21 that were placed in the 10% PEG 4000 conservation solution did not shrink at all during their three months' period at the initial PEG concentration (figure 4-20). At 15% PEG concentration, where the first removal of a specimen took place, four specimens inclusive the one that was removed had shrunk c. 0.5%, while one specimen had not shrunk at all. That specimen had still not shrunk at 30% PEG concentration when it was in turn to be removed. At that occasion the three remaining specimens had shrunk between 1 and 2%. The shrinkage of these three specimens were still quite collected at the 45% PEG concentration level with individual shrinkage values of c. 1.5, 2.5, and 3.5%. The specimen with a shrinkage value of c. 2.5% was in turn to be removed at that point of the conservation programme. The two remaining specimens proceeded to shrink at a moderate pace until their end concentrations of 60 and 80% respectively were reached. At those concentrations the total shrinkage of these were 2.5 and 6% respectively. The shrinkage of the specimens in the conservation solution that was started with a 10% PEG solution did not halt or turn into swelling although the weight losses of two of the specimens stopped during the concluding phase of their individual conservation programme (figure 4-15).

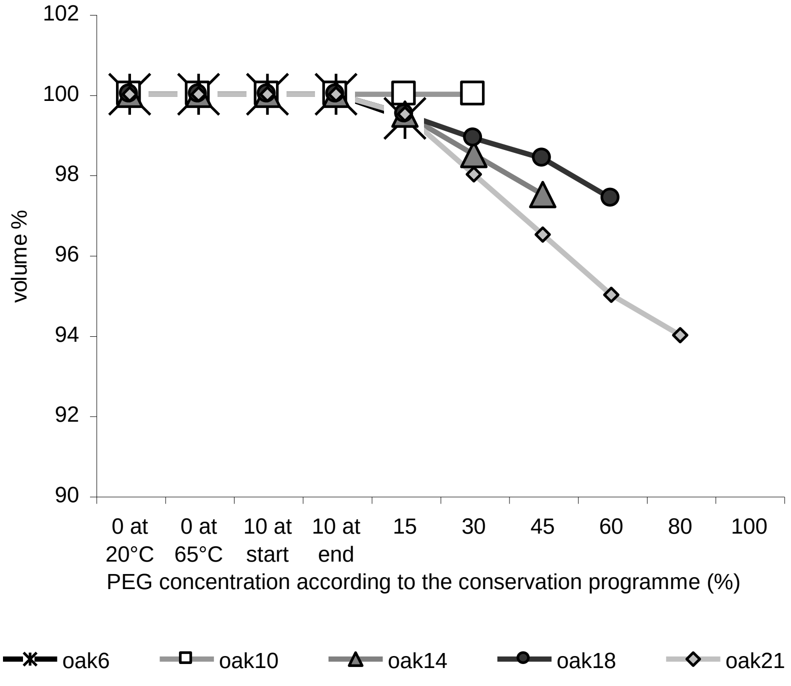

Figure 4-20. Volume shrinkage of the specimens, oak6 (PEG 4000, 10 – 15%), oak10 (PEG 4000, 10 – 30%), oak14 (PEG 4000, 10 – 45%), oak18 (PEG 4000, 10– 60%), and oak21 (PEG 4000, 10 – 80%), during the conservation period.

The volume shrinkage of the four specimens oak7, oak11, oak15, and oak19 respectively amounted to between 1 and 0.5% during their three months' stay in the 20% PEG 4000 conservation solution (figure 4-21). At the 30% PEG concentration point of the conservation programme the shrinkage values of the specimens were well collected between 1 and 2 %. During the next PEG concentration raising interval that ended at 45%, the remaining three specimens shrunk to a total of 3.5 to 5.5 % that exactly coincided with the weight loss pattern for the individual specimens (figure 4-16). This correspondence remained during the PEG concentration raising intervals that ended at 60 and 80% respectively.

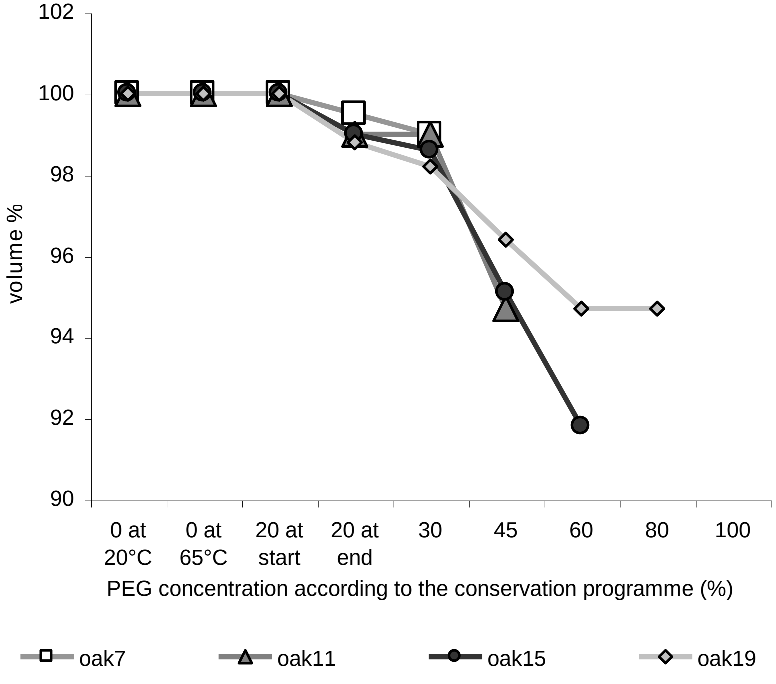

Figure 4-21. Volume shrinkage of the specimens of oak7 (PEG 4000, 20 – 30%), oak11 (PEG 4000, 20 – 45%), oak15 (PEG 4000, 20– 60%), and oak19 (PEG 4000, 20 – 80%), during the conservation period.

The volume shrinkage of the three specimens, oak8, oak12 and oak16 in bath4 amounted to 4, 3 and 6% respectively during their stay in the 40% PEG 4000 solution. There was no further volume change of oak8, that was removed from the conservation solution at 45% PEG concentration. The shrinkage of oak12 and oak16 increased through their respective entire conservation period. Oak12 had shrunk 5.5% when it was removed from the conservation solution at 60% PEG concentration. Oak16, the specimen that stayed until 80% PEG concentration had been reached had shrunk 10% at that point in the conservation process with no sign of decrease of velocity of shrinkage (figure 4-22). This process seems not to coincide with their respective weight loss, which had stopped and turned into weight gain during that period (figure 4-17).

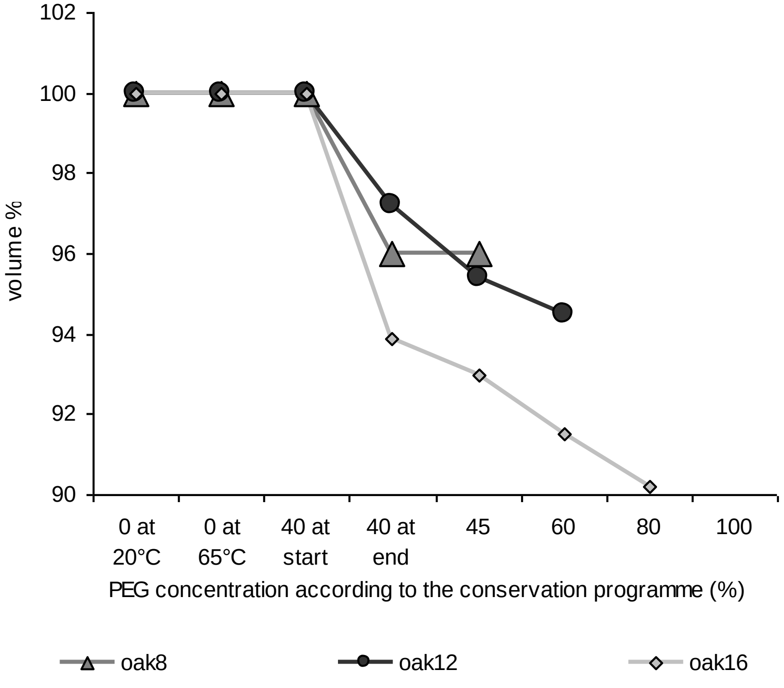

Figure 4-22. Volume shrinkage of the specimens oak8 (PEG 4000, 40 – 45%), oak12 (PEG 4000, 40– 60%), and oak16 (PEG 4000, 40 – 80%), during the conservation period.

The five specimens oak22, oak23, oak24, oak25, and oak26 that were placed in the 5% PEG 1500 conservation solution did not shrink at all during their three months period at that concentration (figure 4-23). During the PEG concentration raising interval 5 to 15% the specimens shrank between 0 and 1.5%. During the PEG concentration interval 15 to 30% the total shrinkage amounted to between 0 and 2.5%. The specimen that was removed at 45% PEG concentration had shrunk from zero to 3.5% during the PEG concentration raise between 30 and 45%. The specimen removed at 60% PEG concentration had accelerated its shrinkage during the 45 to 60% PEG concentration raising period to the highest shrinkage value, 7%, of the specimens taking part in the PEG 1500 conservation programme. The specimen remaining until the 80% PEG concentration level was reached showed no shrinkage during the PEG concentration raising interval between 60% and 80%. This was in correspondence with the weight gain showed by this specimen during that period (figure 4-18).

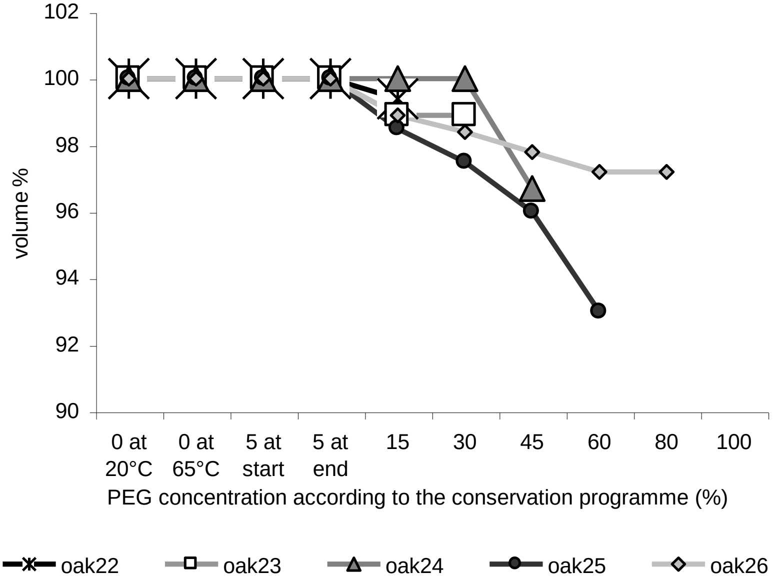

Figure 4-23. Volume shrinkage of the specimens oak22 (PEG 1500. 5 – 15%), oak23 (PEG 1500, 5 – 30%), oak24 (PEG 1500, 5 – 45%), oak25 (PEG 1500, 5 – 60%), and oak26 (PEG 1500, 5 – 80%), during the conservation period.

The reason why the expected correspondence between weight loss and shrinkage, and in relation with weight gain, stopped shrinkage or even swelling, not always occurred might be found in differences of the wood-anatomy of the test specimens. Depending on that these were cut from a deck-batten, longitudinally cut into four pieces, they were specimens with four different wood-anatomical configurations although these were very close to each other. The PEG 4000 conservation programmes each had their main part of specimens from one of these longitudinal pieces. Only oak20 of bath1 and oak21 of bath2 were not in line with the rest of the specimens at their individual conservation programmes. The specimens of the PEG 1500 conservation programme that was introduced after the preparations for the PEG 4000 conservation programmes had started, however, displayed four different transverse surfaces. This made these groups of specimens wood-anatomically slightly different from each other.

After removal from the conservation solutions the specimens were dried to constant weight at 20°C in a series of six climates, each of lower relative humidity (RH) than the preceding one, starting at RH > 90% and ending at 55% RH. To investigate the effect of any failings to keep a stable RH-level in the Vasa museum the final RH level of the experiment was chosen to be a little below the RH level planned for the museum. The various climates were created by saturated salt solutions in tight glass chambers. The specimens were left to dry during 10 weeks at each climate. That made a total of 60 weeks to complete the drying.

When the specimens had dried to constant weight at 55% RH they were placed in a desiccator glass tank with silica gel to dry out to a very low water content. This provided a basis for calculation of the PEG content of each specimen. When the PEG content of the specimens had been calculated the weights of the specimens at their removal from the solutions provided a basis for calculating the water content of each specimen. These two values composed a basis for calculating the mean PEG concentration in the solution inside the specimens.

The result of the mapping of the mean concentrations of an imaginary PEG solution inside the wood of each specimen has been compared to the development of the PEG-concentration in the conservation solutions as derived from the density values (figures 4-24 – 4-28).

To describe the over-all situation of the PEG absorption by the wet archaeological oak wood from the Vasa used in the experiment, linear trends will be used for the two conservation programmes with initial PEG 4000 concentrations of 5 and 10% respectively (bath1 and bath2); (figures 4-24 and 4-25).

Measurements on the diagram of bath1 (figure 4-24) of the angel of inclination of the linear representation of the PEG-concentration of the conservation solution and the angle of inclination of the linear trend of the PEG-concentration inside the test specimens give values of 24.8° and 19.9° respectively. It will be noted that the linear representations of the PEG concentrations outside and inside the specimens of bath1 diverge from each other by an angle of 4.9°.

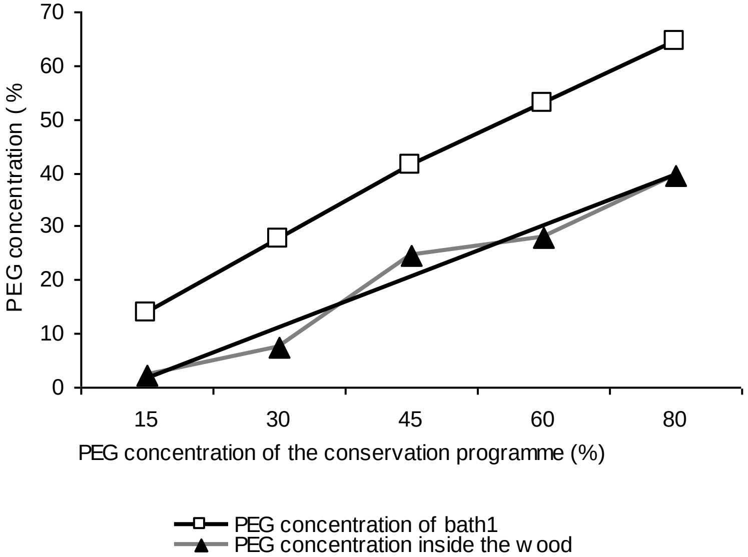

Figure 4-24. The PEG-concentration of the conservation solution of bath1 and the mean PEG-concentration inside the wood structure represented by the test specimens oak5, oak9, oak13, oak17, and oak20 respectively, removed at 15, 30, 45, 60 and 80% PEG-concentration of the conservation programme.

Measurements on the diagram of bath2 (figure 4-25) of the angel of inclination of the linear representation of the PEG-concentration of the conservation solution and the angle of inclination of the linear trend of PEG-concentration inside the test specimens give values of 23.5° and 23.0° respectively for bath2. It will be noted that the linear representations of the PEG-concentrations outside and inside the specimens of bath2 run almost parallel during the entire conservation period. As a result the mean value of the PEG-concentration of the assumed PEG solution inside the wood reached c. 42% while the PEG-concentration of the conservation solution reached c. 62% .

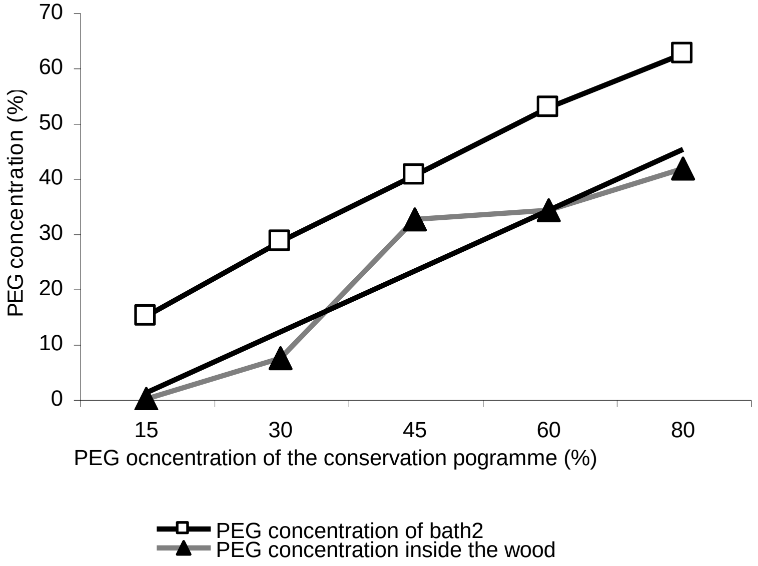

Figure 4-25. The PEG-concentration of the conservation solution of bath2 and the mean PEG-concentration inside the wood structure represented by the test specimens oak6, oak10, oak14, oak18, and oak21 respectively, removed at 15, 30, 45, 60 and 80% PEG-concentration of the conservation programme.

During the 30 to 45% interval of the conservation programme of bath1 the PEG-concentration inside the wood seems to have increased faster than the raise of the PEG-concentration of the conservation solution (figure 4-24). However, at the following concentration raising interval from 45 to 60% there seems to be practically no increase of the PEG-concentration inside the wood. The specimens removed at the levels 45 and 60% respectively, of the conservation programme of bath2 (figure 4-25) show the same pattern, only even more pronounced. If this is to be interpreted as results from some irregularities of the quality of the wood, or from the way the experiment was conducted, would not be possible to elucidate without analysing the test specimens involved.

As a result the mean value of the PEG-concentration of the assumed PEG solution inside the wood has reached c. 40% while the PEG-concentration of the conservation solution has reached c. 65% .

In bath3 (figure 4-26) the PEG 4000 concentrations of the solutions of the conservation bath, and inside the test specimens developed almost parallel from 30 to 60% of the conservation programme. The angle of inclination of the rectilinear PEG concentration graph of the conservation solution was 25.7° while the angle of inclination of the almost straight line connecting the PEG concentration values of the test specimens removed at 30 and 60% was 25.1°. During the 60 – 80% PEG concentration interval of the programme, the PEG concentration level inside the specimens increased at a very slow pace. The angle of inclination of the PEG concentration inside the specimens during that period was only 10.3° while the increase of the PEG concentration of the conservation solution went on at the same pace as before.

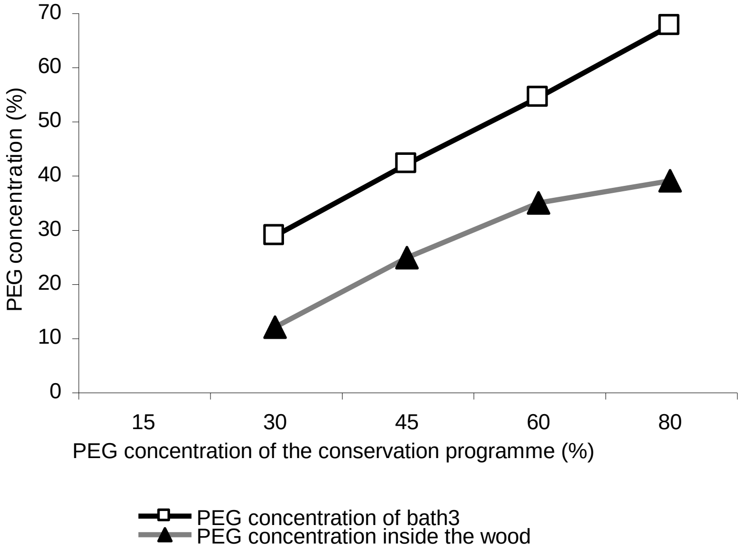

Figure 4-26. The PEG-concentration of the conservation solution of bath3 and the mean PEG-concentration inside the wood structure represented by the test specimens oak7, oak11, oak15, and oak19 respectively, removed at 30, 45, 60 and 80% PEG-concentration of the conservation programme.

In bath4 (figure 4-27) the concentration of the PEG solutions of the conservation bath and inside the test specimens increased at the same pace during the PEG raising interval between 45 and 60%. The angle of inclination of both straight lines representing the conservation solution and the assumed PEG solution inside the wood of the specimens was 23.4°. During the 60 to 80% PEG concentration increase interval the two straight lines representing the outside and the inside PEG concentration diverged markedly from each other, while the PEG concentration of the conservation solution increased faster than before and the increase of the PEG concentration inside the wood increased more slowly than before. The angles of inclination for the straight lines representing the outside and the inside PEG concentrations were 31.2° and 14.0° respectively during that period.

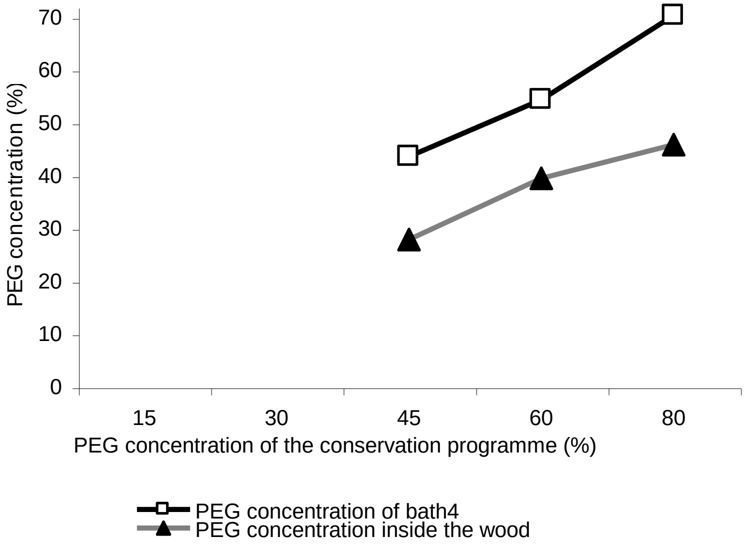

Figure 4-27. The PEG-concentration of the conservation solution of bath4 and the mean PEG-concentration inside the wood structure represented by the test specimens oak8, oak12, and oak16 respectively, removed at 45, 60 and 80% PEG-concentration of the conservation programme.

The conservation programme of bath27 was accomplished with PEG 1500. The graphs that represent the PEG concentration of the conservation solution and the PEG concentration inside the wood had developed as straight lines (figure 4-28). The angle of inclination of the PEG concentration of the conservation solution was 26.6° and the angle of inclination of the PEG concentration inside the wood was 21.7°. This means a divergence of 4.8° between the two lines. This is almost the same divergence as between the two lines representing the corresponding parameters of bath1.

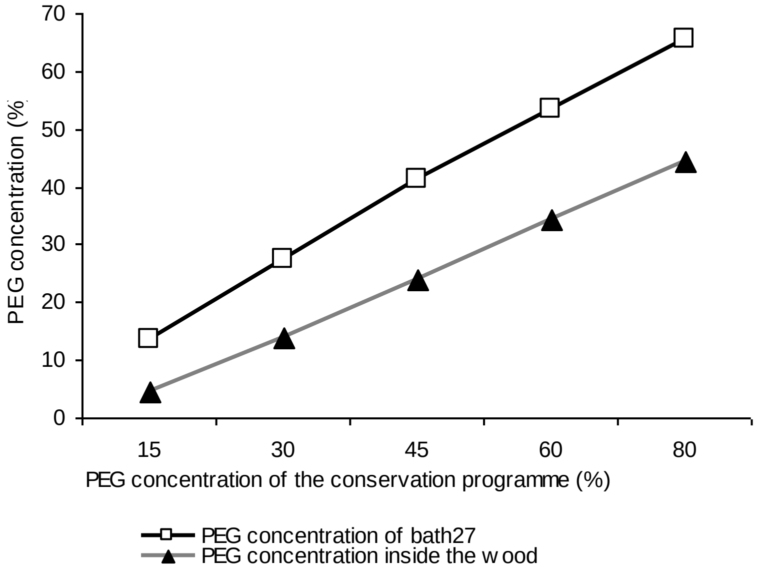

Figure 4-28. The PEG-concentration of the conservation solution of bath27 and the mean PEG-concentration inside the wood structure represented by the test specimens oak22, oak23, oak24, oak25, and oak26 respectively, removed at 15, 30, 45, 60 and 80% PEG-concentration of the conservation programme.

The successive removal of one specimen at the programmed PEG-concentrations of 15%, 30%, 45%, 60% and 80% respectively, provided a means to calculate the PEG-concentration of the PEG solutions building up inside the test specimens during the conservation procedure. These PEG-concentrations are plotted in a diagram against the PEG-concentration of the conservation solutions according to the conservation programmes, to demonstrate the uptake of PEG during the conservation period (figure 4-29).

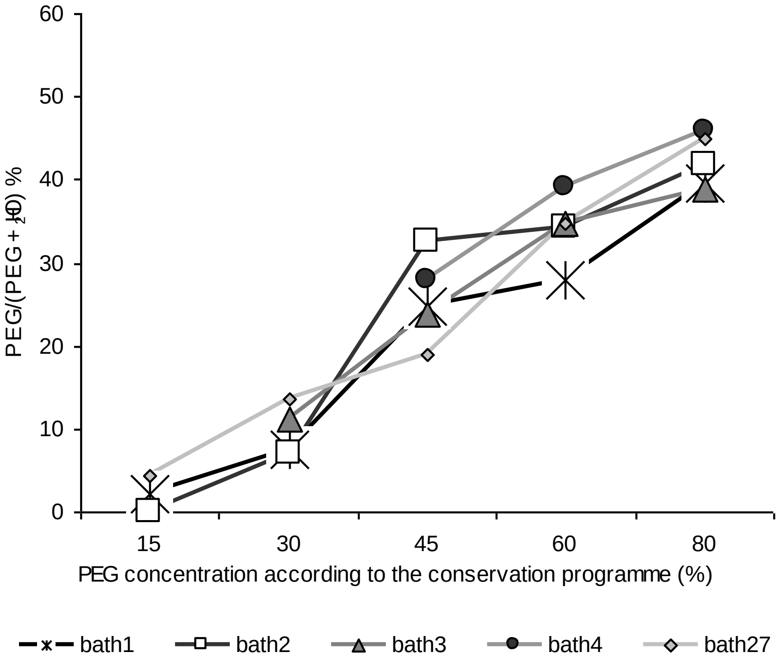

Figure 4-29. Mean value of PEG concentration inside the specimens of the conservation programmes PEG 4000 (5 – 80%), PEG 4000 (10 – 80%), PEG 4000 (20 – 80%), PEG 4000 (40 – 80%), and PEG 1500 (5 – 80%) at removal from their individual conservation solutions.

The conservation procedure in terms of loss of water and absorption of PEG of the test specimens could also be mapped. The graphs representing loss of water during the conservation process were closely connected and the drying procedure seems to have stopped between the 60 and the 80% level of the conservation programmes of bath1, bath3 and bath27, while some loss of water from the test specimens to the solution still existed in bath2 and bath4 (figure 4-30).

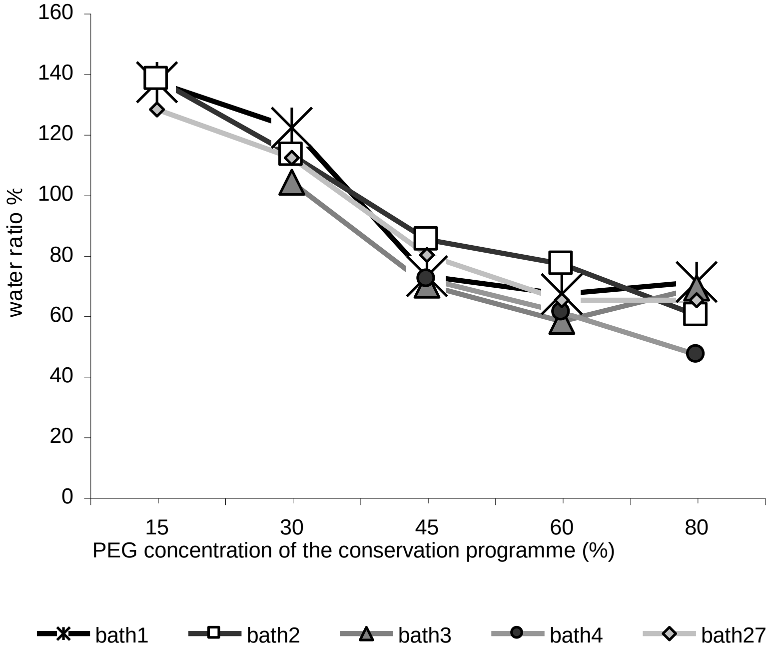

Figure 4-30. Mean value of water-ratio of the specimens of the conservation programmes PEG 4000 (5 – 80%), PEG 4000 (10 – 80%), PEG 4000 (20 – 80%), PEG 4000 (40 – 80%), and PEG 1500 (5 – 80%), at removal from their individual conservation solutions.

Contrary to the graphs representing loss of water, the graphs representing the absorption of PEG by the test specimens were very irregular (figure 4-31). Only the specimens of bath3 showed an almost linear PEG absorption graph. In bath4 there was no PEG absorption during the period between 60 and 80% PEG concentration increase, according to the conservation programme. In bath2 all PEG absorption seems to have occurred between the 30 and 45% levels of the conservation programme. In bath27 there was no PEG absorption at all during the 30 – 45% PEG concentration levels of the programme. In bath1 this standstill occurred at the 45 – 60% PEG concentration levels.

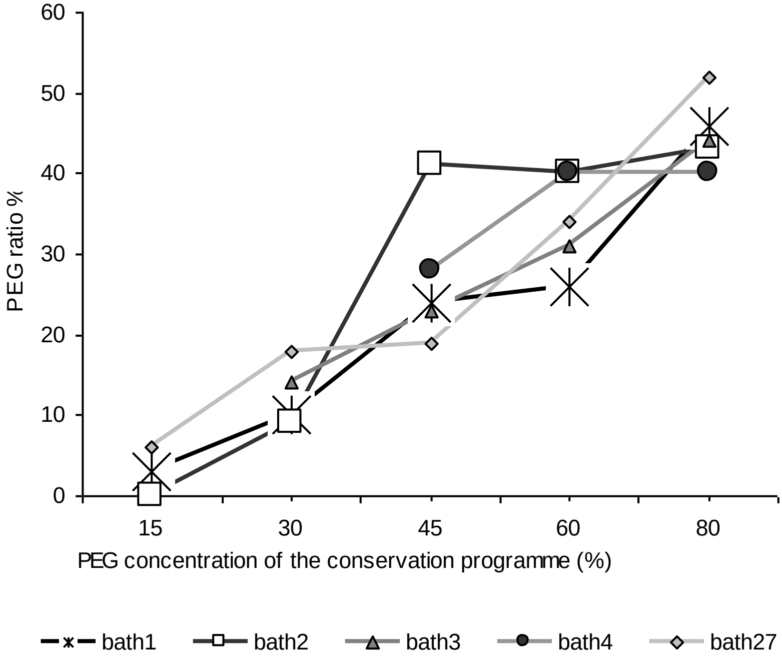

Figure 4-31. Mean value of PEG-ratio of the specimens of the conservation programmes PEG 4000 (5 – 80%), PEG 4000 (10 – 80%), PEG 4000 (20 – 80%), PEG 4000 (40 – 80%), and PEG 1500 (5 – 80%), at removal from their individual conservation solutions.

Considering the weight gain registered of the test specimens representing the 60 – 80% PEG concentration interval of the conservation programmes of the bath1, bath3 and bath27 and the slight gain in water-ratios paralleled by a rather substantial gain in PEG-ratios of the test specimen representing this concentration interval respectively of these conservation experiments there will be no other explanation than that a liquid transport of PEG solution into the wood of the test specimens had occurred. This might have been caused by low pressure inside the specimens that had probably been produced by water leaving the wood at an earlier stage of the conservation procedure. It is possible that such a transport of conservation solution into the wood under conservation may happen at several occasions during a conservation treatment period.

Shrinkage was noted to have been going on starting at c. 30% PEG-concentration according to the conservation programmes. The mean shrinkage of all specimens in each programme at each specific point of removal of one test specimen have been used for composing the diagram (4-32). The specimens from the 5-80% PEG 4000, the 20-80% PEG 4000 and the 5-80% PEG 1500 conservation baths showed a maximum shrinkage at 60% PEG-concentration of the conservation programmes and swelling from 60 to 80%.

The specimens from the 10-80% PEG 4000 bath displayed ongoing shrinkage which accelerated between the 60 to 80% level of the conservation programme. and shrinkage between 60 and 80% and the specimen from the 40-80% PEG 4000 bath had shrunk c. 5% at the 45% level and proceeded in the same direction through to the end point, 80% where the shrinkage had increased to c. 10%.

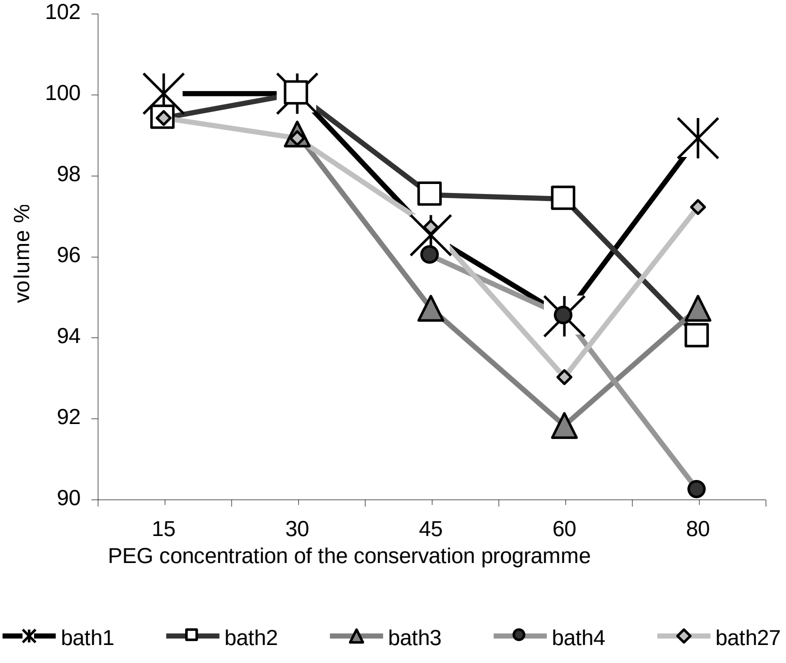

Figure 4-32. Shrinkage or swelling of the specimens of the conservation programmes PEG 4000 (5 – 80%), PEG 4000 (10 – 80%), PEG 4000 (20 – 80%), PEG 4000 (40 – 80%), and PEG 1500 (5 – 80%), at removal from their individual conservation solutions.

Conclusions

The main conclusion from the experiment is that PEG was entering the wood during the whole of the immersion period, however, not at an even pace. There were periods when no increase of PEG was registered in the wood of the specimens that were followed by periods of PEG increase. As with the previous experiment (4.2.) the initial PEG concentration of 10% PEG 4000 seems to have created quite a different pattern of PEG increase in the test specimens compared to the test specimens of the two conservation programmes with PEG 4000 and PEG 1500 that were started with 5% PEG concentration. The end results of PEG absorption though, were nearly identical, 40-46% PEG-ratio, for the specimens of the conservation baths with PEG 4000 while the end result of PEG absorption amounted to above 50% PEG-ratio for the specimens preserved with PEG 1500 (figure 4-31).

The final period, 60-80% PEG in the solution according to the conservation programme displayed swelling of the wood in bath1, bath3 and bath27, while the wood in the bath2 and bath4 displayed shrinkage during the terminating conservation period.

Since still no explanation was found of the difference between the conservation results with a conservation programme that started with 10% PEG 4000 concentration in the conservation solution and one started with 5% PEG 4000 concentration, there would have been a reason for repeating the experiment.

However, a full scale conservation procedure would involve handling of more than 20m^3 conservation solution of 65°C. This fact was considered at the conservation department and found impracticable. As the experimental work had shown that the conservation process was best started with a low PEG concentration the conservation department drew the conclusion that starting the procedure with pure water would be of no harm to the process, and hence would be the best way to handle the situation. This decision made further experimental work with various initial PEG concentrations superfluous.

4.4. Experimenting with the size of daily administered PEG increments for various PEG's and comparing oak from the Vasa hull with seasoned and waterlogged recent oak

In the previous experiments the test specimens had suffered some weight loss and shrinkage during the immersion period — even at conservation programmes with low initial PEG concentration in the conservation baths. As it was assumed that this might be the result of too fast an increase of the PEG concentration of the conservation solution an experiment was designed to provide some information about the impact of different PEG concentration raising programmes. As monitoring parameters were chosen shrinkage measurements and the content of PEG and water of the wood. As at the previous experiments both parameters were to be calculated from weighing the test specimens and measuring the density of the conservation solutions.

To investigate the possibility that further reduction of the daily PEG increment size would be of benefit to the chosen monitoring parameters — or possibly the contrary, if even a faster raise of PEG concentration than the randomly chosen daily 1/3% would make no difference, an experiment was designed with the three PEG increment sizes 4/3, 1/3 and 1/12%, administered five days a week. That meant that the programme with an increment size of 4/3% would bring the PEG concentration to the chosen end-concentration in one fourth of the time needed for the 1/3% increment programme. The programme with an increment size of 1/12% per week-day would require four times as long as the 1/3% increment programme to reach the end concentration chosen. Since the chosen end-concentration, like in the previous experiment (4.3.) was 80%, the resulting duration of the conservation periods was three months, one year and four years respectively.

At the time when the experiment was started PEG 1500 had already been brought to use in the spraying system of the conservation solution for the Vasa hull. Hence it was natural to select this molecular weight PEG for the experiment along with the PEG 4000. To establish a broader perspective PEG 1000 and 600 were also added to the experiment. Thus, twelve conservation programmes were designed.

4. DEVELOPMENT OF THE IMMERSION TREATMENT PROCEDURE

Oak from a deck-batten situated in the same part of the Vasa lower gun-deck as the ones used before (u_{max} = 150%) was selected as test material. To investigate the reaction of another material for comparison, nine specimens were cut from a plank of seasoned recent oak. These specimens were immersed in water until they obtained stable weights. At that point they presented a water ratio of c. 100% that was accepted as u_{max} for this waterlogged recent oak.

Twelve test specimens were cut from the Vasa deck-batten to the same size as those used in the preceding experiment (4.3.). The recent oak specimens had been cut to the same dimensions before being waterlogged. All transverse surfaces were painted with Araldite as at the previous immersion experiments. The experimental set-up was the same as with the experiment described in 4.2. (figure 4-1).

Before the experiment was started, the need of a reference for the Vasa oak series for the drying period was recognized. This reference would have to be of the same size as the specimens that were to be preserved. Consequently, one of the Vasa oak test specimens was removed for this purpose. This made it necessary to exclude one of the conservation programmes. The programme abandoned was the 4/3% daily increment programme with PEG 1000. For the recent oak series that contained only nine specimens all the PEG 1000 conservation programmes were abandoned.

The eleven remaining Vasa oak specimens together with the nine recent oak specimens were weighed and measurements were made for monitoring the shrinkage process even during the drying period. Each specimen was placed in an individual beaker with a measured volume of pure water. The beakers containing the specimens were placed in a thermostatic bath that was heated stepwise to a temperature of 65 °C, during a period of three weeks.

After the period of heating in water each specimen was subjected to its individual conservation programme. At the start and end of the heating period and at pre-scheduled occasions during the conservation period the test specimens were monitored by weighing both submerged into their individual conservation solutions with a spring-balance, and on a balance in the laboratory atmosphere. This was performed every two weeks during the three months programmes and once a month during the longer programmes. At the weighing occasions measuring the density of the conservation solutions was also performed. From the collected figures the ratios of the sum of PEG and water were derived, calculated in proportion to the dry fibre weight of each specimen (figures 4-32 – 4-35, Vasa oak; and figures 4-36 – 4-38, recent oak). The volume of each specimen was also calculated at the weighing occasions during the conservation process (figures 4-39 – 4-42, Vasa oak; and figures 4-43 – 4-45, recent oak).

After the conservation period each specimen was subjected to a drying programme that lasted for c. two years. The drying programme was concluded with drying the specimens to a stable weight
at a final climate created with silica gel. From the stable weight of the reference and the test specimens respectively obtained at that climate and from their calculated individual fibre weight, the residual water-ratio and the PEG-ratio of the specimens were calculated.

At the end of the conservation period the ratio of the sum of PEG and water of the three Vasa oak test specimens that had been subjected to the 1/12% daily increment programmes showed slightly enhanced values compared to the initial water ratio whereas the forth one showed a slightly reduced value. The specimens subjected to the 1/3% daily increment programmes in PEG 1000 and PEG 600 conservation solutions also showed enhanced values of the ratio of the sum of PEG and water at the end of the conservation period, whereas the ones that had been treated in PEG 4000 and PEG 1500 conservation solutions showed c. 30 and c. 15 percentage units lower values respectively, of this ratio compared to the initial water ratio. The three specimens subjected to the very short programmes of 4/3% daily concentration raise showed decrease of the ratio of the sum of PEG and water from c. 25 percentage units at the PEG 600 programme to more than 60 percentage units at the PEG 4000 programme, compared to the initial water ratio (table 4-II).

Test material	Designation of PEG	(PEG + H_2O)-ratio (%) of the specimens of the 1/12 % increment programme	(PEG + H_2O)-ratio (%) of the specimens of the 1/3 % increment programme	(PEG + H_2O)-ratio (%) of the specimens of the 4/3 % increment programme
Oak from the Vasa hull	PEG 4000	156	118	87
	PEG 1500	154	136	106
	PEG 1000	152	158	-
	PEG 600	148	155	125

Table 4-II. The ratios of the sum of PEG and water of the Vasa oak specimens calculated on their respective dry fibre weight at the end of the conservation period.

After the experiment the ratio of the sum of PEG and water of the water-logged recent oak specimens had increased by c. 14 percentage units compared to the initial water-ratio at both the 1/12% increment and the 1/3% increment programmes. The 4/3% increment programme had given no change or possibly in the case of the PEG 4000 programme a slight decrease of the final ratio of the sum of PEG and water compared to the initial water ratio (table 4-III).

Test material	Designation of PEG	(PEG + H_2O)-ratio (%) of the specimens of the 1/12 % increment programme	(PEG + H_2O)-ratio (%) of the specimens of the 1/3 % increment programme	(PEG + H_2O)-ratio (%) of the specimens of the 4/3 % increment programme
Waterlogged recent oak	PEG 4000	114	114	97
	PEG 1500	116	112	103
	PEG 600	114	114	101

Table 4-III. The ratios of the sum of PEG and water of the recent oak specimens calculated on their respective dry fibre weight at the end of the conservation period .

The conservation result in terms of PEG-ratio at the end of the conservation procedure has been obtained from the weight gain at the end of the drying procedure in relation with the calculated fibre weight of each specimen. The values have been adjusted for residual water ratio, expressed as the water ratio of the reference specimen.

The values obtained by the Vasa oak specimens generally stay between c. 50 and c. 60% PEG ratio. Two specimens, namely the one of the 1/12% increment PEG 4000 programme and the one of the PEG 600 programme of the same increment series have obtained the extremes of PEG ratios of the Vasa oak specimens, c. 70% and c. 40% respectively. The specimen of the 4/3% increment PEG 4000 programme also showed a PEG ratio of c. 40% (table 4-IV).

Test material	Designation of PEG	PEG-ratio (%) of the specimens of the 1/12 % increment programmes	PEG-ratio (%) of the specimens of the 1/3 % increment programmes	PEG-ratio (%) of the specimens of the 4/3 % increment programmes
Oak from the Vasa hull	PEG 4000	69	52	38
	PEG 1500	59	64	52
	PEG 1000	53	61	-
	PEG 600	44	52	58

Table 4-IV. PEG-ratio of the Vasa oak specimens at the end of the conservation period.

The PEG ratio values obtained by the newly waterlogged recent oak specimens were generally lower than those of the Vasa oak specimen series. The lowest values are presented by the 1/12% increment series where the PEG's 4000 and 1500 specimens have obtained PEG-ratios of c. 30% whereas the PEG 600 specimen has obtained a PEG-ratio of only c. 25%. The same pattern is prevalent in the 1/3% increment series where the PEG's 4000 and 1500 specimens show PEG ratios of c. 50%, but the PEG 600 specimen shows a PEG ratio of only c. 40%. The specimens of the 4/3% increment series display an intermediate situation where the PEG 1500 specimen shows the highest PEG ratio of c. 45%, the PEG 600 specimen c. 40% and the PEG 4000 specimen c. 35% (table 4-V).

Test material	Designation of PEG	PEG-ratio (%) of the specimens of the 1/12 % increment programmes	PEG-ratio (%) of the specimens of the 1/3 % increment programmes	PEG-ratio (%) of the specimens of the 4/3 % increment programmes
Waterlogged recent oak	PEG 4000	32	49	34
	PEG 1500	31	48	45
	PEG 600	24	42	39

Table 4-V. PEG-ratio of the recent oak specimens at the end of the conservation period.

Beside PEG uptake by the specimens during the conservation process water was removed from the specimens. The amounts of water left in the specimens have been calculated as ratios, by subtracting the PEG-ratios from the ratios of the sum of PEG and water (tables 4-II, 4-IV and 4-VI: Vasa oak specimens; tables 4-III, 4-V and 4-VII: recent oak specimens).

Test material	Designation of PEG	H_2O-ratio (%) of the specimens of the 1/12 % increment programme	H_2O-ratio (%) of the specimens of the 1/3 % increment programme	H_2O-ratio (%) of the specimens of the 4/3 % increment programme
Oak from the Vasa hull	PEG 4000	87	66	49
	PEG 1500	95	72	54
	PEG 1000	99	97	-
	PEG 600	104	103	67

Table 4-VI. Water-ratio of the Vasa oak specimens at the end of the conservation period.

The water ratio values retained at the end of the conservation procedure of the specimens of corresponding conservation programmes of the Vasa oak series and the recent oak series respectively, present similar series from lower to higher values with PEG's of declining molecular weight. Even the PEG ratio levels are similar, except for the PEG 4000 and 1500 of the 4/3% increment programme and the PEG 600 of the

1/12% and 1/3% programmes (tables 4-V and 4-VII). However, at the recent oak series this means that the wood has retained between 90 and 60% of its initial content of water, whereas the Vasa oak has retained only between 70 and 30% of its initial content of water.

Test material	Designation of PEG	H_2O-ratio (%) of the specimens of the 1/12 % increment programme	H_2O-ratio (%) of the specimens of the 1/3 % increment programme	H_2O-ratio (%) of the specimens of the 4/3 % increment programme
Waterlogged recent oak	PEG 4000	82	65	63
	PEG 1500	85	64	58
	PEG 600	90	72	62

Table 4-VII. Water-ratio of the recent oak specimens at the end of the conservation period.

In order to present additional aspects of the PEG uptake into the wood structure of the specimens, the PEG contents inside the specimens at the end of the conservation procedures were calculated as percentage of the sum of PEG and water inside the specimens as an assumed PEG solution (tables 4-VIII and 4-IX). Each of these “PEG concentrations” inside the wood may be related to the PEG end-concentrations of their corresponding conservation solution (tables 4-X and 4-XI).

Test material	Designation of PEG	PEG concentration (%) inside the specimens of the 1/12% increment programme	PEG concentration (%) inside the specimens of the 1/3% increment programme	PEG concentration (%) inside the specimens of the 4/3% increment programme
Oak from the Vasa hull	PEG 4000	44	44	44
	PEG 1500	38	47	49
	PEG 1000	35	39	-
	PEG 600	30	34	46

Table 4-VIII. Mean percentage value of PEG/PEG + water ("PEG-concentration") inside the Vasa oak specimens at the end of the conservation period.

Test material	Designation of PEG	PEG concentration (%) inside the specimens of the 1/12% increment programme	PEG concentration (%) inside the specimens of the 1/3% increment programme	PEG concentration (%) inside the specimens of the 4/3% increment programme
Waterlogged recent oak	PEG 4000	28	43	35
	PEG 1500	27	43	44
	PEG 600	21	37	38

Table 4-IX. Mean percentage value of PEG/PEG + water ("PEG-concentration") inside the recent oak specimens at the end of the conservation period.

All of the PEG concentrations of the conservation solutions were higher than the corresponding average PEG concentrations inside the wood. However, the differences between outside and inside PEG concentrations of the Vasa oak series may be grouped into two categories, one with c. 10 percentage units difference that included all tested conservation programmes with 4/3% daily PEG concentration increments, and the programmes with PEG 4000 and PEG 1500 with 1/12% and 1/3% daily PEG concentration increments and another of c. 20 percentage units difference between inside and outside PEG concentration that included the PEG's 1000 and 600 of the conservation programmes with 1/12% and 1/3% daily PEG concentration increments.

Even the specimens of the recent oak series had a tendency to show the same pattern of two categories of differences between the PEG concentration of the conservation solutions and the average PEG concentrations of the constructed PEG solutions inside the wood. The specimens of the PEG 4000 and 1500 programmes of the recent oak series of 1/3% PEG concentration increments display c. 10 percentage units and the PEG 600 specimens approach c. 20 percentage units differences between the inside and the surrounding PEG concentrations. The specimens of the other series show differences of 20 to 30 percentage units between the inside and the surrounding PEG concentrations, except for the specimen of the PEG 1500 programme of the 4/3% increment programme that belongs to the category of c. 10 percentage units difference.

Test material	Designation of PEG	PEG concentration (%) of the conservation solutions of the 1/12% increment programme	PEG concentration (%) of the conservation solutions of the 1/3% increment programme	PEG concentration (%) of the conservation solutions of the 4/3% increment programme
Oak from the Vasa hull	PEG 4000	54	56	58
	PEG 1500	50	58	59
	PEG 1000	55	61	-
	PEG 600	50	57	60

Table 4-X. PEG concentration of the conservation solutions of the Vasa oak specimens at the end of the conservation period.

Test material	Designation of PEG	PEG concentration (%) of the conservation solutions of the 1/12% increment programme	PEG concentration (%) of the conservation solutions of the 1/3% increment programme	PEG concentration (%) of the conservation solutions of the 4/3% increment programme
Waterlogged recent oak	PEG 4000	53	55	55
	PEG 1500	52	54	57
	PEG 600	53	54	60

Table 4-XI. PEG concentration of the conservation solutions of the recent oak specimens at the end of the conservation period.

The observation that the PEG's of 4000 and 1500 molecular weight were absorbed to about the same, or even to a higher extent by the Vasa oak wood than the PEG's of 1000 and 600 molecular weight (table 4-IV) had not been expected when the experiment was designed. Looking at the recent oak wood series, it was hard to explain the observation that the specimens of the 1/12% increment programme had arrived at a markedly lower PEG content than the specimens of the other increment programmes (table 4-V). These differences were not at hand with the Vasa oak wood series. However, the weighing occasions during the conservation period provided a means to map the conservation process in terms, partly of changes of the sum of PEG and water and, partly of changes of volume. Considered together these two aspects might provide information.

The earlier mentioned calculations of the (PEG + water)-ratio of each of the specimens, made at programmed time intervals during the entire conservation procedure, have been assembled into diagrams representing each of the PEG's investigated within the experiments and, both of the test materials, Vasa oak wood and recent waterlogged oak wood (figures 4-33 – 4-36, Vasa oak wood specimens; and 4-37 – 4-39, recent oak wood specimens). The swelling or shrinking of the specimens during the conservation period is the other evaluation parameter. These values may be derived from calculation of the volumes of the specimens at the weighing occasions.

The swelling or shrinking behaviour may be discussed from the volume diagrams (figures 4-40 – 4-43, Vasa oak wood specimens; and 4-44 – 4-46, recent oak wood specimens).

Development of the (PEG + water)-ratio of the specimens during the conservation procedure

To describe the development of the (PEG + water)-ratio during the conservation procedures of both the Vasa oak specimen series and the waterlogged new oak series four main behaviours have been identified as follows:

1. Weight gain during the entire duration of the conservation programme or during parts of this interchanging with periods of no weight change.
2. Weight loss during the entire length of the conservation programme or during parts of this interchanging with periods of no weight change.
3. Weight loss during the initial part of the conservation programme followed by weight gain during the whole remainder of the conservation programme or during parts of this interchanging with periods of no weight change.

The Vasa oak wood specimen series

Considering the graphs of the (PEG + water)-ratio of the Vasa oak wood specimens preserved with PEG 4000 the following notations are made:

The overall representation of the three increment programmes of 1/12, 1/3 and 4/3% per day, respectively, shows widely diverging (PEG + water)-ratio graphs. The (PEG + water)-ratios at the end of the conservation period were 156, 118 and 87% (figure 4-33; table 4-II).

From the 25 to the 55% PEG concentration level of the conservation programme the graph of the 1/12% increment series indicate an upwards tendency which increases during the 55 to 80% PEG concentration raising period of the conservation programme. This graph corresponds clearly to behaviour group 1.

The graph of the specimen of the 1/3% increment shows a declining tendency that starts at c. 20% PEG concentration of the conservation programme. The downward course of the graph proceeds until reaching c. 60% PEG concentration of the conservation programme. At that level the declining tendency is arrested and the graph proceeds at constant level until the end of the conservation programme. This places the graph in behaviour group 2.

The graph of the specimen at the conservation programme based on 4/3% PEG increments indicates a declining direction to a greater extent than the graph of the 1/3% increment specimen, and runs at a steep downward gradient during the 20 to 60% PEG concentration raising period of the conservation programme. This changes during the concluding phase of the conservation period when the graph runs less and less steep. Like the graph of the 1/3% increment programme the graph of the 4/3 increment programme is classified as behaviour group 2.

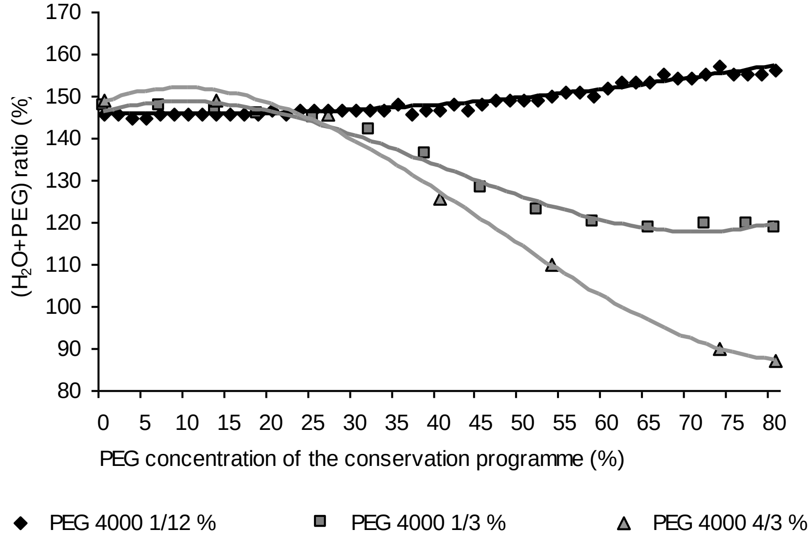

Figure 4-33. (PEG + water)-ratio of Vasa oak specimens at conservation programmes of 1/12, 1/3 and 4/3% PEG 4000 increments respectively, five days per week during the conservation period. Trend-lines; least square fittings.

Considering the graphs of the (PEG + water)-ratio of the specimens of the PEG 1500 group of the Vasa oak series it is observed that these are diverging although not to the same extent as the graphs of the specimens of the PEG 4000 group. The (PEG + water)-ratios at the end of the conservation period were 154, 136 and 106% (figure 4-34; table 4-II).

During the entire conservation period the graph of the 1/12% increment series indicates a slightly upwards tendency. The upwards tendency stops at the 65% concentration level of the conservation programme and the graph remains at constant level to the end of the conservation period. The graph is classified as behaviour group 1.

The graph of the specimen of the 1/3% increment series shows a declining tendency from the 20 to the 45% PEG concentration level of the conservation programme. From the 45 to the 70% PEG concentration level of the conservation programme the graph remains at constant level. During the final part of the conservation programme a faint upward tendency of the graph may be present. The graph is classified as behaviour group 2.

The graph of the specimen of the 4/3% increment conservation programme shows a steep downward gradient from the 20 to the 65% PEG concentration level of the conservation programme. At the 65% PEG concentration level the graph changed its gradient and proceeded less steeply and terminated nearly horizontal between the 75 and 80% PEG concentration levels of the conservation programme. The graph is classified as behaviour group 2.

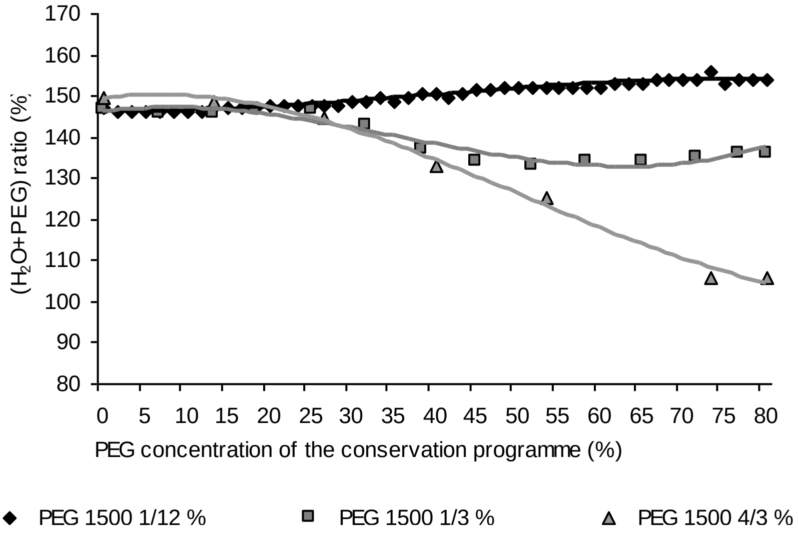

Figure 4-34. (PEG + water)-ratio of Vasa oak specimens at conservation programmes of 1/12, 1/3 and 4/3% PEG 1500 increments respectively, five days per week during the conservation period. Trend-lines; least square fittings.

Depending on the removal of one specimen to be a reference the PEG 1000 group contains only two specimens. These are the 1/12% increment specimen and the 1/3% increment specimen. Considering the graphs of the PEG and water content of the two specimens of the PEG 1000 group of the Vasa oak series it is observed that these are almost identical during the main part of the conservation programme. The (PEG + water)-ratios at the end of the conservation period were 152, and 158% (figure 4-35; table 4-II).

During most of the conservation period the graph of the 1/12% increment series indicates a slightly upwards tendency. The upward tendency stops at the 65% concentration level of the conservation programme and the graph shows a faint downward tendency from there on to the end of the conservation period. The graph is classified as behaviour group 1.

During the entire conservation period the graph of the 1/3% increment specimen indicates a slightly upwards tendency. It is identical with the graph of the 1/12% increment specimen until the 55% level of the conservation programme. Between the 55 and the 75% concentration level of the conservation programme the graph of the 1/3% increment PEG 1000 specimen proceeds uniformly and levels out to a constant value during the final phase of the conservation procedure. The graph is classified as behaviour group 1.

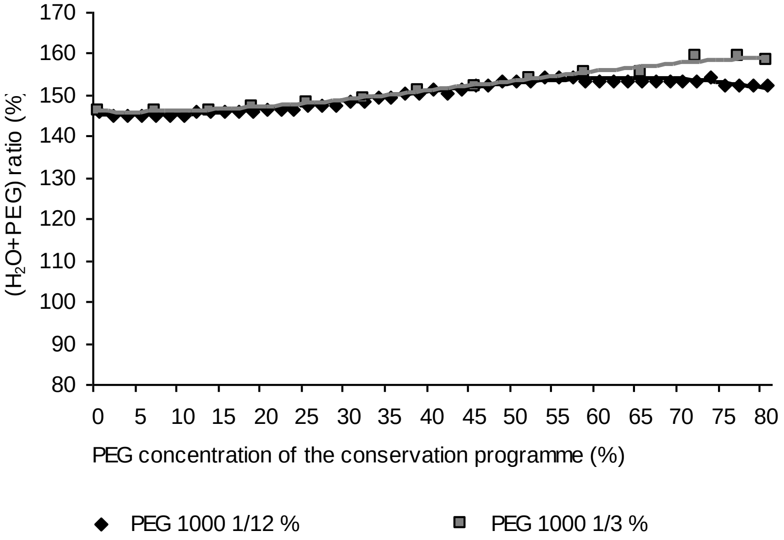

Figure 4-35. (PEG + water)-ratio of Vasa oak specimens at conservation programmes of 1/12 and 1/3% PEG 1000 increments respectively, five days per week during the conservation period. Trend-lines; least square fittings.

Considering the graphs of the (PEG + water)-ratio of the specimens of the PEG 600 group of the Vasa oak series it is observed that these are rather close together although the one representing the specimen preserved with the 4/3% increment programme shows diverging behaviour to the two specimens preserved with the 1/12 and the 1/3% increment programmes. The (PEG + water)-ratios at the end-conservation period were 148, 155 and 125%, respectively (figure 4-36; table 4-II).

The upward tendency of the graph of the 1/12% increment specimen is not as strong as with the other PEG's tested on the Vasa oak specimens, and stops at the 70% concentration level of the conservation programme. and the graph remains at constant level from there on to the end of the conservation period. The graph is classified as behaviour group 1.

The graph of the specimen of the PEG 600 series of the 1/3% increment series indicates a slightly upward tendency during the entire conservation programme. It parallels the graph of the 1/12% increment specimen until the 25% level of the conservation programme from where it proceeds with a more pronounced upward tendency than this. As end result there is a difference of c. 10 percentage units of PEG and water ratio of the 1/3% increment specimen compared to the 1/12% increment specimen. The graph is classified as behaviour group 1.

During the raise from 20 to 60% PEG concentration of the conservation solution the graph of the specimen at the PEG 600 4/3%-increment conservation programme shows a downward gradient and finally the graph levels out at c. 125% (PEG + water)-ratio. The graph is classified as behaviour group 2.

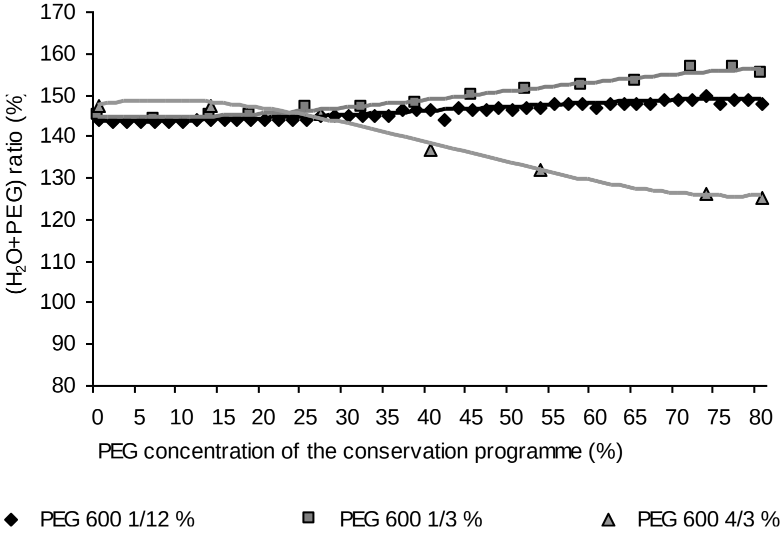

Figure 4-36. (PEG + water)-ratio of Vasa oak specimens at conservation programmes of 1/12, 1/3 and 4/3% PEG 600 increments respectively, five days per week during the conservation period. Trend-lines; least square fittings.

Special observations of the Vasa oak wood specimen series

Considering the graphs of the (PEG + water)-ratios of the specimens of the PEG 4000, 1500, 1000 and 600 groups of the Vasa oak series it is observed that the spaces between them diminishes when passing down the molecular weight series. The specimens of the 1/12% increment group all belong to behaviour group 1. The 1/3% increment specimens of the PEG 4000 and 1500 groups belong to behaviour group 2 while those of the PEG 1000 and 600 groups belong to behaviour group 1. Obviously a turn-over from an over-all loss of weight to an over-all gain of weight has occurred between the PEG 4000 and 1500 group and the PEG 1000 and 600 group. All specimens preserved at the 4/3 increment programmes belong to the behaviour group 2.

The recent oak wood specimen series

Considering the graphs of the (PEG + water)-ratio of the recent oak wood specimens preserved with PEG 4000 the following notations are made:

The overall representation of the three increment programmes of 1/12, 1/3 and 4/3% per day, respectively, shows similar (PEG + water)-ratio graphs. The (PEG + water)-ratios at the end of the conservation period were 114, 114 and 97%, respectively (figure 4-37; table 4-III).

The graph of the specimen of the 1/12% increment programme shows a marked increase of the (PEG + water)-ratio during the raise of the PEG concentration from 0 to 10%. During the PEG concentration raise from 10 to c. 25% the graph remains at a constant level and, from c. 25 to 60% the graph has a faint upward tendency. During the 60 to 75% raise of PEG concentration the graph remains at constant level and, during the 75 to 80% PEG concentration raise it makes another sharp upwards bend. The graph is classified as behaviour group 1.

The graph of the specimen of the PEG 4000 1/3% increment programme shows a uniformly rising tendency during the entire conservation period. The graph is classified as behaviour group 1.

The graph of the specimen of the PEG 4000 4/3% increment programme, however, takes a slightly declining direction that changes into a slightly growing direction from the 55% level to the end of the conservation programme. This specimen of the PEG 4000 programme showed a loss of (PEG + water)-ratio of c. 10% at the 55% level of the conservation programme but had nearly regained its starting value at the end of the conservation procedure. The graph is classified as behaviour group 3.

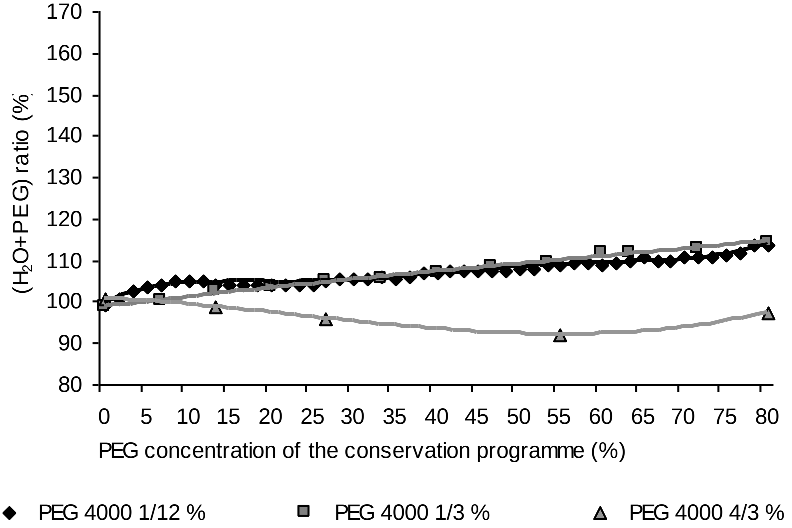

Figure 4-37. (PEG + water)-ratio of waterlogged recent oak specimens at conservation programmes of 1/12, 1/3 and 4/3% PEG 4000 increments respectively, five days per week during the conservation period.
Trend-lines; least square fittings.

Considering the graphs of the (PEG + water)-ratio of the recent oak wood specimens preserved with PEG 1500 the following notations are made:

The overall representation of the three increment programmes of 1/12, 1/3 and 4/3% per day, respectively, shows similar (PEG + water)-ratio graphs. The (PEG + water)-ratios at the end of the conservation period were 116, 112 and 103%, respectively (figure 4-38; table 4-III).

The graph of the 1/12% increment specimen shows a marked increase of the (PEG + water)-ratio during the raise of the PEG concentration from 0 to 10%. During the PEG concentration raise from 10 to c. 50% the graph remains at a constant level and from c. 50 to 75% the graph has a faint upward tendency. During the 75 to 80% PEG concentration raise the graph makes another upwards bend. The graph is classified as behaviour group 1.

The graph of the specimen of the PEG 1500 1/3% increment programme shows a uniformly rising tendency inclination angle during the entire conservation period. The graph is classified as behaviour group 1.

The 4/3% increment specimen of the PEG 1500 programme had lost c. 5 percentage units of its (PEG + water)-ratio value at the 55% PEG concentration level of the conservation programme. With the 55% level as a turning point it started regaining weight and had obtained a slightly higher (PEG + water)-ratio value than its starting value at the end of the conservation procedure. The graph is classified as behaviour group 3.

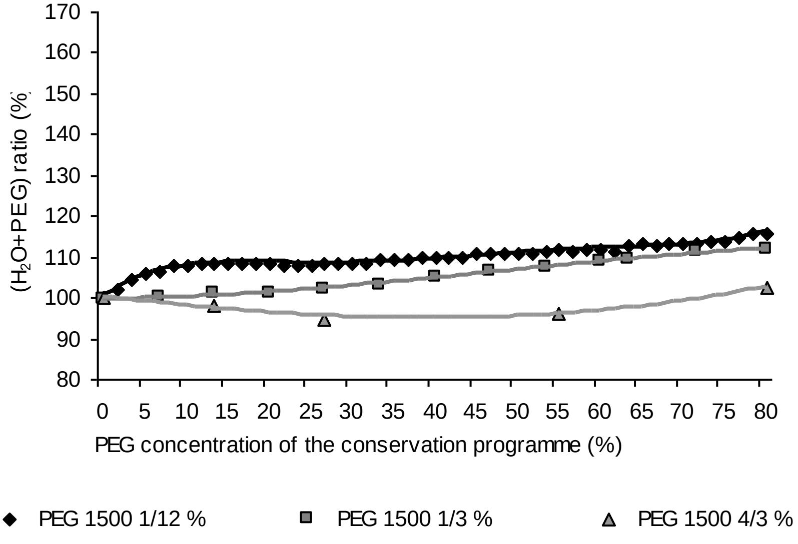

Figure 4-38. (PEG + water)-ratio of waterlogged recent oak specimens at conservation programmes of 1/12, 1/3 and 4/3% PEG 1500 increments respectively, five days per week during the conservation period.
Trend-lines; least square fittings.

Considering the graphs of the (PEG + water)-ratio of the recent oak wood specimens preserved with PEG 600 the following observations are made:

The overall representation of the three increment programmes of 1/12, 1/3 and 4/3% per day, respectively, shows similar (PEG + water)-ratio graphs. The (PEG + water)-ratios at the end of the conservation period were 114, 114 and 101%, respectively (figure 4-39; table 4-III).

The graph of the 1/12% increment specimen shows a marked increase of the (PEG + water)-ratio during the raise of the PEG concentration from 0 to 10%. During the PEG concentration raise from 10 to c. 40% the graph remains at a constant level and, from the 40% level to the end of the conservation period the graph has a faint upward tendency. The graph is classified as behaviour group 1.

The graph of the specimen of the PEG 600 1/3% increment programme proceeds at constant level until 10% PEG concentration of the conservation programme. During the remainder of the conservation programme the graph shows an uniformly raising tendency. The graph is classified as behaviour group 1.

The 4/3% increment specimen of the PEG 600 programme had lost c. 5% of its PEG and water ratio value and had already started regaining its ratio value at the 55% level of the conservation programme. At the end of the conservation process it had obtained a slightly higher PEG and water ratio than its starting value. The graph is classified as behaviour group 3.

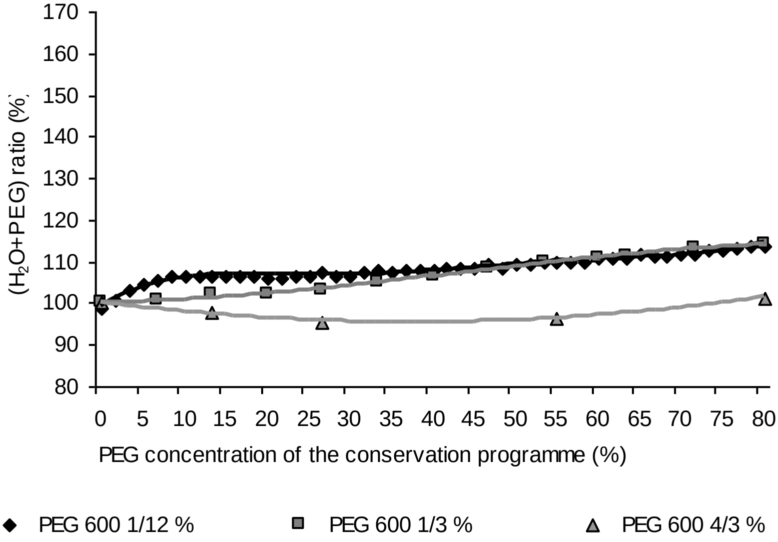

Figure 4-39. (PEG and water)-ratio of waterlogged recent oak specimens at conservation programmes of 1/12, 1/3 and 4/3% PEG 600 increments respectively, five days per week during the conservation period.
Trend-lines; least square fittings.

Special observations of the recent oak wood specimen series

Considering the diagrams of the graphs of the (PEG + water)-ratios of the specimens of the PEG 4000, 1500 and 600 groups of the recent oak series it is observed that these show substantial similarities with each other. The specimens of the 1/12 and 1/3% increment groups all belong to behaviour group 1 while all of the specimens of the 4/3% increment group belong to the behaviour group 3.

To be noted is that the 1/12% increment group of recent oak specimens show a substantial increase in (PEG + H_2O)-ratio during the 0-10% period of the conservation programmes. This phenomenon has not been observed with the Vasa oak specimens.

Swelling and shrinking in the conservation solution of the specimens

The swelling or shrinking of the specimens during the conservation period is the other evaluation parameter that may be derived from calculation of the volumes of the specimens at the weighing occasions. The swelling or shrinking behaviour may be discussed from the volume diagrams (figures 4-40 – 4-43, Vasa oak specimens; and 4-44 – 4-46, new oak specimens).

To summarize the observations of the volume during the conservation programmes of both the Vasa oak specimen series and the waterlogged new oak series, three behaviours have been identified:

1. Swelling during the entire duration of the conservation programme or during parts of this interchanging with periods of constant volume.
2. Shrinkage during the entire duration of the conservation programme or during parts of this interchanging with periods of constant volume.
3. Shrinkage during the initial part of the conservation programme interchanging with periods of constant volume followed by swelling during the remainder of the conservation programme.

The Vasa oak wood specimen series

Considering the graphs of the volumes of the specimens of the PEG 4000 group of the Vasa oak series (figure 4-40) it is observed that each of these is quite different from each one of the others although they all describe volume change of a similar Vasa oak specimen during the conservation process from pure water to 80% PEG 4000 added to the conservation solutions. The only difference is the size of the daily increments administered and the different duration of the conservation procedures that emanates from this.

Until the 30% PEG concentration level of the conservation programme there was a faint upwards tendency of the graph of the 1/12% increment series. From the 30 to the 65% PEG concentration level this tendency became more pronounced. The upwards tendency increased further during the 65 to 80% PEG concentration raising period of the conservation programme. The total swelling of the PEG 4000 specimen during the conservation period amounted to c. 3%. The graph is classified as behaviour group 1.

After a period of constant volume from 0 to 20% PEG concentration of the conservation programme the graph of the PEG 4000 specimen of the 1/3% increment programme shows a downward slope during the raise from 20 to 60% PEG concentration. At the 60% PEG concentration level the shrinkage of the PEG 4000 specimen has reached c. 3% and remained at that level until the end of the conservation programme. The graph is classified as behaviour group 2.

The graph of the PEG 4000 specimen that was treated at the 4/3% increment programme started a downward slope between the 35 to 45% PEG concentration level of the conservation programme. From the 45 to the 60% PEG concentration level the downward slope became steeper and between the 60 and the 75% PEG concentration level still steeper. During the final part of the conservation programme it has not been possible with the chosen methods to follow the shrinkage of the 4/3% increment specimen. The total volume shrinkage of the specimen has exceeded 8% during the conservation period. The graph is classified as behaviour group 2.

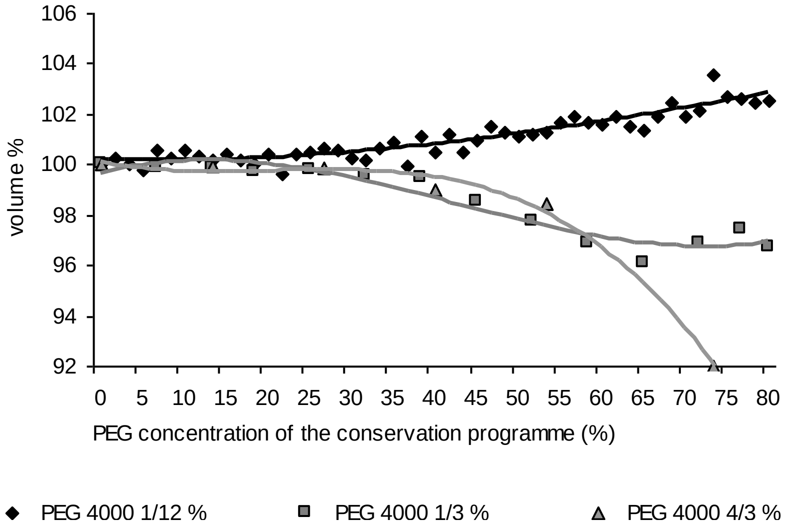

Figure 4-40. Volume shrinkage or swelling of Vasa oak specimens at conservation programmes of 1/12, 1/3 and 4/3% PEG 4000 increments respectively, five days per week during the conservation period. Trend-lines; least square fittings.

Considering the graphs of the volumes of the specimens of the PEG 1500 group of the Vasa oak series (figure 4-41) it is observed that each of these is quite different from each one of the others although they all describe volume change of a similar Vasa oak specimen during the conservation process from pure water to 80% PEG 1500 added to the conservation solutions. The only difference is the size of the daily increments administered and the different duration of the conservation procedures that emanates from this.

The graph of the volume of the PEG 1500 1/12% increment specimen shows an upward tendency starting from the 30 to the 70% PEG concentration level of the conservation programme. During the final part of the conservation programme the graph remains at constant level. The total swelling of the PEG 1500 specimen amounted to c. 2%. The graph is classified as behaviour group 1.

The graph of the 1/3% increment specimen shows a downward direction from the 10 to the 45% PEG concentration level of the conservation programme. The shrinkage of the PEG 1500 specimen reached nearly 2% at which level it remained during the 45 to 60% PEG concentration raising period of the conservation programme. At 60% PEG concentration the graph takes a vigorous turn upwards which brings the volume of the specimen back to c. 100% before the conservation period was finished. The graph is classified as behaviour group 3.

The graph of the 4/3% increment PEG 1500 specimen runs horizontally until the PEG concentration programme reached 30%. From 30 to 55% the graph proceeds downwards and from 55 to 65% the downwards tendency increased. At 65% PEG concentration of the conservation programme there is a further acceleration of the shrinkage and the curve of the PEG 1500 specimen took a steep dive of nearly the same magnitude as the corresponding specimen of the PEG 4000 programme. The total volume shrinkage of the specimen amounted to 8% during the conservation period. The graph is classified as behaviour group 2.

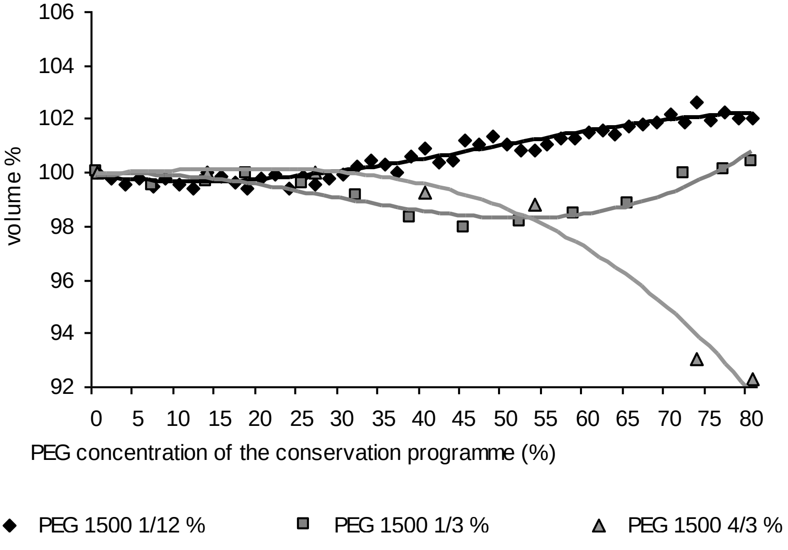

Figure 4-41. Volume shrinkage or swelling of Vasa oak specimens at conservation programmes of 1/12, 1/3 and 4/3% PEG 1500 increments respectively, five days per week during the conservation period. Trend-lines; least square fittings.

Depending on the removal of one specimen to be a reference the PEG 1000 group contains only two specimens. These are the 1/12% increment specimen and the 1/3% increment specimen. Considering the graphs of the volume of the two specimens of the PEG 1000 group of the Vasa oak series (figure 4-42) it is observed that both of these show an upward tendency during the main part of the conservation programme.

The graph of the 1/12% increment specimen showed an upward tendency during the raise from 15 and 60% PEG concentration of the conservation programme. Between 60 and 70% PEG concentration the graph remained at constant level. During the final part of the conservation programme the graph changed into a declining direction. The volume of the specimen increased as much as 3% that was maintained from 60 to 70% of the conservation programme. The swelling was, however, reduced to 2% at the end of the conservation period. The graph is classified as behaviour group 1. The faint shrinkage during the final part of the conservation period should, however, be noted.

The graph of the 1/3% increment specimen shows a faint upward tendency from 35% PEG concentration to the end of the of the conservation programme. The total increase of volume amounted to 1%. The graph is classified as behaviour group 1.

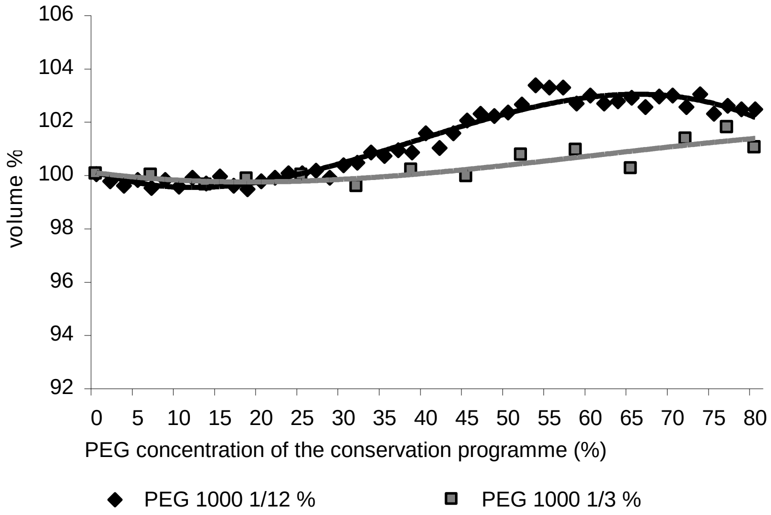

Figure 4-42. Volume shrinkage or swelling of Vasa oak specimens at conservation programmes of 1/12 and 1/3% PEG 1000 increments respectively, five days per week during the conservation period.
Trend-lines; least square fittings.

Considering the graphs of the volume of the specimens of the PEG 600 group of the Vasa oak series (figure 4-43) it is observed that the 1/12% increment specimen and the 1/3% increment specimen are similar and parallel each other with an upward tendency while the 4/3% increment specimen has a declining tendency. However, all the three graphs remain closer together than the graphs of the specimens of the PEG 4000 and 1500 groups.

The graph of the specimen of the 1/12% took an ascending direction At the 15% PEG concentration level of the conservation programme the graph started a faintly ascending direction. The total increase of volume, that was reached at the 70% PEG concentration level of the conservation programme, amounted to c. 1%. The graph is classified as behaviour group 1.

The graph of the 1/3% increment specimen took a descending direction at the start of the conservation programme that proceeded to the 30%

PEG concentration level of the conservation programme. At 30% PEG concentration the graph changed into ascending direction and during the period of raising of the PEG concentration from 30 to 70%. At this point in the conservation programme the volume shrinkage of the specimen amounted to c. 1%. During the final part of the conservation programme the graph remained at constant level. The graph is classified as behaviour group 1.

The graph of the 4/3% increment specimen showed an uniformly proceeding, faint downward slope. The shrinkage during the conservation procedure totals 2%. The graph is classified as behaviour group 2.

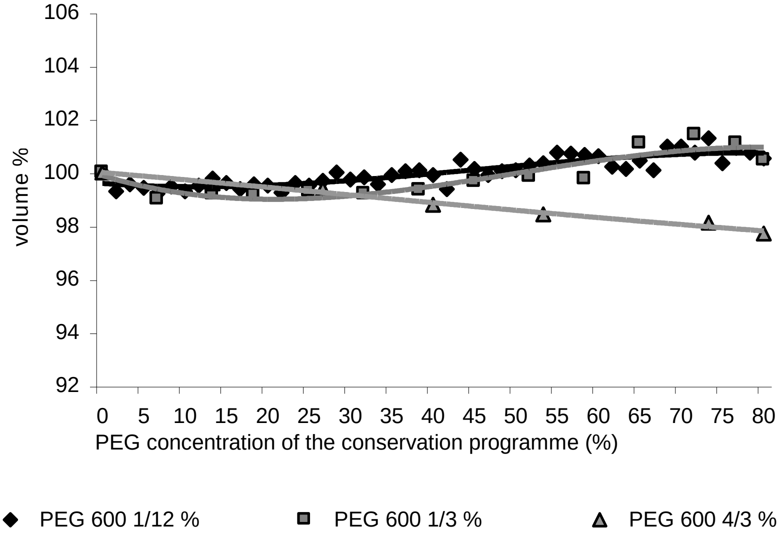

Figure 4-43. Volume shrinkage or swelling of Vasa oak specimens at conservation programmes of 1/12, 1/3 and 4/3% PEG 600 increments respectively, five days per week during the conservation period. Trend-lines; least square fittings.

The recent oak wood specimen series

Considering the graphs of the volumes of the specimens of the PEG 4000 group of the recent oak specimens series (figure 4-44) it is observed that two of these proceed at an ascending direction while the third one starts by following a declining path that changes into an ascending direction during the latter part of the conservation programme.

The 1/12% increment specimen of the PEG 4000 programme showed a pronounced swelling from the 15 to the 75% PEG concentration level of the conservation programme. The swelling even increased during the final part of the conservation programme that made a total of 4% swelling at the end of the conservation programme. The graph is classified as behaviour group 1.

The graph of the specimen of the 1/3% increment programme proceeded at an upwards direction during the PEG concentration raise from 15 to 70%. During the final part of the conservation programme the graph remained at constant level. The total swelling of the 1/3% increment specimen amounted to c. 2%. The graph is classified as behaviour group 1.

Finally, the graph of the PEG 4000 new oak specimen of the 4/3% increment programme took a downward direction from 20 to 55% PEG concentration of the conservation programme. At that point of the conservation programme the specimen had shrunk c. 0.5%. The graph changed direction and showed a swelling that had reached c. 0.5% at the end of the conservation programme. The graph is classified as behaviour group 3.

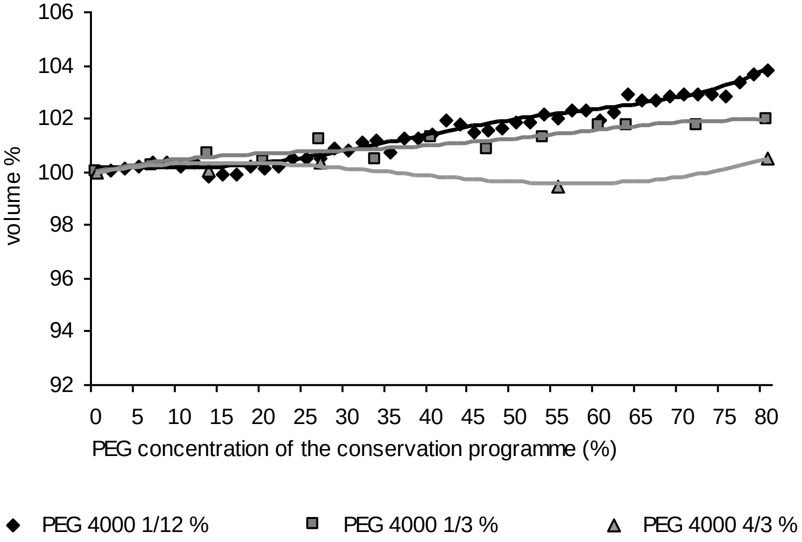

Figure 4-44. Volume shrinkage or swelling of recent oak specimens at conservation programmes of 1/12, 1/3 and 4/3% PEG 4000 increments respectively, five days per week during the conservation period. Trend-lines; least square fittings.

Considering the graphs of the volumes of the specimens of the PEG 1500 group of the recent oak specimen series (figure 4-45) it is observed that all three of these proceed with an upwards direction.

The graph of the specimen of the 1/12% increment programme displays an upwards direction from c. 20% PEG concentration of the conservation programme. The total swelling of the 1/12% increment specimen amounts to 3%. The graph is classified as behaviour group 1.

The graph of the 1/3% increment specimen from 20% PEG concentration to the end of the conservation programme proceeds along an upward path. The total swelling of the 1/3% increment specimen amounts to a little less than 2%. The graph is classified as behaviour group 1.

The graph of the specimen of the 4/3% increment programme took a lower but upwards pointing path compared to the 1/3% increment specimen. The total swelling of the 4/3% increment specimen amounted to less than 1%. The graph is classified as behaviour group 1.

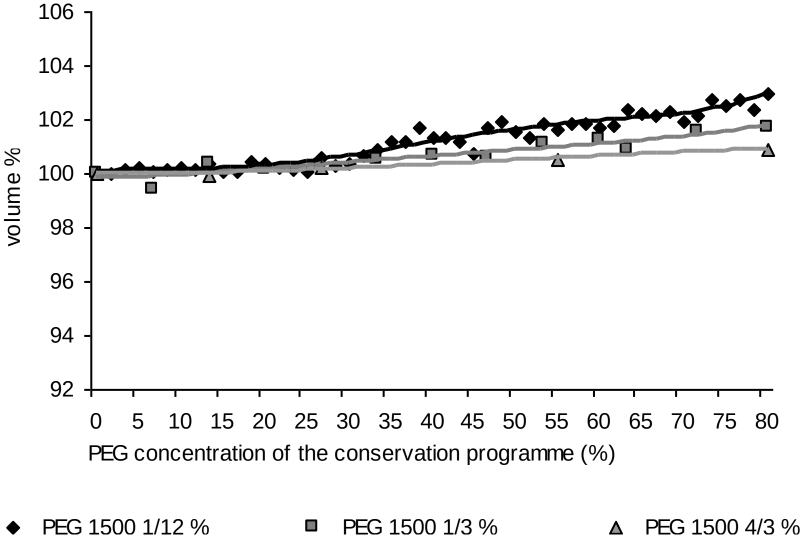

Figure 4-45. Volume shrinkage or swelling of recent oak specimens at conservation programmes of 1/12, 1/3and 4/3% PEG 1500 increments respectively, five days per week during the conservation period. Trend-lines; least square fittings.

Considering the graphs of the volumes of the specimens of the PEG 600 group of the recent oak series (figure 4-46) it is observed that all three of these proceed mainly in an ascending direction.

The graph of the specimens of the 1/12 increment programme turns into a upwards direction at the 15% PEG concentration level of the conservation programme. It proceeded at a uniform development until the end of the conservation programme. The total swelling during the conservation period amounted to c. 3%. The graph is classified as behaviour group 1.

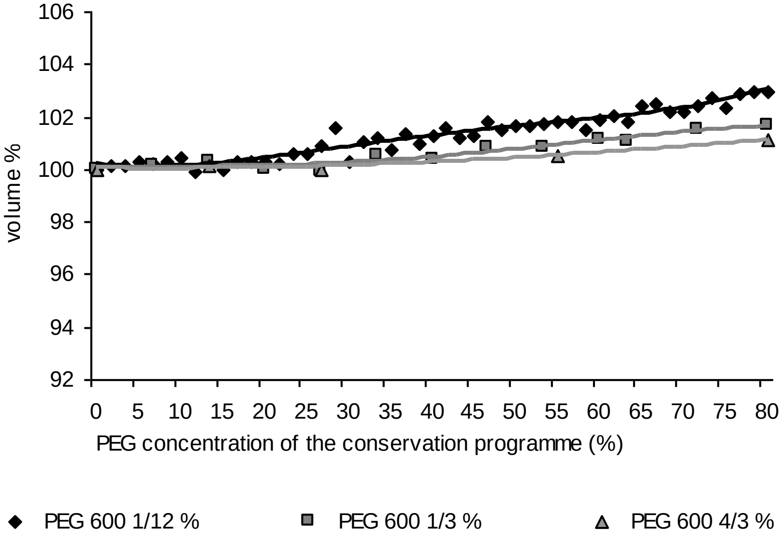

Figure 4-46. Volume shrinkage or swelling of recent oak specimens at conservation programmes of 1/12, 1/3 and 4/3% PEG 600 increments respectively, five days per week during the conservation period. Trend-lines; least square fittings.

The graph of the specimen of the 1/3% increment programme proceeded in an upward direction from 30% PEG concentration to the end of the conservation programme. The volume of the specimen shows a total swelling of c. 2% during the conservation period. The graph is classified as behaviour group 1.

The graph of the specimen of the 4/3% increment programme proceeded along a path just below the 1/3% increment programme specimen. The total swelling of the specimen of the 4/3% increment programme amounted to c. 1%. The graph is classified as behaviour group 1.

Conclusions

The assumption made, when designing the experiment, that the rate at which the raising of the PEG-concentration was accomplished in the conservation solution, would be crucial for the balance between the diffusion of PEG molecules from the conservation solution into the water contained inside the wood. The diffusion of water molecules in the opposite direction has been confirmed in each of the groups of specimens preserved at the 1/12%, 1/3% and 4/3% daily PEG increment rates of each of the molecular weights of PEG that have been applied (figures 4-33 – 4-39).

It has also been confirmed that the shrinkage of the test specimens during the conservation procedure is connected to how well this balance is maintained. However, where shrinkage is concerned there is a difference between the Vasa oak wood specimens and the recent oak wood specimens. Despite the strain put on the 4/3% increment groups of the recent oak wood specimens by a slight weight loss of 5.1 and 4.9%, respectively followed by a weight gain that had brought their weights back to the initial values, the 4/3 increment specimens of the PEG's 1500 and 600 have been able to produce a slight swelling of a total of 0.9 and 1.1%, respectively during the conservation procedure. The specimen of the 4/3% increment group preserved with PEG 4000, that had suffered a weight loss of 7.9%, had shrunk c. 0.5% at the middle of the conservation programme. The shrinkage had, however, been recaptured during the latter part of the programme so that the specimen ended up with its initial volume (figures 4-44 – 4-46).

To be specially noted is the rapid increase in (PEG + water)-ratio in the recent oak specimens of the 1/12% increment programmes between the 0 and 10% level of the PEG concentration of the conservation solutions. The recent oak specimen treated with PEG 4000 had gained one third of the total increase of the (PEG + water)-ratio during this initial period of the conservation programme, while the recent oak specimens treated with PEG 1500 and 600 had gained weight corresponding to c. 50% of the total increase in (PEG + water)-ratio, respectively, during the same period of the conservation programmes. Neither of the specimens of the 1/3 or the 4/3 increment programmes or any of the Vasa oak specimens displayed such fast a weight gain during the initial period of the conservation programme. A possible explanation of the phenomenon may be that the recent oak specimens may not have been completely filled with water at the beginning of the experiment although these had been stored in water for more than six months. Such a situation may have been camouflaged in the 1/3 and 4/3% increment conservation treatments by a faster diffusion of water molecules from these specimens compared to the specimens of the 1/12% increment programmes (figures 4-37 – 4-39).

The graphs of the (PEG + water)-ratios of the Vasa oak wood specimens of the 1/12% increment programmes were slightly ascending during the conservation period while the graphs of the (PEG + water)-ratio of the specimens of the 1/3% increment programmes of the Vasa oak wood specimens displayed a change in characteristics between the PEG's 1500 and 1000, where there was a switch over from a descending to an ascending direction. This also applied to the corresponding diagrams of shrinkage and swelling.

The graphs of the (PEG + water)-ratios of the Vasa oak wood specimens of the 4/3% increment programmes were vigorously descending where the PEG's 4000 and 1500 were concerned and were still descending for the specimens preserved with PEG 600. The graphs of the change of volume corresponded with the graphs of weight loss even in those cases (figures 4-33 – 4-36; 4-40 – 4-43).

A result to be noted is that the PEG-ratios of the recent oak specimens of the 1/12% increment series were lower by c. 40% compared to the PEG-ratios of the specimens of the 1/3 increments series, although these two series had displayed nearly identical curves of (PEG + water)-ratios. This might indicate that the osmosis had had a weaker development in the 1/12% increment series of the recent oak wood than in the 1/3% increment series albeit the former series had had four years to complete the conservation programme while the latter one had only had one year for that performance. This might also indicate osmosis as an important factor to bring PEG into the wood by the immersion treatment (figures 4-37 – 4-39; tables 4-III, 4-IX).

A corresponding comparison of the specimens of the Vasa oak series of the 1/12% and the 1/3% increment programmes showed that only the (PEG + water)-ratio curves of the PEG 1000 and 600 specimens of these programmes were of the ascending type, while the (PEG + water)-

ratio curves of the 1/12% increment of the PEG 4000 and 1500 specimens were of the ascending type, but the (PEG + water)-ratio curves of the PEG 4000 and 1500 specimens of the 1/3% increment programmes were of the descending type. If, however, the PEG-ratios of the two 1/12% increment groups and the 1/3% increment groups of specimens from the PEG 4000 and 1500 programmes and the PEG 1000 and 600 programmes, respectively, are compared both of these groups display c. 10% lower PEG-ratios in the 1/12% increment group.

This might indicate that the osmosis had had a slightly weaker development in both of the 1/12% increment series of the Vasa oak wood than in the two 1/3% increment series and might also point to osmosis as an important factor to bring PEG into the wood by the immersion treatment (figures 4-33 – 4-36; tables 4-II, 4-VIII).

The reactions of the specimens of the 1/12% and the 1/3% increment programmes strengthens the assumption that osmosis is the main driving force of the conservation process expressed by the author of this dissertation at the ICOM-WOAM meeting in Portland, Maine, USA in the following way: "… by the removal of water that according to the author's hypothesis is the main feature and driving force in the conservation process".[100]

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[100] Håfors, 1993, p 51.

4.5. Experimenting with variation of time intervals for administering PEG increments of varying sizes for conservation programmes of equal duration and equal end-concentration

When the Vasa project was started the ruling idea was that the raising of the PEG concentration of the conservation solution should be performed as uniformly as possible. A continuous supplying of a PEG solution of a concentration to match both the evaporation of water and to administer a specified and controlled amount of PEG per time unit as Morén & Centervall has proposed would present an ideal situation.[101] With the large conservation tanks of the Vasa conservation laboratory to administer one increment PEG per day would be a way to achieve this as accurately as possible. This lead to the situation that staff had to come to the working place even on Sundays to administer the daily portion of PEG. When the working week by labour-market agreement was reduced from six to five days, there were two days every week when staff had to come in extra. This became rather expensive. The conservation programme for immersion conservation at the Vasa conservation laboratory had been performed with 0.25% daily PEG increments administered seven days a week. After the introduction of the five days working week this had to be abandoned and the administration of PEG increments was restricted to five days a week. In order not to prolong the conservation period, the size of increments was increased to 1/3% per workday.

The experiment tests different sizes of PEG 4000 increments administered at different time intervals, during conservation periods of equal length. The four increment sizes chosen were 1/5% administered every workday, 2% administered every two weeks, 5% administered every five weeks and 10% administered every 10 weeks. This made the total duration of the conservation period of the experiment amount to 82 weeks (figure 4-47).

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[101] Morén & Centerwall, 1960; this dissertation, section 2.2.1.

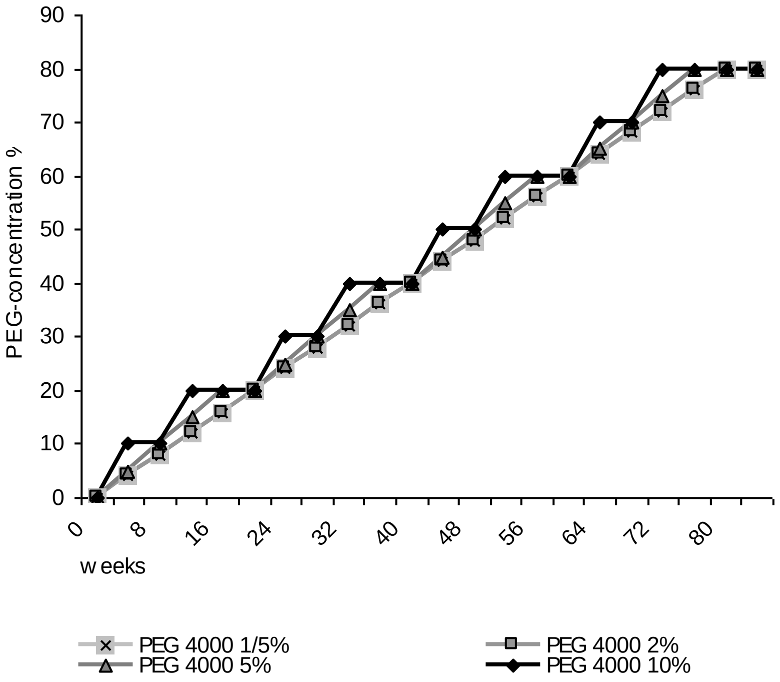

Figure 4-47. The conservation programmes.

Vasa oak specimens, of the same size as those used in the preceding experiments (4.3. and 4.4.) were used for the experiment, and were cut from a deck-batten removed from the same area of the Vasa hull as those removed earlier for experimental work. The transverse surfaces of the specimens were painted with Araldite as in the previous experiments. The experimental set-up was the same as the one described in 4.2. (figure 4-1).

Four 800 ml beakers placed in a thermostatic bath were used for the experiment. Each test specimen was weighed, and measurements of dimensions were made, for monitoring the shrinkage during the drying phase. During the conservation procedure the volume of each specimen was derived from weight values of submerged weighing of each specimen into its individual solution together with weighing the specimen on a balance in the laboratory atmosphere and also measuring the density of the solution at the temperature of the experiment. Those monitoring activities were decided to be performed once a month. Each specimen was placed in its individual beaker with a measured volume of pure water.

The thermostatic bath was heated stepwise during a period of three weeks to a temperature of 65°C, before supplying of PEG increments was started. The endpoint of the conservation programmes was fixed to 80% PEG added to the measured volume of water. As the water content of the specimens was not included in the calculations, the increase of PEG concentration during the conservation period was slower than the sum of added increments, and the final concentration reached was lower than the endpoint of the conservation programme (figure 4-48).

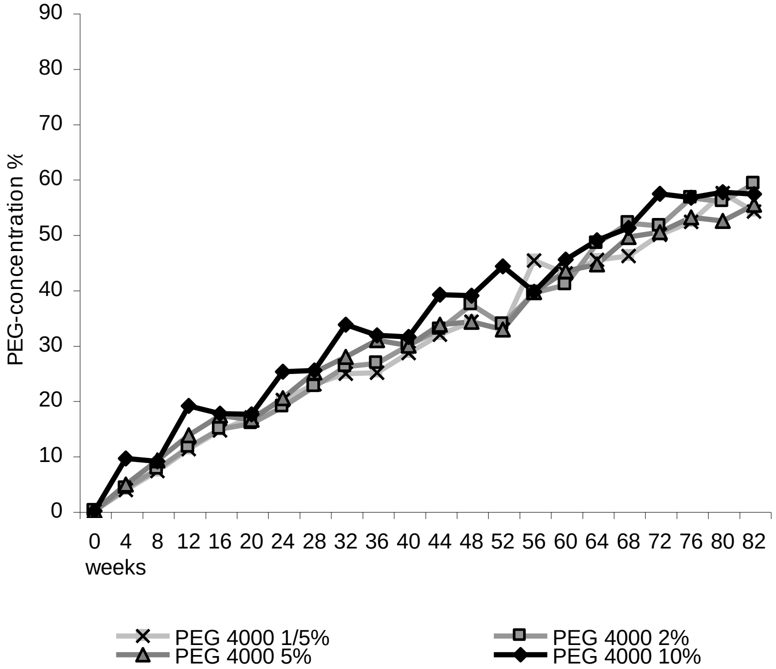

Figure 4-48. Actual PEG-concentration of the conservation baths during the conservation period.

The graphs of the sum of PEG and water ratio all show declining gradients during the first c. 55 weeks of the conservation period. After that there was a phase of stability that lasted c. 10 weeks and then a raise of the ratio of the sum of PEG and water content during the concluding part of the conservation process. With a starting water ratio value of 150%, the specimen of the 10% increment programme suffered a loss of PEG and water ratio of 38 percentage units that was the greatest loss among the specimens. The specimen of the 2% increment programme was the next in turn, with a loss of PEG and water ratio equalling 32 percentage units. The 5% increment specimen came next and showed a loss of 24 percentage units PEG and water ratio and finally the 1/5% increment programme specimen with a loss of PEG and water content equalling 18 percentage units ratio. It may be noted that the graphs of the 2% and the 5% increment specimens had changed places as compared with the order of the increment programmes.

The gain in PEG and water ratio during the terminating period of the conservation process was equally large for all four specimens and amounted to c. 5 percentage units PEG and water ratio (figure 4-49).

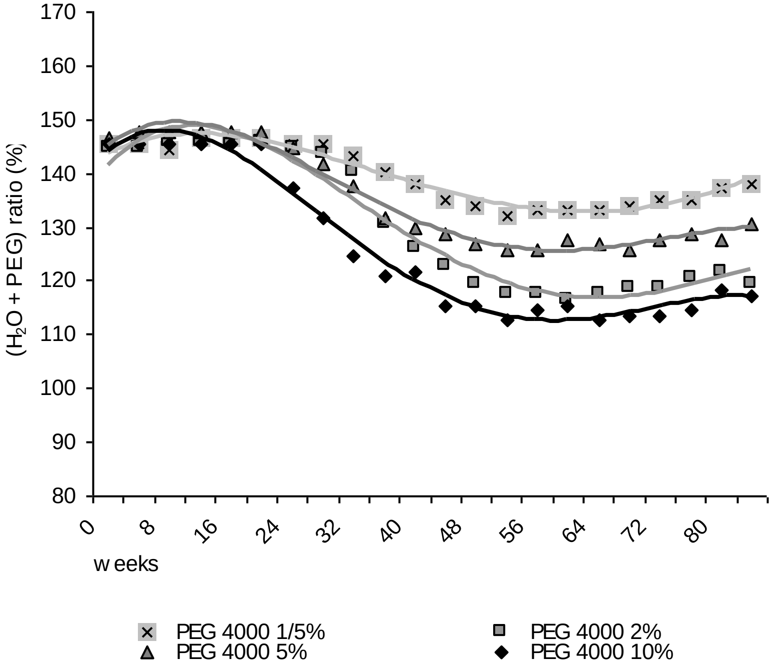

Figure 4-49. (PEG and water)-ratio of oak specimens at conservation programmes of 1/5, 2, 5 and 10% PEG 4000 increments respectively, evenly distributed during the 82 weeks conservation period.
Trend-lines; least square fittings.

The PEG ratios of the specimens were determined after a more than two years drying programme, ending with drying in a low RH-level atmosphere, created with silica gel. The PEG ratios of the specimens from the 1/5%, the 2%, the 5% and the 10% increment programmes amounted to 54, 55, 59 and 62%, respectively. This equalled a proportion of 35, 35, 37 and 38% of PEG 4000, respectively in the dry matter of the specimens taken in the same order. The mean PEG concentrations inside the test specimens at the termination of the conservation experiment amounted to 39, 46, 45 and 53%, corresponding to differences against the PEG-concentrations of the surrounding conservation solutions of 15, 13, 10 and 4 percentage units, respectively.

The unexpected change of places between the 2 and 5% increment graphs of (H_2O + PEG)-ratios may be the effect of slight differences of wood anatomy between the specimens depending on the fact that these were cut parallel to each other from the same 10 cm length piece of the deck-batten.

As deviating from the above stated order the plotting of the calculations of the volumes of the specimens at the occasions of measurements places the graphs in the same order as the increment sizes of the programmes. This places the graph of the 1/5% increment programme specimen at the top and the graph of the 10% increment specimen at the bottom as with the graphs of PEG and water content. The graphs of the 2% increment specimen and the 5% increment specimen lands in between the two others and very close to each other, but this time with the graph of the 2% increment specimen on top of the graph of the 5% increment specimen.

The 1/5% increment specimen shows a swelling tendency during the conservation process despite the loss of 18 percentage units in the sum of PEG and water content at the middle of the conservation period. The swelling tendency was more pronounced during the concluding part of the conservation process when the there was a regain of PEG and water content equalling c. 5 percentage units. The swelling amounted to between 1 and 2% at the end of the conservation process.

The other specimens show a shrinkage behaviour that levelled out during the concluding phase of the conservation period. The specimens of the 2 and 5% increment programmes each ended up with a shrinkage of between 1 and 2%. The total shrinkage of the specimen of the 10% increment programme amounted to c. 4% (figure 4-50).

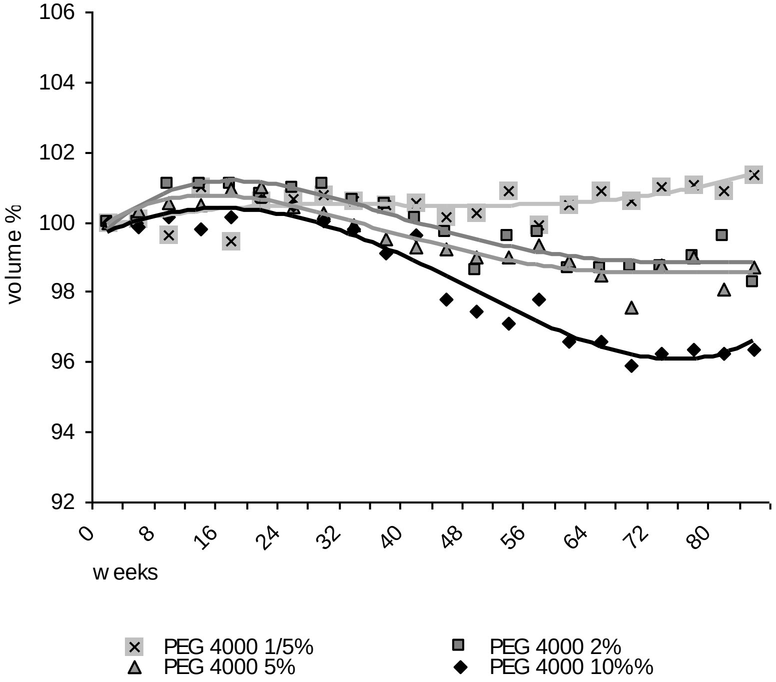

Figure 4-50. Volume shrinkage or swelling of oak specimens at conservation programmes of 1/5, 2, 5 and 10% PEG 4000 increments respectively, evenly distributed during the 82 weeks conservation period. rend-lines; least square fittings.

For further evaluation of the reaction of a piece of waterlogged archaeological oak wood to different conservation programmes the graphs of PEG and water ratio and the graphs of volume registration of each of the specimens of the 82 weeks programmes is compared with the graphs of these evaluation parameters of the PEG 4000 series conservation programmes described in the section 4.4. (figures 4-51 – 4-58).

A comparison between the graphs of the PEG and water content of the specimens of the PEG 4000 experiment described in the section 4.4. and the 1/5% increment specimen of the experiment at hand shows that the graph of this specimen fits neatly between the 1/12% and the 1/3% increment specimens of that programme (figure 4-51).

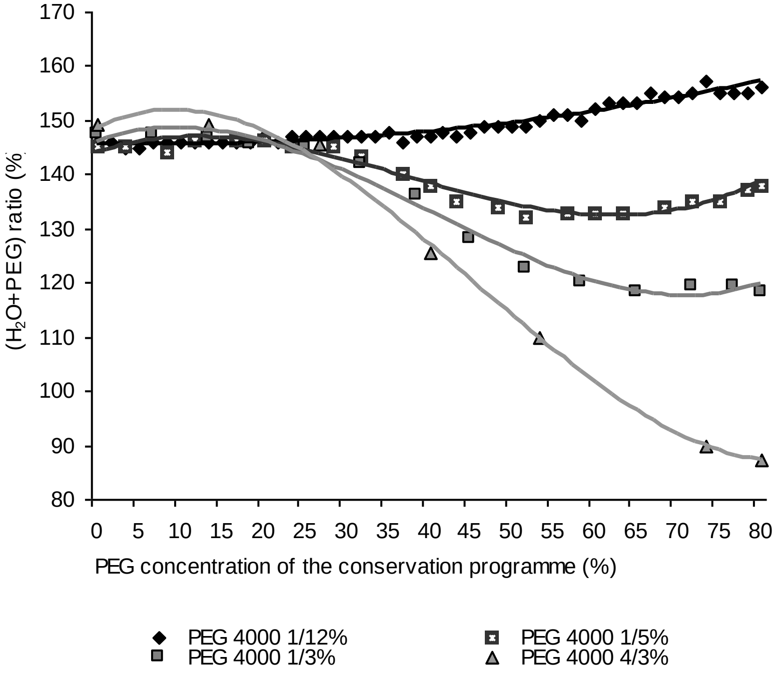

Figure 4-51. (PEG and water)-ratio of oak specimens at conservation programmes of 1/12, 1/5, 1/3 and 4/3% PEG 4000 increments respectively. Trend-lines; least square fittings.

The series of graphs from bottom to top expresses both growing duration of the conservation period and smaller PEG increments per administering occasion. This seems to benefit an equilibrium situation between the PEG and water contained inside the specimens and the PEG and water of the surrounding conservation solution.

The graph of the 1/5% increment specimen assumes a shape resembling that of the 1/3% increment specimen although it shows an upward direction during the concluding part of the conservation programme. This places the 1/5% increment specimen in behaviour category 3 where PEG and water content is concerned while the 1/3% increment specimen belongs to behaviour category 2.[102]

However, the regain of PEG and water content during the latter phase of the conservation programme may be interpreted as an indication of liquid transport of conservation solution into the specimen. The cause of this may be that a low pressure may have been established inside the specimen by diffusion of water molecules from the wood structure into the conservation solution that had not been compensated by diffusion of PEG-molecules in the opposite direction.

The graph of the volume changes of the 1/5% increment specimen has been represented together with the graphs of the volume changes of the specimens of the PEG 4000 experiment described in the section 4.4. (figure 4-52). As has been noted (p 99) this specimen shows a swelling tendency that is especially pronounced during the concluding phase of the conservation programme. At the comparison with the PEG 4000 experiment described in section 4.4. the graph of the 1/5% increment specimen showed a closer resemblance with that of the specimen of the 1/12% increment programme although the total swelling was about half of that of this specimen. This places the 1/5% increment specimen together with the 1/12% increment specimen in the behaviour category 1, where volume is concerned.[103]

Although the 1/5% increment specimen in total showed a loss in PEG and water ratio during the conservation procedure, it ended up with a swelling of c.1.5%. This swelling took place during a period of regaining some of the weight previously lost during the conservation process.

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[102] This dissertation, p 102.

[103] This dissertation, p 114.

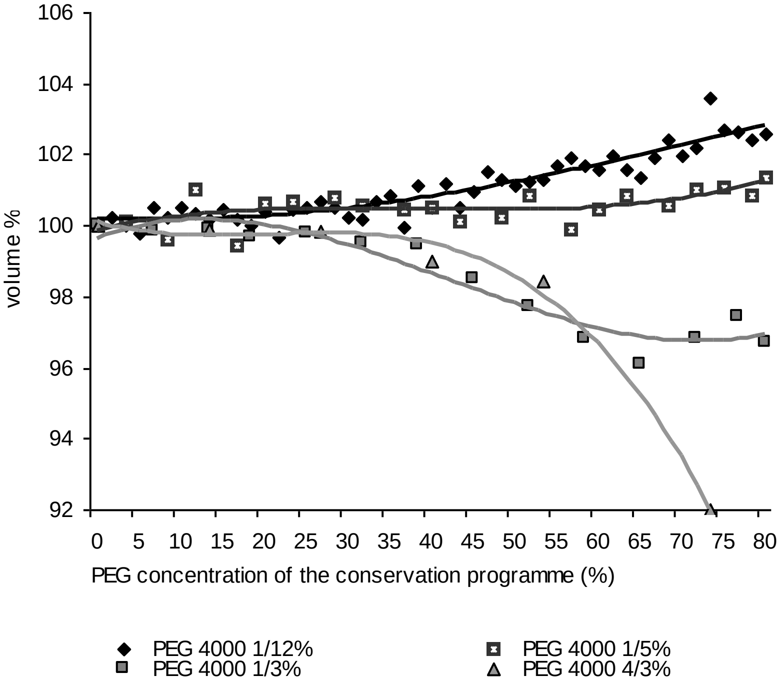

Figure 4-52. Volume shrinkage or swelling of oak specimens at conservation programmes of 1/12, 1/5, 1/3 and 4/3% PEG 4000 increments respectively. Trend-lines; least square fittings.

When the graph of PEG and water content of the 2% increment specimen is presented in the same diagram as the PEG 4000 specimens of the experiment described in the section 4.4. it lands up close to the graph of the 1/3% increment specimen (figure 4-53). The graph of the 2% increment specimen assumes a shape resembling that of the 1/3% increment specimen, but in contrast to this it shows an upward gradient during the concluding part of the conservation programme. This places that specimen in behaviour category 3 where PEG and water content is concerned while the 1/3% increment specimen belongs to behaviour category 2.[104]

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[104] This dissertation, p 102.

As with the 1/5% increment specimen the 2% increment specimen regains PEG and water during the concluding phase of the conservation period. As was assumed with the 1/5% increment specimen this may indicate lowering of the pressure inside the specimen by faster diffusion of water molecules from the interior of the specimen compared to the diffusion of PEG-molecules in the opposite direction. The lowered pressure might make possible liquid transport of conservation solution into the wood structure of the specimen.

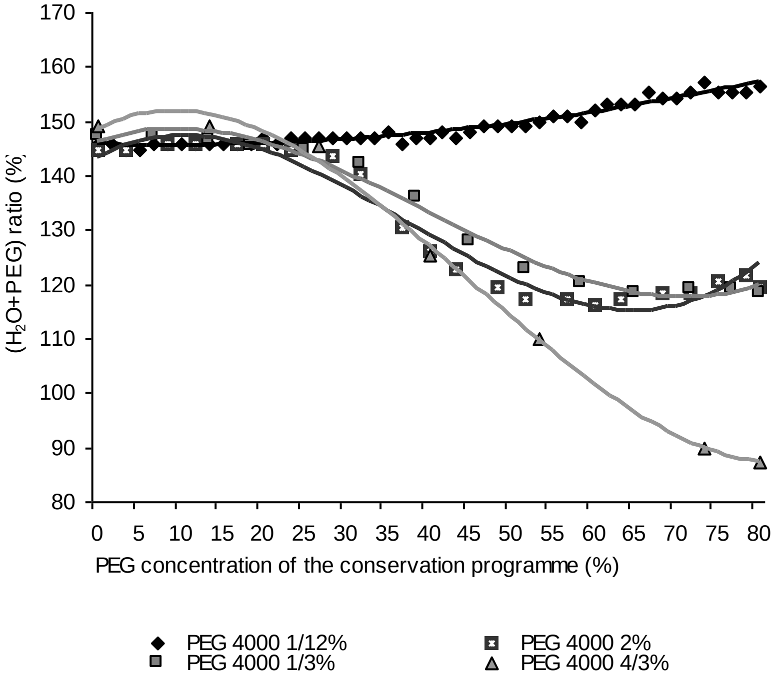

Figure 4-53. (PEG and water)-ratio of oak specimens at conservation programmes of 1/12, 2, 1/3 and 4/3% PEG 4000 increments respectively. Trend-lines; least square fittings.

The graph of the volume changes of the 2% increment specimen has been represented together with the graphs of the volume changes of the specimens of the PEG 4000 experiment described in the section 4.4. (figure 4-54). At the comparison with those the graph of the volume of the 2% increment specimen shows the closest resemblance with the graph of the 1/3% specimen. The two graphs run very much on parallel to each other with the 2% increment specimen above the 1/3% increment specimen by c. two percentage units. This places the 2% increment specimen together with the 1/3% increment specimen in the behaviour category 2 where volume is concerned.[105]

Although the 2% increment specimen in total showed as large a loss in PEG and water ratio during the conservation procedure as the 1/3% increment specimen, it ended up with c. 2 percentage units less shrinkage than the 1/3% increment specimen.

The other difference in treatment is the duration of the conservation period where the 2% increment specimen is treated during 1.5 years while the 1/3% increment specimen is treated during c. 1 year.

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[105] This dissertation, p 114.

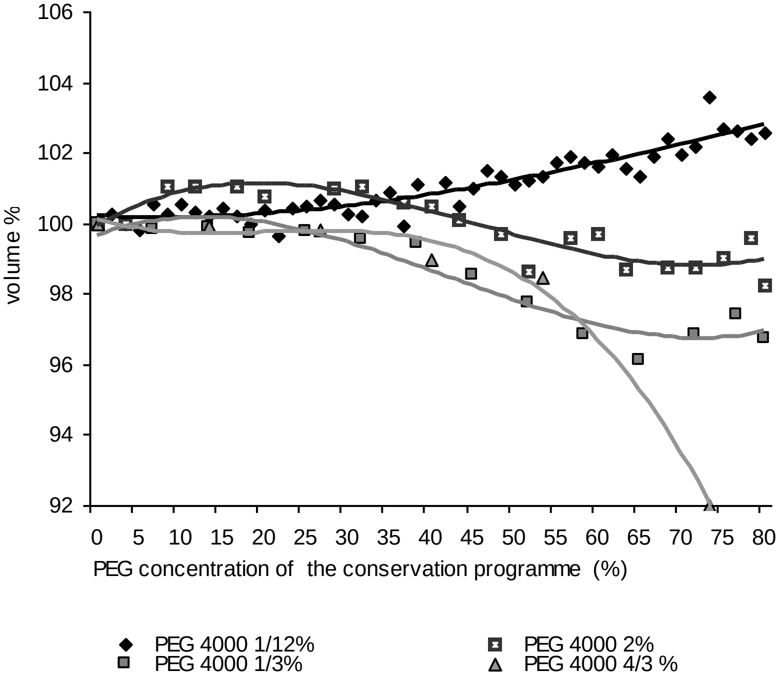

Figure 4-54. Volume shrinkage or swelling of oak specimens at conservation programmes of 1/12, 2, 1/3 and 4/3% PEG 4000 increments respectively. Trend-lines; least square fittings.

When the graph of PEG and water content of the 5% increment specimen is presented in the same diagram as the graphs of the PEG 4000 specimens of the experiment described in the section 4.4. graph of the specimen of the programme with 5% increment increase of PEG concentration administered every five weeks of the experiment at hand lands up close to the graph of the 1/3% increment specimen of that experiment (figure 4-55). The graph of the 5% increment specimen assumes a shape resembling that of the graph of the 1/3% increment specimen although it shows an upward gradient during the concluding part of the conservation programme. This places that specimen in behaviour category 3 where PEG and water content is concerned while the 1/3% increment specimen belongs to behaviour category 2.[106]

As with the 2% increment specimen the 5% increment specimen regains PEG and water during the concluding phase of the conservation period. As was assumed with the 2% increment specimen this may indicate lowering of the pressure inside the specimen by faster diffusion of water molecules from the interior of the specimen than the diffusion of PEG-molecules in the opposite direction. The lowered pressure might make possible liquid transport of conservation solution into the wood structure of the specimen.

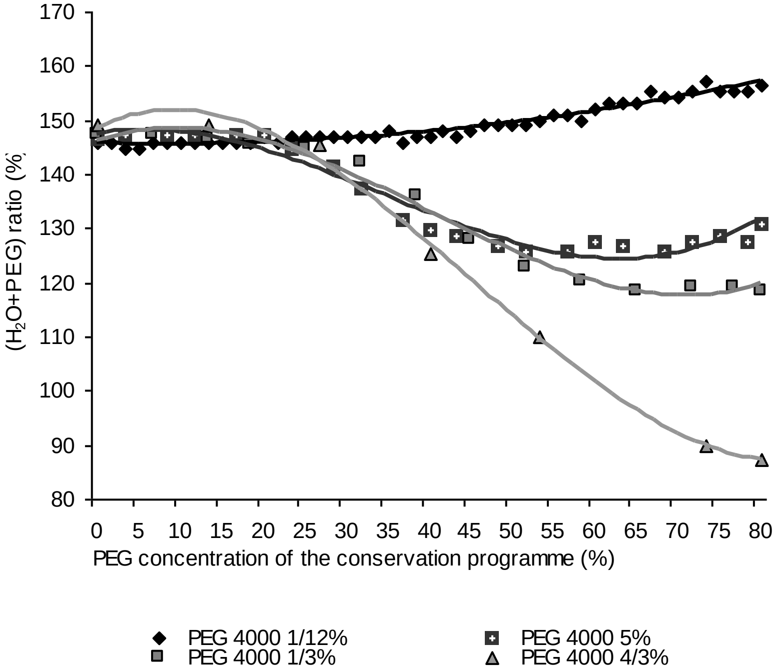

Figure 4-55. (PEG and water)-ratio of oak specimens at conservation programmes of 1/12, 5, 1/3 and 4/3% PEG 4000 increments respectively. Trend-lines; least square fittings.

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[106] This dissertation, p 102.

The graph of the volume changes of the 5% increment specimen has been represented together with the graphs of the volume changes of the specimens of the PEG 4000 experiment described in the section 4.4. (figure 4-56). At the comparison with those the graph of the volume of the 5% increment specimen shows the closest resemblance with the graph of the 1/3% specimen. The graphs of their volumes run very much on parallel to each other with the 5% increment specimen above the 1/3% increment specimen by c. two percentage units. This places the 5% increment specimen together with the 1/3% increment specimen in the behaviour category 2 where volume is concerned.[107]

The 5% increment specimen showed in total c. 20 percentage units loss in PEG and water ratio during the conservation procedure while the 1/3% increment specimen ended up with c. 30 percentage units loss. The 5% increment specimen also showed a total volume shrinkage of c. 1% while the 1/3% increment specimen had shrunk c. 3% during the conservation process.

The graphs of the 5% increment specimen (figures 4-55 and 4-56) resemble those of the 2% increment specimen (figure 4-53 and 4-54).

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[107] This dissertation, p 114.

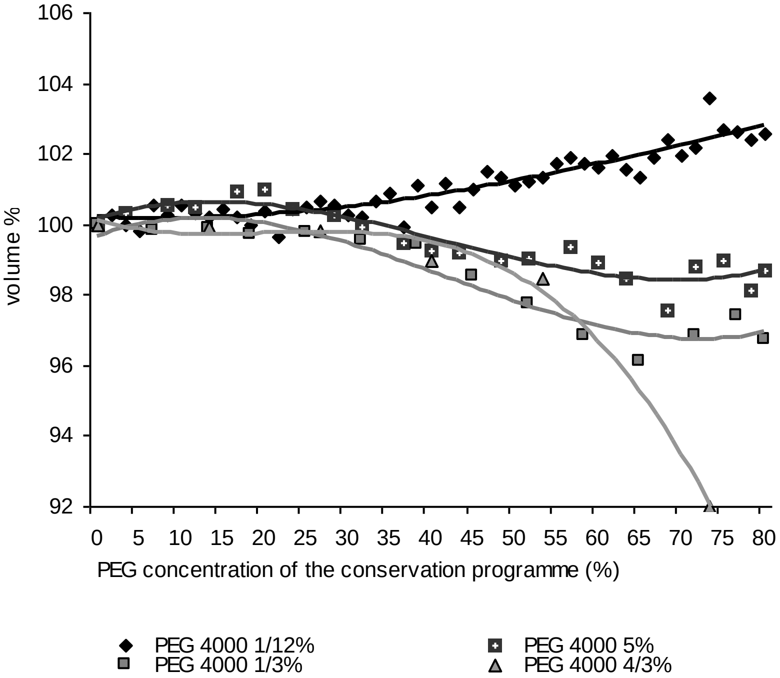

Figure 4-56. Volume shrinkage or swelling of oak specimens at conservation programmes of 1/12, 5, 1/3 and 4/3% PEG 4000 increments respectively. Trend-lines; least square fittings.

The graph of the PEG and water content of the10% increment specimen is the only one that lands below the 1/3% increment specimens graph in the diagram of the PEG 4000 specimens of the experiment described in the section 4.4. (figure 4-57). Although the graph of the 10% increment specimen takes a faster downward course than the graph of the 1/3% increment specimen the two run on parallel during two thirds of the conservation period with the graph of the 10% increment specimen c. 10 percentage units PEG and water ratio below the graph of the 1/3% increment specimen. The graph of the 10% increment specimen reverses its gradient during the concluding part of the conservation period and meets with the graph of the 1/3% increment specimen at the endpoint of the conservation period. This places the 10% increment specimen in behaviour category 3 where PEG and water content is concerned while the 1/3% specimen belongs to the behaviour category 2.[108]

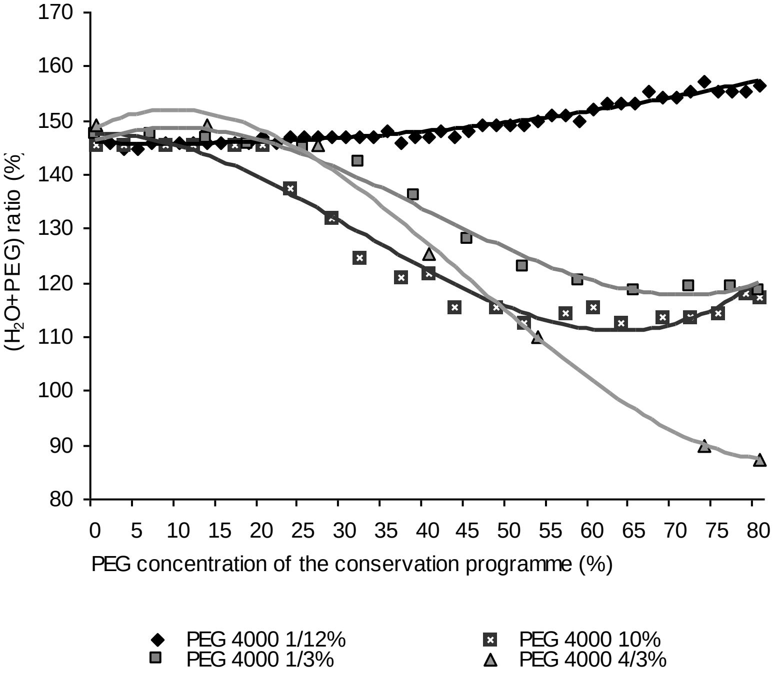

Figure 4-57. (PEG and water)-ratio of oak specimens at conservation programmes of 1/12, 10, 1/3 and 4/3% PEG 4000 increments respectively. Trend-lines; least square fittings.

As with the 5% increment specimen the 10% increment specimen regains PEG and water during the concluding phase of the conservation period. As was assumed with the 5% increment specimen this may indicate lowering of the pressure inside the specimen by faster diffusion of water molecules from the interior of the specimen than the diffusion of PEG-molecules in the opposite direction. The lowered pressure might make possible liquid transport of conservation solution into the wood structure of the specimen.

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[108] This dissertation, p 102.

The graph representing the volume of the10% increment specimen follows closely the graph of the volume of the 1/3% increment specimen of the PEG 4000 experiment described in the section 4.4. during two thirds of the conservation programme (figure 4-58). However, the two graphs diverge with the graph of the 1/3% increment specimen taking a position above the graph of the 10% increment specimen during the concluding phase of the programme. The two graphs show almost identical shapes, and fit with behaviour category 2 where volume is concerned.[109]

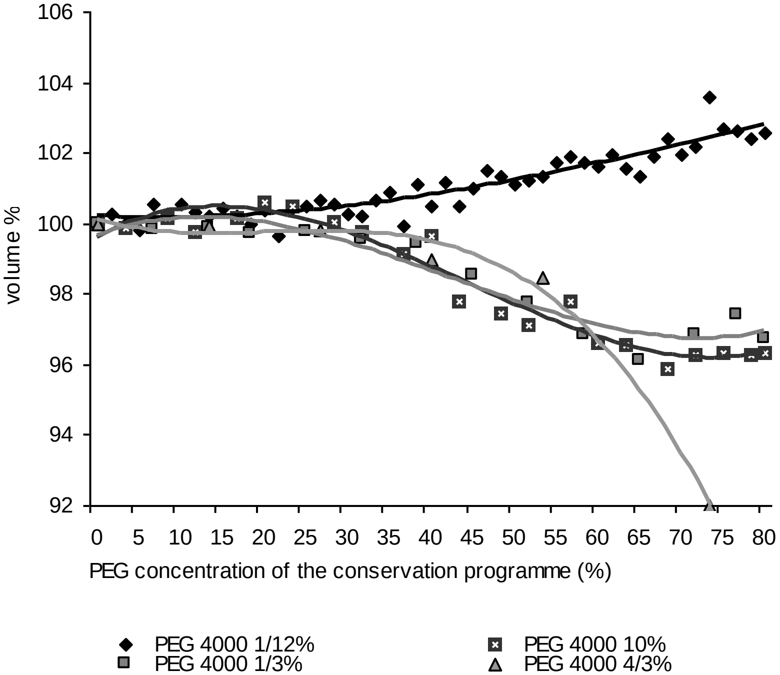

Figure 4-58. Volume shrinkage or swelling of oak specimens at conservation programmes of 1/12, 10, 1/3 and 4/3% PEG 4000 increments respectively. Trend-lines; least square fittings.

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[109] This dissertation, p 114.

When enlarging the PEG increments the experiment demonstrates a growing loss of PEG and water content and a growing degree of shrinkage of the test specimens. The inconsistency of order between the two specimens in the middle of the increment series that in the case of PEG and water content change places with each other and where shrinkage is concerned run unexpectedly close to each other, may be attributable to the circumstance that all four test specimens have been cut parallel to each other from the deck-batten. This means that they do not have equal wood anatomical characteristics and thus may react differently to the conservation process.

Compared to the specimens of the PEG 4000 experiment described in the section 4.4. the specimens of the experiment at hand — like the 1/3% increment specimen of that experiment — all fall into the behaviour category 2, where PEG and water content is concerned. This behaviour category says: "Weight loss during the entire length of the conservation programme or during parts of this interchanging with periods of no weight change".[110] The concluding period of the conservation programme of every one of these specimens is a period of no weight change.

The characteristics of volume changes during the conservation period of the specimens are not as homogenous as their characteristics of changes of PEG and water content. The 1/5% increment specimen resembles the 1/12% increment specimen in showing a category 1 behaviour with "swelling during the entire duration of the conservation programme or during parts of this interchanging with periods of constant volume".[111]

The characteristics of volume change during the conservation period for the specimens of 1/3, 2, 5, and 10% increment sizes show category 2 behaviour with "shrinkage during the entire duration of the conservation programme or during parts of this interchanging with periods of constant volume".[112] The concluding period of the conservation programme of every one of these specimens is a period of no change of volume.

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[110] This dissertation, p 102.
[111] This dissertation, p 114.
[112] This dissertation, p 114.

As a general conclusion of the two experiments 4.4. and 4.5. may be stated that a long duration of the conservation period is an important feature of a successful immersion conservation with PEG 4000 of waterlogged archaeological oak of moderate degree of deterioration.

4.6. Conclusions: Development of the immersion treatment procedure

In the section “development of the immersion treatment procedure“ temperature and PEG-concentration programmes were studied in order to define a conservation programme for the immersion treatment of the Vasa wooden material. This was performed in a series of laboratory experiments by varying the numerical values and varying the duration of action of the selected values of these parameters. The conservation programme developed by Morén & Centervall was used to identify the parameters of importance to the immersion process. Weight change and change of volume were selected as monitoring parameters.

The importance of the experiments was stressed by the fact that test material from the Vasa hull was granted after the initial experiment had been performed.

The initial experiment, 4.2. “Laboratory testing of the Morén & Centervall conservation programme” tested a temperature programme starting at room temperature and ending at the pre-chosen temperature of 65°C, compared to a stable temperature of 65°C during the whole process. The experimental set-up included four different initial PEG-concentrations of 5, 10, 20, and 40% at each temperature programme.

Due to extensive weight loss of the test specimens at the temperature raising programme explained by the fact that water was leaving the specimens because a temperature gradient with lower temperatures inside the wooden specimens than in the surrounding solution was created at every raise of the temperature of the solution. This temperature gradient accelerated the velocity of water molecules leaving the wooden specimens and moving towards the zone with a higher temperature. The experiment led to abandoning of the temperature raising programme and choosing of a stable temperature level for the remaining conservation experiments.

The same series of initial PEG-concentrations as were used in the experiment 4.2. were, however, used at the succeeding experiment, 4.3. "further development of the immersion conservation programme". In that experiment a series of test specimens were preserved in each of the conservation baths. In order to map the conservation process, one test specimen was removed from the conservation bath at pre-chosen PEG-concentrations of the conservation programmes. The test specimens removed were dried, that made possible calculation of the quantity of PEG and water in each specimen at the occasion of removal from the conservation solution. From these quantities the PEG-concentration of an assumed PEG solution inside the wood of each test specimen was calculated. This provided a series of concentrations describing the development of the conservation process in the wood in relation to each of the conservation programmes.

Registered weight gain of test specimens during some of the pre-designed conservation periods was the basis for an assumption that liquid transportation of conservation solution into the test specimens occurred during those periods.

The next experiment, 4.4. "Experimenting with the size of daily administered PEG increments for various PEG's and comparing oak from the Vasa hull with seasoned and waterlogged recent oak" used an experimental set-up with the PEG's 4000, 1500, 1000, and 600. The increment sizes selected were: 1/12%, 1/3% and 4/3%. Since the increments were administered daily, the different increment sizes produced different duration of the time intervals for the conservation procedures (4 years, 1 year and c. 3 months). The diagrams of weight changes and changes of volume of the test specimens provide the information that:

- exchange of water in the wood for PEG involves a more careful procedure the more slowly the PEG-concentration of the conservation solution is raised,
- the exchange proceeds at a higher speed with the PEG's of lower molecular weights, and
- the exchange of water in the wood for PEG proceeded faster by recent oak than by the Vasa oak.

Conclusion:

The best way to avoid tension in the wood during the conservation procedure is to use PEG of as low molecular weight as possible and to raise the PEG-concentration of the conservation solution as slowly as possible.

The last experiment presented, 4.5. “Experimenting with variations of time intervals for administering PEG increments of varying sizes for conservation programmes of equal duration and equal end concentration”, was performed in order to investigate the sensitivity of the conservation process to larger PEG increments at longer time intervals compared to small PEG increments on a daily basis. PEG 4000 was selected for the experimental set-up. An increment series of 1/5%, 5 days a week, 2%, every 2 weeks, 5%, every 5 weeks and 10%, every 10 weeks was tested. The experiment went on for 1.5 years.

The result of the experiment was that according to evaluation both by the weight change related parameter and with the change of volume parameter the graphs came out in the same order as the increment series with the 1/5% increment as the better choice. Even compared to the 1/3% increment programme the 1/5% increment programme showed less weight loss and less shrinkage during the conservation period.

5. Characteristics of the Wood-Polymer Composite

PEG's are highly hydrophilic substances.[113] This makes them water soluble and hygroscopic. Wood is also a hygroscopic material. This made it important to investigate this property for the wood-PEG composite material created by conservation of archaeological wood from wet sites with PEG's, compared to pure PEG's, and to untreated wood.

5.1. Hygroscopicity of PEG of different molecular weights

To investigate how the hygroscopicity would work out in practise for the PEG's of the molecular weights that were likely to be discussed as dimension stabilizing preservatives for the wet archaeological wood of the Vasa conservation project, an experiment was performed, involving PEG's 4000, 1500, 600 and 400.

The experimental set-up consisted of a series desiccators (figure 5-3) that were charged with saturated solutions of calcium nitrate, sodium bromide, sodium nitrite, sodium chloride, ammonium sulphate, and potassium bromide, respectively as climatic chambers (table 5-I). These salts were chosen from values in literature,[114] of the relative humidity (RH) produced in a climatic chamber above the surfaces of the saturated solutions of the salts to gain an even distribution of measuring points covering the RH range of interest to the drying of the Vasa wood. To check the RH values a calibrated hair hygrometer was placed in each of the climatic chambers.

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[113] Baily and Koleske, 1991, p 153.

[114] Lange, 1961.

Salt	RH %	Note
$Ca(NO_3)_2$	55	Interpolated 1)
NaBr	58	Abbreviated 2)
$NaNO_2$	66	
NaCl	76	Abbreviated 2)
$(NH_4)_2SO_4$	81	
KBr	84	

Table 5-I. Table of RH values in the atmosphere above saturated solutions of the salts at c. 20°C, listed in the handbook (Lange). The RH value is selected between the values at 24 and 18.5°C respectively; the RH value was selected as the abbreviated RH value at 20.7°C .

The experiment was performed by preparing a small volume of PEG solution of a specified concentration by weighing an amount of dried PEG in a weighing glass with a lid and then adding an amount of water to the PEG in the weighing glass, weighing the two components together and then mixing them thoroughly without using any stirring device. The weighing glass together with its removed lid then was placed in the special RH atmosphere of the climatic chamber for a specified time interval.

At the end of the time interval the lid was replaced on the weighing glass with the PEG solution test sample, and the weighing glass was removed from the climatic chamber and weighed on an analytical balance. If the test sample had either gained weight or lost weight, another test PEG solution was prepared with a concentration more close to the equilibrium concentration at the RH value chosen. This procedure was repeated until a sample of stable weight had been found. The stable weight test samples were considered to be equivalent to the equilibrium concentrations of PEG 4000, 1500, 1000, 800, 600 and 400 at each of the six chosen RH values (table 5-II).

RH %	PEG 4000 %	PEG 1500 %	PEG 1000 %	PEG 800 %	PEG 600 %	PEG 400 %
55	99	98	95	91	90	88
58	99	98	94	88	88	86
66	99	98	88	85	84	82
76	98	93	76	76	74	73
81	97	88	72	70	69	69
84	97	88	72	69	69	68

Table 5-II. Equilibrium concentrations of PEG-solutions at c. 20°C.

The water fraction of the PEG solutions is plotted to describe the reaction of the PEG's to raising RH values of the surrounding atmosphere (figures 5-1, 5-2).

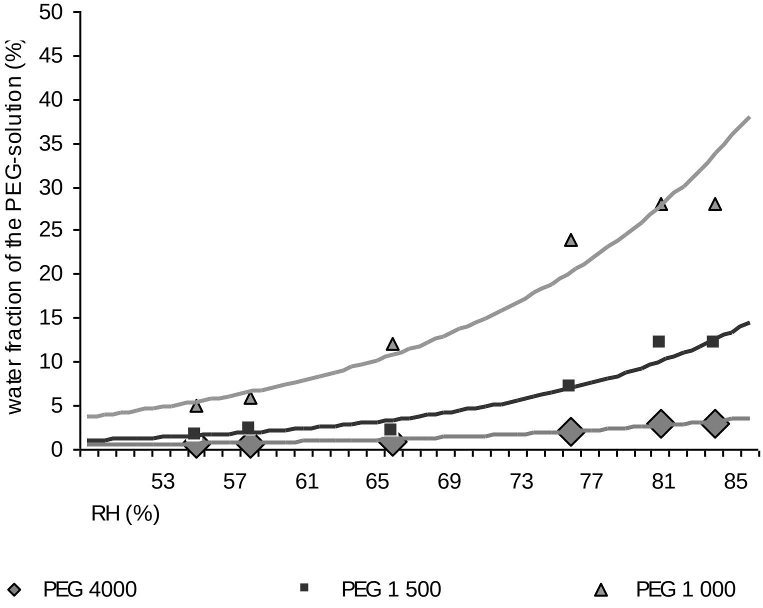

Figure 5-1. Diagram of equilibrium water content of PEG 4000, 1500, and 1000-solutions from 55 to 84% RH at 20°C. Trend-lines; least square exponential fittings.

The graph of the water fraction of the PEG 4000 shows a very faint upwards slope during the RH-interval examined. The low hygroscopicity was one of the characteristics that made PEG 4000 be considered the PEG best suited as preservative for wood from archaeological wet sites. PEG 1500 shows a similar hygroscopicity level as PEG 4000 at 55, 58, and 66% RH but tends to deviate from this at higher RH-levels.[115]

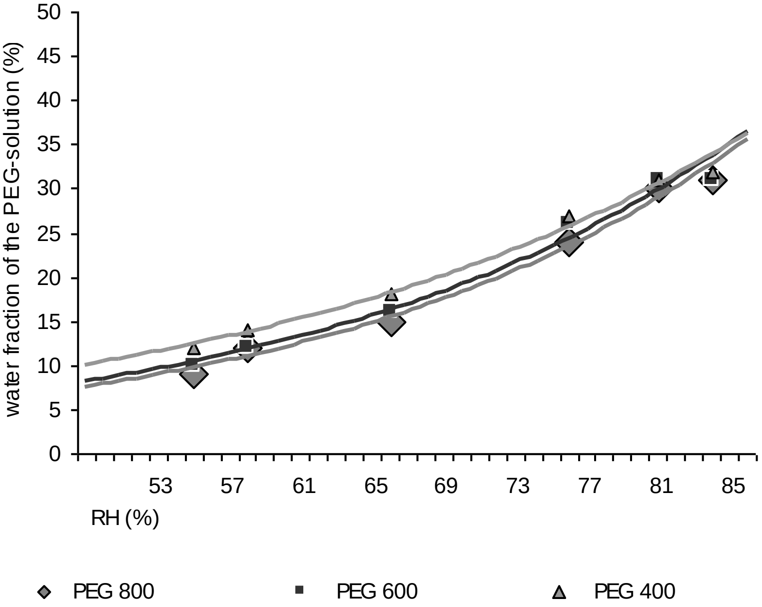

Figure 5-2. Diagram of equilibrium water content of PEG 800, 600 and 400-solutions from 55 to 84% RH at 20°C. Trend-lines; least square exponential fittings.

The group of lower molecular weight PEG's contain larger amounts of water at lower RH values, and their graphs show uniformly developing upward slopes.

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[115] Håfors, 2001, pp 64-65.

5.2. Hygroscopicity of a conserved oak specimen from the VASA under water site

As PEG 4000 was considered the PEG best suited for conservation of wooden objects from wet archaeological sites, mainly depending on its allegedly low hygroscopicity, an experiment was designed to investigate how a conserved and dried specimen containing PEG 4000 would react to an ascending series of RH values of the atmosphere of the climatic chamber used for investigation of the hygroscopicity of the PEG's. For the experiment a section of c. 1.5 x 1.5 x 7 cm was cut from oak7 of the experiment described in 4.2. A similarly sized untreated specimen of oak belonging to another piece of timber found on board the Vasa was chosen as reference.

Both of the specimens were placed in separate weighing glasses, each with a lid. The lids were kept together with the weighing glasses in the climatic chamber during the experiment. Before the experiment was started the specimens were dried to equilibrium at low RH, produced in the climatic chamber by silica gel. The dried section of oak7 weighed c. 15g, and the dried reference specimen weighed c. 10g. The exact weights of the specimens after the drying period were taken as basis of calculation of the absorbed amount of water.

The atmospheres chosen ranged from 55 to 98% RH. Apart from these initial and final levels, the levels of equilibrium chosen were 66, 76, 81 and 91 % RH. The RH atmospheres chosen were, as before attained by saturated solutions of calcium nitrate, sodium nitrite, sodium chloride, ammonium sulphate, sodium carbonate and calcium sulphate (gypsum). During the conservation period the humidifying system of store rooms and exhibition areas for the Vasa wooden material consisted of finely sprinkled water droplets into the atmosphere why a period of humidifying of the test atmosphere with pure water was put in between the 91% RH (sodium carbonate) and the 98% RH (calcium sulphate) levels.

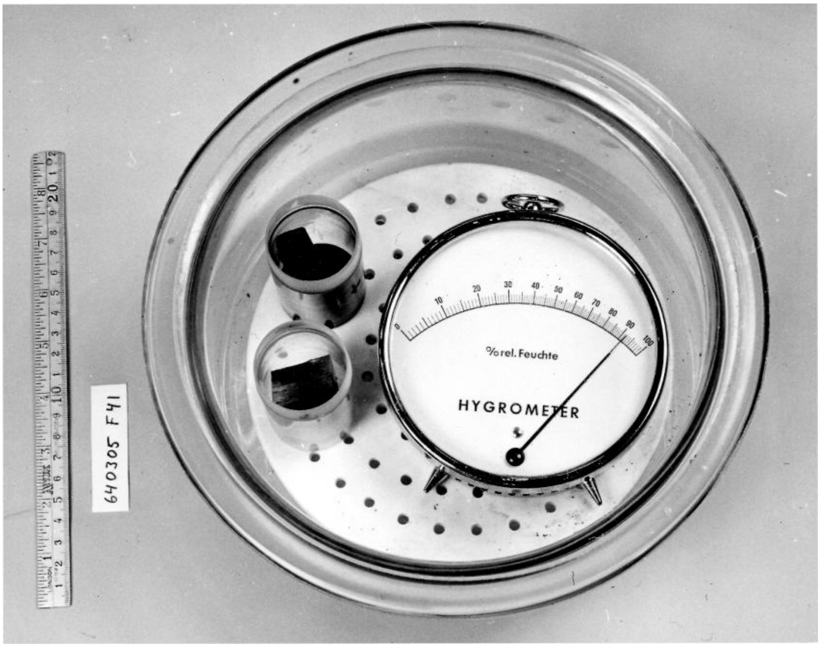

Figure 5-3. Experimental arrangement of hygroscopicity test.

When the dry weights of the specimens had been established the experiment was started by placing the test and reference specimens in the climatic chamber with the 55% RH atmosphere. Monitoring was performed by weighing the specimens at regular intervals in the same way as at the experiment with the pure PEG's (see 5.1.). This time, however, the weighings were to be performed until stable weight had been attained by both of the specimens at each RH. This happened during a period of c. three months, at 55, 66 and 76% RH respectively. In the climatic chamber with the 81% RH atmosphere the specimens stayed for c. seven months before both of them had reached stable weights. They were then moved to the climatic chamber with the 91% RH atmosphere. After a couple of months the conserved specimen started to leak a liquid that was collected in the weighing glass around the lower part of the specimen (figure 5-3, the uppermost weighing glass in the photograph). The experiment was continued at 91% RH for a total of 12 months. The conserved specimen, however, did not reach stable weight, despite this long period of time.

Pure distilled water was exchanged for the saturated sodium carbonate solution, resulting in a somewhat higher RH reading on the hygrometer than with the saturated sodium carbonate solution. The experiment was continued for 10 months when both of the specimens had reached stable weights, and the preserved specimen had maintained stable weight for five weeks.

A saturated calcium sulphate solution was exchanged for the pure water in the climatic chamber as a RH stabilizer. The final period of the experiment that was performed at 98% RH was continued for six months. The experiment was terminated before equilibrium weight had been attained by the PEG 4000 treated specimen.

The total water content of each of the specimens was calculated at the occasions of changing the RH atmosphere of the climatic chamber. It had only been possible to express the water content of the reference specimen in the usual term of water ratio during the experimental period as the fibre weight of the PEG treated specimen, being a section of a conserved larger specimen, was not known at the beginning of the experiment. This could be calculated by subtracting the weight of the original PEG content of the conserved specimen from its known dry weight. For this to be performed the PEG remaining in the specimen had to be determined, and also the PEG content of the liquid that had formed outside the conserved specimen.

The first step in calculating the original PEG content and the fibre weight of the PEG treated specimen was to separate the oak-PEG composite specimen from the liquid that had gathered at the bottom of the weighing glass. The amount of liquid was c. 9g. Analysing the liquid gave the information that it consisted of a c. 37% PEG solution. The PEG must have left the oak-PEG composite specimen and changed the dry weight of that specimen during the experiment. In order to obtain the PEG-fraction of the oak-PEG composite and for calculation of the water ratio, the PEG was extracted from the oak-PEG composite specimen. To be sure not to loose any material this was performed by extraction of the whole specimen in water for as many times as was needed to get the PEG out of the wood. The 33rd extraction gave only traces of PEG, and therefore led to the decision to terminated this activity.

The generally adopted basis of calculation, the dry fibre weight, was obtained by subtracting the total weight of extracted and leaked-out PEG of the oak-PEG composite specimen from the dry weight of the specimen at the beginning of the experiment. The PEG fraction in the dry weight of the conserved specimen was calculated to be c. 50% at the beginning of the experiment and c. 30% when the experiment was terminated. Depending on the leakage of PEG from the conserved specimen at 91% RH it was not possible to calculate neither PEG fraction nor water ratio of the specimen.

The water ratio of the not conserved specimen has been calculated with the dry fibre weight at the specific RH value as basis and the water ratio of the oak-PEG composite has been calculated with the sum of the dry fibre weight and the dry weight of the PEG contained in the specimen at the specific RH value as basis (figure 5-4).

The diagram (figure 5-4) shows that the water ratio of both of the untreated archaeological oak wood and the archaeological oak wood-PEG 4000 composite were stable between 60 and 70% RH. As the last value in the graph of the water ratio of the archaeological oak wood-PEG 4000 composite was not an equilibrium value, but the value at the termination of the experiment, it can not be told from the experiment how far the leakage of PEG from the specimen might proceed and to what level this might bring the water ratio.

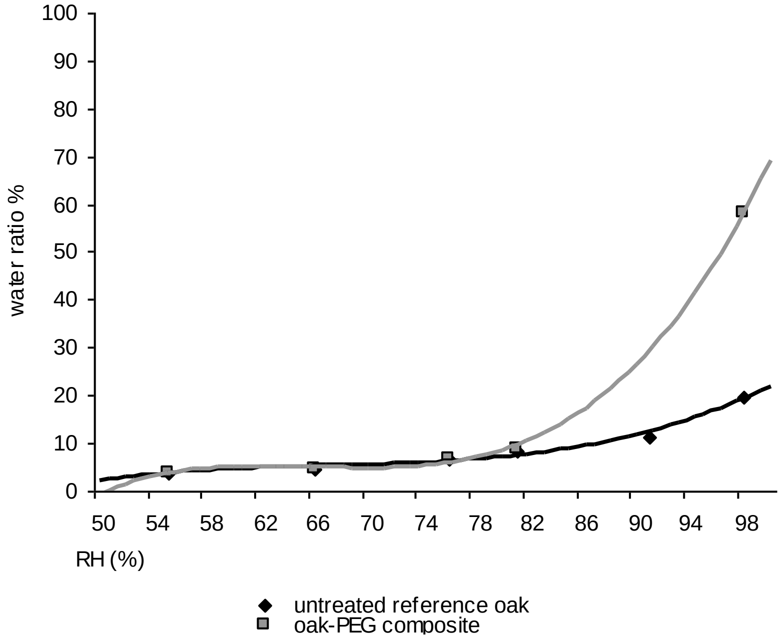

Figure 5-4. Water ratio of unpreserved wet site archaeological oak wood calculated as ratio of the dry fibre weight, and of the oak-PEG composite calculated as ratio of the total sum of dry fibre weight and the dry PEG 4000. Trend-lines; least square fittings.

5.3. Shrinkage of a Vasa oak wood-PEG 4000 composite specimen and an untreated Vasa oak wood specimen

As the purpose of treatment of wet archaeological wood with PEG was to prevent shrinkage and distortion of the wood, an experiment was designed to learn if the shrinkage prevention wanted had been obtained, or if at least a reduction of the magnitude of shrinkage had occurred.

The material for this experiment — as in most of the previous experiments — was an oak batten removed from under the lower gun-deck of the Vasa. The oak batten was cut transversely into five specimens of 2.5 cm of length and one piece of about 15 cm of length. This last piece was cut lengthwise into three specimens each c. 2.5 cm thick. Two specimens from the group of transversely cut specimens and one specimen from the group of longitudinally cut specimens were chosen as references. Each one of the five transversely cut specimens was equipped with four stainless steel nails for measurements in the radial and the tangential directions, respectively. The three specimens that were cut lengthwise were equipped with six stainless steel nails to enable measurements in the lengthwise direction of the wood fibre. The aim was to gain similar measurement intervals in the different directions of the wood structure.

The dimensions of the test specimens were chosen in order to facilitate the conservation procedure so that the wood structure would not be subjected to any strain that might initiate shrinkage before the conservation was finished. Moreover, contrary to the preceding experiments the transverse surfaces of the test specimens used in the present experiment were not sealed off.

The conservation procedure of the experiment was accomplished from November 1966 to November 1967. As PEG 4000 was the only molecular weight PEG used for immersion conservation of the Vasa wooden material at that time, all the specimens not set aside as references were treated with PEG 4000.

The experiment was conducted with the test specimens placed directly in 10 000 ml (10 l) of water in a 12 l glass tank in the same manner as described earlier.[116] The present experiment, however, was started by stepwise heating of the contents of the tank to 65°C. The conservation programme chosen was 1/3 % raise of PEG concentration of the conservation solution five days a week. The adding of PEG increments was to proceed until 80% PEG 4000 had been provided.

All specimens were weighed and measurements were made before the experiment was started. Then the reference specimens were returned to the water tank where they were kept during the conservation period at ambient laboratory temperature, while the test specimens were placed in the experimental glass tank. The heating was started in the experimental glass tank with the measured volume of water containing the test specimens. When the temperature of the water had reached 65°C after c. a month, the test specimens were taken out of the water and were

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[116] This dissertation, 4.3.

weighed and measured again. This weighing and measuring was executed once a month during the entire conservation period. The reference specimens also were weighed and measured during their stay in water storage.

After the conservation programme had been completed all specimens were subjected to a drying programme consisting of a series of RH-controlled climates. The first climate was simply a high RH level, that was produced by pure distilled water in the bottom tank of the climatic chamber. Then followed the five RH levels 91%, 81%, 76%, 66% and 55% produced by the saturated salt-solution mentioned earlier.[117] Finally the specimens were dried to constant weight at c. 10% RH, produced by silica gel. At this RH-level the not-preserved reference specimens contained c. 4% water content, compared to the dry fibre weight values that had been calculated on basis of oven dry weight (102 °C), for each of them before the drying process. This value of 4% water content has been adopted for the preserved specimens as well as a basis for calculation of their respective PEG-content.

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[117] This dissertation, 4.4.

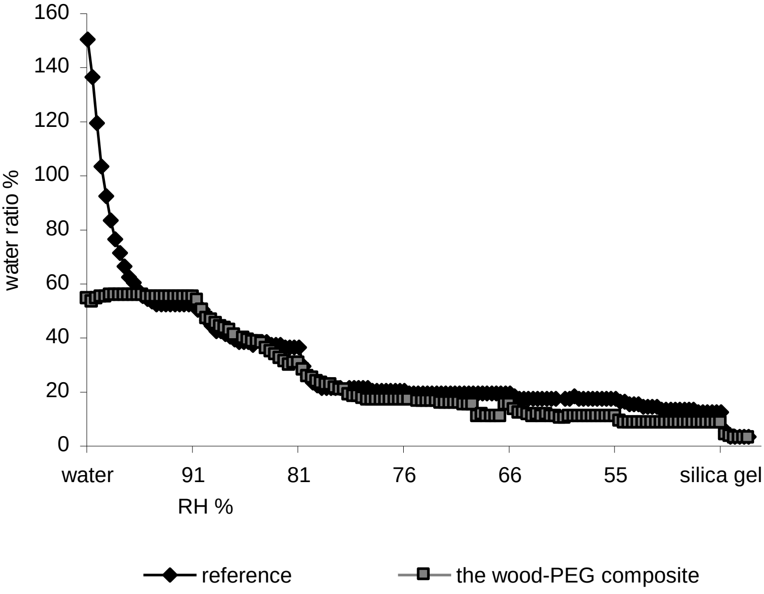

Figure 5-5. Water ratio during the drying period of two transversely cut oak specimens, one treated with PEG 4000 (Vasa oak wood-PEG 4000 composite), and the other one an untreated reference.

During the drying programme all specimens were weighed and measured once a week The specimens were kept at each RH level for at least four months, or as long as needed for their weight to stabilize. A drying period of four months was found to be enough at all RH levels, except the 91% - level, where the specimens needed six months to reach stable weight.

The PEG-contents of the five preserved specimens have been calculated by subtracting the fibre weight of each specimen, calculated at the start of the experiment from their actual weights at the RH produced by silica gel. The PEG ratios have been calculated on the basis of the dry fibre weight of the specimens. The PEG ratios amounted to between 64 and 66 %. This means that the dry weight of the Vasa oak wood-PEG 4000 composite specimen contained c. 40% PEG.

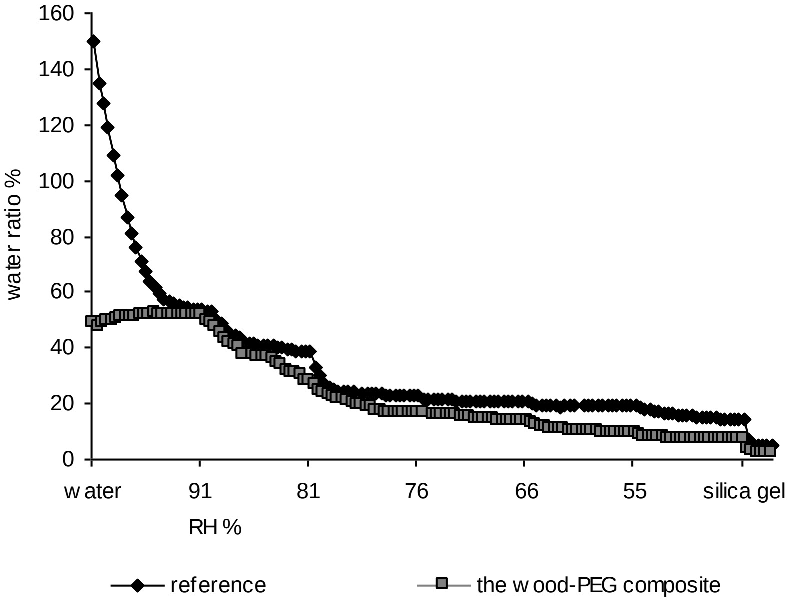

Figure 5-6. Water ratio during the drying period of two axially cut oak specimens, one treated with PEG 4000 (Vasa oak wood-PEG 4000 composite), and the other one an untreated reference.

Acknowledging the Vasa oak wood-PEG 4000 polymer composite as a special material, although the polymer is nonbonded-leachable,[118] the water ratio of the specimens during the drying procedure has been calculated on basis of their individual dry weight. The water ratio diagrams of one transversely cut and one axially cut composite specimen together with the water ratio diagrams of their transversely and axially cut reference specimens respectively, present lower water ratios of the composite specimens compared to the reference specimens (figures 5-5 and 5-6).

The diagrams show that the Vasa oak wood-PEG 4000 composite material was less hydrophilic than the reference oak wood, measured at all RH values. The slightly more pronounced difference between the

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[118] Wallström, 1998, p 24.

composite and the reference shown in the graph of the axially cut specimens might be only a random coincidence.

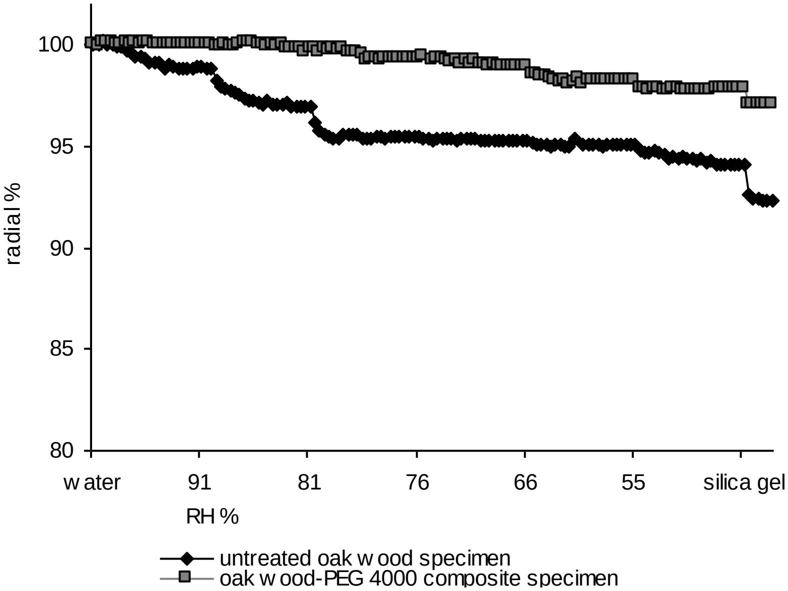

Figure 5-7. Radial shrinkage during the drying period of two transversely cut oak specimens, one treated with PEG 4000 (Vasa oak wood-PEG 4000 composite), and the other one an untreated reference.

Both of the composite and the reference specimens have shrunk during the drying programme. Two radial and two tangential measurement intervals were measured on each of the transversely cut specimens. The measurements of the largest of the two radial and tangential measurement intervals respectively, together with the measurements of the corresponding measurement intervals of their respective reference specimens are presented in the diagrams (figures 5-7, 5-8). On the axially cut specimens four different longitudinal measurement intervals were measured. One of these is presented together with the measurement of the corresponding measurement interval of its untreated reference specimen (figure 5-9).

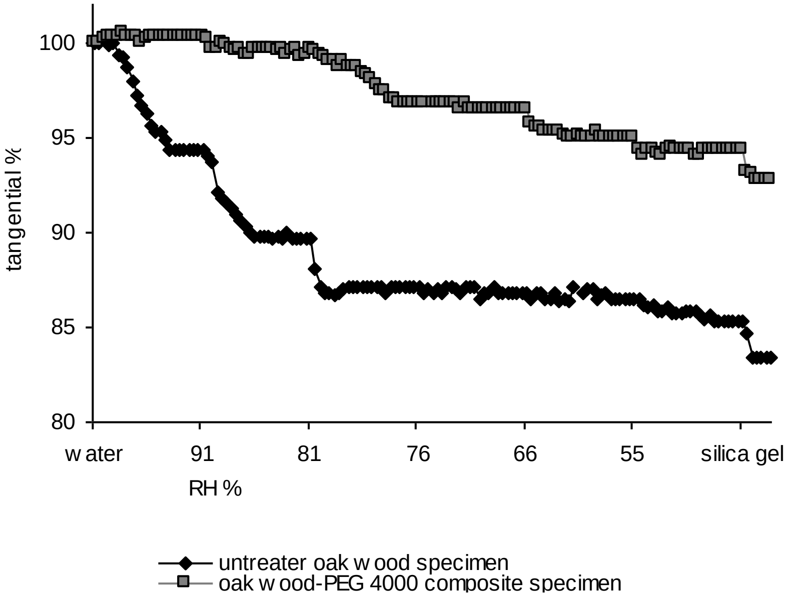

Figure 5-8. Tangential shrinkage during the drying period of two transversely cut oak specimens, one treated with PEG 4000 (Vasa oak wood-PEG 4000 composite), and the other one an untreated reference.

During the two first periods of the drying programme, the first one with the high humidity produced by pure water in the bottom tank of the climatic chamber, and the second one with a RH controlled at 91% by a saturated sodium carbonate solution there was no dimensional change at all of the Vasa oak wood – PEG 4000 composite specimens. Contrary to this, the reference specimen shrank more than half of its whole amount of shrinkage during these two periods. That means c. 3.5% in the radial direction, c. 10% in the tangential direction, and c. 1.5% in the axial direction.

During the third period of the drying programme, when the specimens were moved to a climatic chamber with an atmosphere of 81% RH, the Vasa oak wood-PEG 4000 composite specimens still showed practically no shrinkage in the radial and axial directions (figures 5-7, 5-9). In the tangential direction, however, shrinkage started and went on until the last few weeks of the period producing a tangential shrinkage of 3% (figure 5-8). The reference specimens started a new period of shrinkage in the radial and tangential directions immediately after the RH was lowered and reached its equilibrium level in a few weeks producing a radial shrinkage of c.1% and a tangential shrinkage of c. 2.5% during the period with 81% RH. There was no shrinkage in the axial direction of the reference specimens during this period.

During the fourth period of the drying programme the RH was kept at 76%. During this period there was practically no shrinkage in any direction, either of the Vasa oak wood-PEG 4000 composite specimens, or of the reference specimens (figures 5-7, 5-8 and 5-9).

At the RH controlled at 66% that was the fifth period of the drying programme all three directions of the Vasa oak wood-PEG 4000 composite shrank to a faint but noticeable extent of 0.8% in the radial, 1.3% in the tangential, and 0.2% in the axial directions (figures 5-7, 5-8 and 5-9). However, there was no shrinkage of the reference specimens in this phase of the drying programme.

During the final step of the drying programme that was controlled at 55% RH only the tangential direction of the Vasa oak wood-PEG 4000 composite specimens shrank by c. 0.7%, while there was no shrinkage at all in the radial and axial directions. In this atmosphere, however, the reference specimens shrank 1.0% in the radial, 1.2% in the tangential and 0.6% in the axial directions.

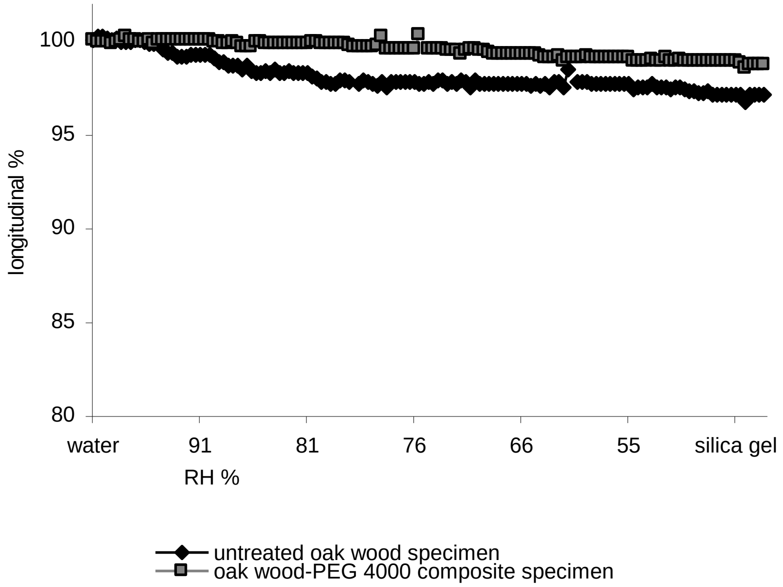

Figure 5-9. Longitudinal shrinkage during the drying period of two axially cut oak specimens, one treated with PEG 4000 (Vasa oak wood-PEG 4000 composite), and the other one an untreated reference.

The total shrinkage in the radial, tangential and axial directions of the composite specimens was 2.2%, 5.7% and 1.1%, respectively. The total shrinkage in the radial, tangential and axial directions of the reference specimens was 5.9%, 14.7 and 2.9%, respectively.

In principle, there is no shrinkage in the axial direction of the wood cell. The measured shrinkage in that direction is judged to be the result of un-linear direction of the wood fibres in relation to the axis of the tree trunk.

It is shown in the diagrams (figures 5-7, 5-8 and 5-9) that the Vasa oak wood-PEG 4000 composite specimens shrunk less than the un-treated reference specimens. This fact is transferred to mean that the test specimen would have shrunk as much as the reference specimen if it had not been preserved with PEG 4000. This is called the "anti-shrink efficiency" (ASE), in this case of the PEG 4000 on that wood specimen.

The ASE is calculated as the difference between the shrinkage of the untreated reference, and the shrinkage of the treated (composite) specimen as a fraction of the shrinkage of the reference specimen.

The anti-shrink efficiency (ASE) of the axial, the radial, and the tangential directions respectively, of the wood has been calculated at equilibrium at different RH-levels during the drying process (table 5-III).

Equilibrium RH %	ASE %		
	axial	radial	tangential
91	89	90	94
81	79	86	75
76	68	78	74
66	60	64	62
55	62	63	61
10 (silica gel)	55	62	56

Table 5-III. ASE % at different RH levels of the three main directions of the wood structure.

Wood shrinks during the drying process, mainly as a result of water molecules leaving the cell wall. The shrinkage is non-isotropic, meaning that the magnitude of the shrinkage is different in each of the main directions of the wood structure. These directions are defined as radial, tangential and axial respectively.[119]

The ASE values at 66 and 55 % RH for each of the three directions of the wood amounts to between 60 and 64 %, which means a reduction but not a prevention of the shrinkage that would occur without conservation. In the present experiment the radial shrinkage of the oak wood PEG-4000 composite specimen at 66 and 55% RH amounted to c. 2% and the shrinkage of the reference specimen to c. 5%, the tangential shrinkage of the composite specimen at 66 and 55% RH amounted to c. 5% and the shrinkage of the reference specimen to c. 13 and 15 % respectively at 66 and 55% RH. The axial shrinkage, e.g. the shrinkage occurring in the grain direction of the wood is attributed to shrinkage in the other two directions, transmitted to axial direction as a result of the fact that the fibres are not exactly parallel to the wood axis. In the

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[119] Thunell, 1952, pp 39-43; Esping, 1992, pp 169-170.

present experiment the shrinkage in the grain direction of the composite specimen amounted to c. 1%, and the shrinkage of the reference specimen to c. 2.5%.

The result of the experiment is that the Vasa oak wood-PEG 4000 composite specimen and the Vasa oak wood reference specimen both have undergone dimensional change and distortion,[120] during the drying process.

5.4. Shrinkage behaviour of Vasa oak wood-PEG (4000, 1500 and 600) composite specimens

In order to widen the scope of the Vasa oak-PEG composites a similar experiment as the one described in 5.3. was designed with three molecular weight PEG programmes. The experiment was set up with PEG 4000, 1500 and 600 in three 12 l glass tanks. In order to obtain a number of series of specimens containing increasing amounts of PEG each tank was designed to contain the same number of Vasa oak specimens, each of which was designed to be removed at pre-chosen concentrations of the conservation programme.

The material for this experiment – as in most of the previous experiments – was an oak batten removed from under the lower gun-deck of the Vasa. The oak batten was cut transversely into twenty-four specimens of 2.5 cm of length. Each one of the specimens was equipped with four stainless steel nails for measurements in the radial and the tangential directions. Every third one of the specimens cut from the deck-batten was allocated to each of the separate PEG conservation baths. This means that each conservation programme contained eight specimens. Each specimen of the group of three specimens in continuation was designed in succession to the PEG 4000, 1500 and 600-programme respectively. The three specimens of each such group were designed to be subjected to the same PEG concentration programme. The successive removal of specimens from the conservation solutions was designed to be performed at the programmed PEG-concentrations of 5%, 10%, 15%, 20%, 30%, 45%, 60% and 75%, respectively.

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[120] Thunell, 1952, p 40, fig. 39; Esping, 1992, p 177, figure 5.7.

To enable to execute a large scale experiment despite shortage of material all test specimens were taken for the conservation and no references were kept. An idea was that the references of the experiment 5.3. that were cut from a deck-batten from the same area could be used.

The experiment was started in November 1969 and the drying period was finished at the end of April 1972 (10.5 months + 19 months = 2.5 years).

All specimens were weighed and the measurements were taken before the conservation was started. Each glass tank was charged with 10 000 ml (10 l) of water, and the first month of the conservation period was used to heat the water step-wise to 65° C. The conservation programme chosen was 1/3% raise of PEG concentration of the conservation solution each working-day. The adding of PEG increments was to proceed until 75% of PEG had been provided. Once a month during the conservation period all specimens were taken out of their conservation baths to be weighed and measured. Samples of the conservation solutions were also analysed to determine the PEG concentration.

As may be read from the graph (figure 5-10) the PEG concentration develops in a rather linear manner, with a slight recess at the end where it reaches 50%, despite the 75% concentration raising programme. Part of the explanation for this is the fact that there has been no adjustment for the volume of the specimens removed from the conservation bath, but the volume was filled up by water. That means that there was a calculable lowering of the PEG-concentration every time a specimen was removed from the conservation bath. As the total volume of the specimens was c. 1600 cm^3, that was the same volume as the total volume of the compensating water, meaning a decrease of the PEG end concentration from 75 to 65% that was effected by this.

The amount of PEG absorbed by the specimens of each conservation bath respectively was c. 200g. This amounted to c. 2.5% of the PEG added to each conservation bath and lowered the PEG concentration of each of the baths only by 1.7%. The rest of the loss of PEG, c. 1500 g from each of the PEG solutions, is unaccounted for.[121]

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[121] cf. this dissertation, 4.3.

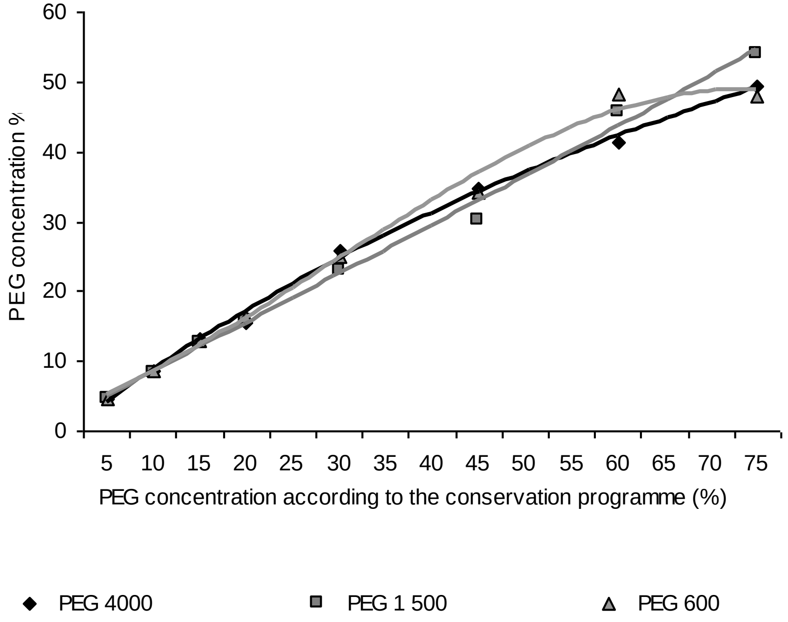

Figure 5-10. PEG concentration in the conservation solutions.
Trend-lines; least square fittings.

After the conservation programme had been completed all specimens were subjected to a drying programme consisting of a series of RH-controlled climates. The first climate was simply a high RH that was produced by pure distilled water in the bottom tank of the climatic chamber. Then followed the five RH levels 91%, 81%, 76%, 66% and 55% respectively, produced by the saturated salt-solution mentioned earlier.[122] Finally the specimens were dried to constant weights at c. 10% RH ,produced by silica gel.

During the drying programme all specimens were weighed and measured once a week The specimens were kept at each RH level for at least four months, or as long as needed for their weights to stabilize. A drying period of three months was observed to be enough at all RH levels except for the 91% level, where the specimens required six months to reach stable weights.

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[122] This dissertation, 5.1.

After drying, the PEG content of the specimens were calculated individually from their weights, and their dry fibre weights calculated on the basis of their weights before conservation, and the u_{max} value of each particular deck-batten being used for the experiment. The value of 4% water content has been adopted for the equilibrium of the preserved specimens as basis for calculation of their respective PEG-content.

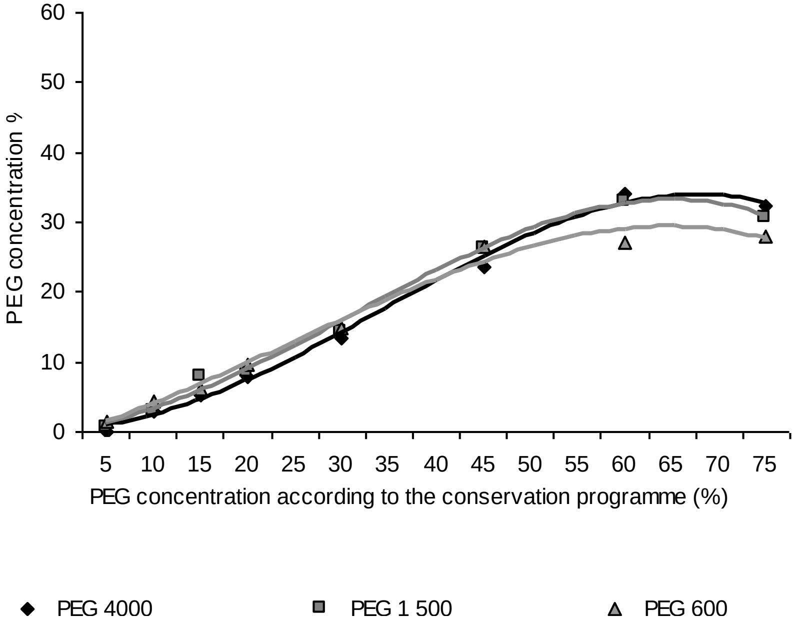

Figure 5-11. PEG concentration inside the wood. Trend-lines; least square fittings.

After the PEG content of each specimen had been calculated the weight of the water contained in each individual specimen was calculated at its removal from the conservation solution was calculated. From those figures the mean value of an assumed PEG solution inside the wood of each individual specimen (figure 5-11).

Between 15 and 45% of the conservation programme the PEG concentration of this assumed PEG solution seems to have developed in parallel to the analysed PEG concentration of the surrounding conservation solution, but at c. 10 percentage units lower concentration levels (figures 5-10, 5-11). From 45 to 60% of the conservation programme the PEG concentration of the internal assumed PEG solution did slow down in growing, and during the period between 60 and 75% of the conservation programme the PEG concentration of the inside assumed PEG solution ceased to grow and ended up with c. 20 percentage units lower PEG concentration than in its surrounding conservation solution (figures 5-10, 5-11).

The PEG-ratios obtained from the individual specimens removed from the conservation solutions during the conservation procedures with PEG 1500 and 600 respectively are very similar to each other below the 45% level of the conservation programmes, while the PEG 4000 ratios lag behind with c. 5 percentage units during that part of the conservation. Above the 45% level of the conservation programmes the PEG 4000 and 1500 come together while the PEG 600 lags behind by c. 5 percentage units. None of the specimen series preserved with the tested PEG's showed any increase in PEG-ratio from the 60% to the 75% level of the conservation programme (figure 5-12). This phase of the conservation programmes corresponded to the interval of proper PEG-concentration from c. 45 to c. 50% of the conservation solutions (figure 5-10).

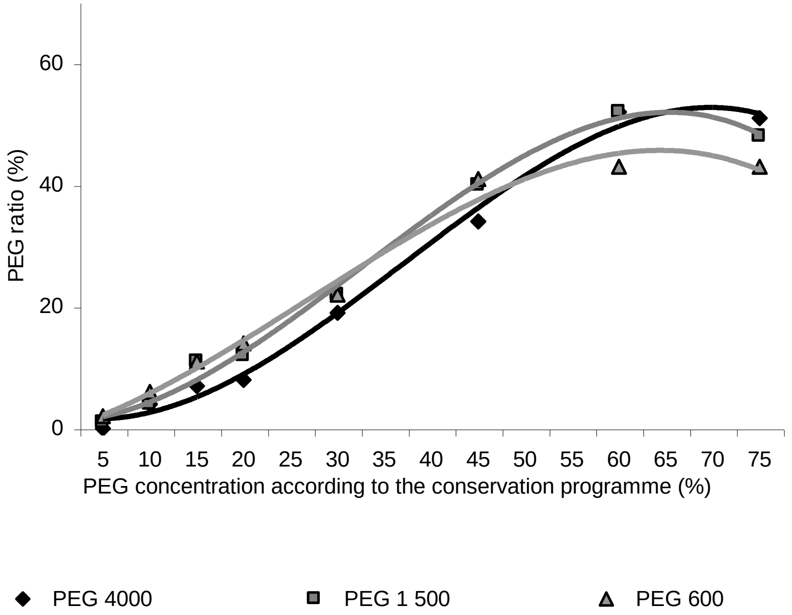

Figure 5-12. PEG ratio of the conserved specimens.
Trend-lines; least square fittings.

The first evaluation of the results of the experiment was reported by Barkman to the Symposium held at the National Maritime Museum at Greenwich on 5 - 6 October 1973.[123] The evaluation was performed by calculating the surface shrinkage of the specimens at each equilibrium RH during the drying period. The result was presented as shrinkage diagrams for the specimens of each of the molecular weight PEG used in the experiment. Each graph of the diagrams was labelled with the PEG ratio of the specimen. In all three series of diagrams the individual specimens show the same order of shrinkage behaviour as was their individual position in the conservation series. Although considered sensational by the Vasa conservation laboratory there was no comment to this observation registered in the report from the meeting.

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[123] Barkman, 1975, pp 84 – 94.

The water content of the specimens was presented in three tables and three diagrams as ratio of the dry fibre weight.[124] This, however, did not consider the hygroscopicity of the PEG:s contained in the wood. As in the experiment 5.3. the water ratio should be calculated with the dry weight of Vasa oak wood-PEG composite as a basis. The experiment contains Vasa oak wood in combination with PEG 4000, 1500 and 600. Moreover, each of these three PEG:s respectively occur in a series of proportions to the fibre weight of each specimen (table 5-IV).

Fraction of PEG in the dry weight of the Vasa oak-PEG composite (%)			
Conservation programme	PEG 4000	PEG 1500	PEG 600
0 – 5	0	1	2
0 – 10	4	4	6
0 – 15	7	10	8
0 – 20	10	11	12
0 – 30	16	18	18
0 – 45	25	29	29
0 – 60	34	34	30
0 – 75	34	32	30

Table 5-IV. Fraction of PEG of the dry weight of the Vasa oak-PEG composit specimens.

Evaluation of the conservation result by the drying characteristics

As there was no reference specimen put aside for the experiment, the possibility to use the same references as in the experiment 5.3. was considered. Another possibility was to use the first specimen of each series as a reference. The differences regarding water content and radial as well as tangential shrinkage between the untreated reference specimen of experiment 5.3. and each of the three specimens removed at the 5% level of their respective conservation programme executed in experiment 5.4. has been presented in three diagrams (figures 5-13 – 5-15).

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[124] Barkman, 1975, pp 99 – 103.

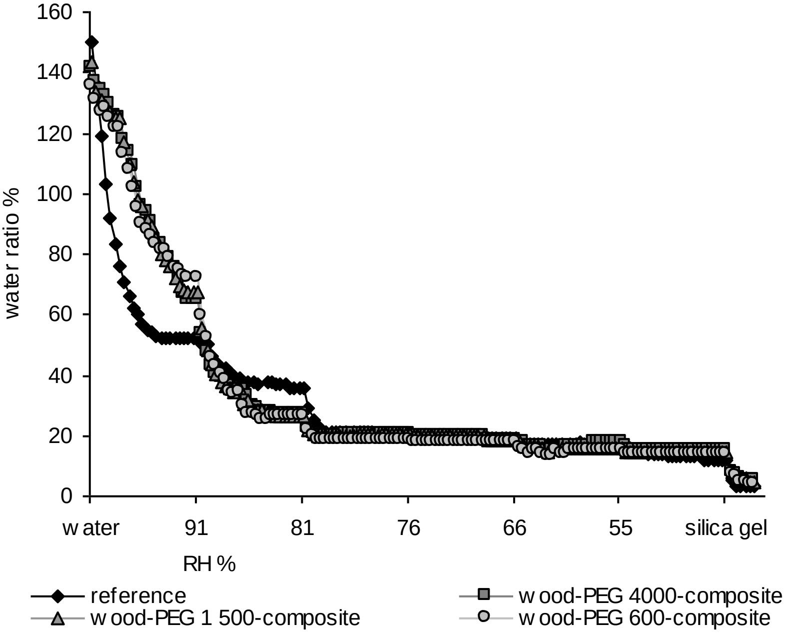

Figure 5-13. Water-ratio during the drying period of the untreated specimen of experiment 5.3., and the three specimens removed at the 5% level of the conservation programmes of the experiment 5.4. (Vasa oak wood-PEG composite specimens with 0% PEG 4000, 1% PEG 1500 and 2% PEG 600, respectively).

The graphs of the three specimens that were removed from their respective conservation bath at the 5% level of the conservation programme were very similar during the whole drying programme. The graph of the drying procedure of the untreated specimen, on the contrary, shows a different scenario during the two initial phases of the drying programme with a faster and steeper course, that did not stop until the water-ratio was c. 10 percentage units lower than that of the specimens of the 0-5% conservation programmes during the initial period where the high humidity was produced by pure water. During the second period of the drying programme when the RH was produced by a saturated solution of sodium carbonate, the specimens of the 0-5% conservation programmes dried faster and lost c. 35 percentage units water-ratio while the untreated specimen only lost c. 10 percentage units water-ratio. During the rest of the drying programme the diagrams of water-ratio of all four specimens were almost identical.

During the drying period of the three specimens of the 0-5% conservation programmes, even the graphs of the radial and the tangential shrinkage respectively, were almost inseparable while there was a difference between these and the graphs of the corresponding shrinkages of the untreated reference specimens during every phase of the drying procedure.

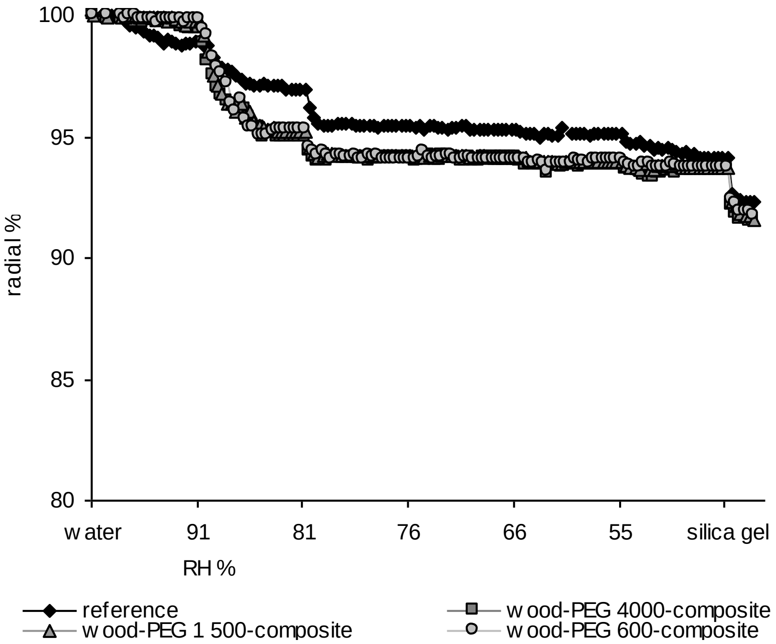

Figure 5-14. Radial shrinkage during the drying period of the untreated specimen of experiment 5.3., and the three specimens removed at the 5% level of the conservation programmes of the experiment 5.4. (Vasa oak wood-PEG composite specimens with 0% PEG 4000, 1% PEG 1500 and 2% PEG 600, respectively).

During the initial phase of the drying programme when the high humidity was maintained by pure water in the bottom tank of the climatic chamber the three specimens of the 0-5% conservation programmes show close to neither radial nor tangential shrinkage while the untreated reference shows c. 1% shrinkage in the radial direction and c. 5% shrinkage in the tangential direction. The situation changed during the second phase of the drying programme when the RH was maintained at 91% by a saturated solution of sodium carbonate when the radial and tangential shrinkage of the three specimens of the 0-5% conservation programmes amounted to c. 5 and c. 12% respectively while the radial and tangential shrinkage of the untreated specimen amounted to c. 3 and c. 8%, respectively. The graphs of the radial shrinkage of the three specimens of the 0-5% conservation programmes remained at a level c. 1.5% below the level of the graph of the radial shrinkage of the untreated specimen and the graphs of the tangential shrinkages of the three specimens of the 0-5% conservation programmes remained c. 2% below the graph of the tangential shrinkage of the untreated specimen. However, all four graphs of radial and tangential shrinkage respectively end up at the same level of c. 6% radial and c. 12% tangential shrinkage at 55% RH. (figures 5-14, 5-15).

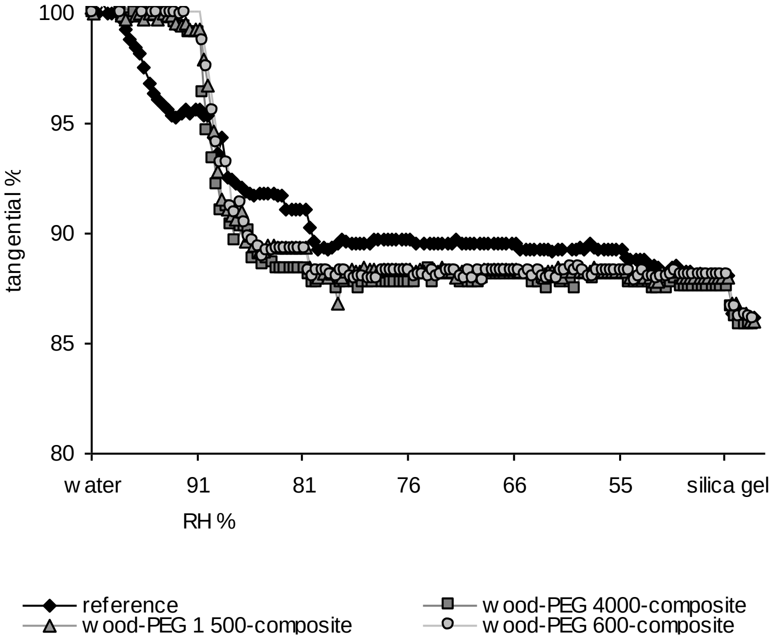

Figure 5-15. Tangential shrinkage during the drying period of the untreated specimen of experiment 5.3., and the three specimens removed at the 5% level of the conservation programmes of the experiment 5.4. (Vasa oak wood-PEG composite specimens with 0% PEG 4000, 1% PEG 1500 and 2% PEG 600, respectively).

The fact that the radial and the tangential shrinkage of the untreated specimen was of less magnitude than the corresponding shrinkage of the specimens of the 0-5% conservation programmes gave negative values to the ASE of these specimens both of the radial and of the tangential directions if and when the untreated specimen was used as reference. Thus, there would be at least one preserved specimen of each of the PEG 4000, 1500 and 600 conservation programmes that would have negative ASE values with the untreated reference of experiment 5.3. as a reference. It is not possible to decide whether these differences of shrinkage behaviour resulted from the heating and/or the conservation treatments, or if they might be explained as normal variations between wood pieces from two different tree trunks although they had been cut from corresponding parts of the individual trunk. There is also the possibility that the two different deck-battens have had slightly different burial circumstances, although they have been removed from the same area of the Vasa hull.

For the presentation of the radial and tangential shrinkage during the drying period of experiment 5.4. the first specimen of each series has been chosen as a reference specimen for the succeeding specimens of that particular series. This gave a reference specimen to each PEG molecular weight series that was cut equally close to the rest of the specimens of the series. The reference specimens had been included in the treatments during the heating programmes, and then in the initial part of the conservation programmes during the raise of the PEG concentration of the conservation solutions from zero to 5%.

The drying process of the Vasa oak wood-PEG composite specimens of each of the three PEG series is illustrated by the specimens that remained in the conservation solutions during the entire conservation process (figures 5-16, 5-17 and 5-18). The water ratio values during the drying procedure of the preserved specimens, considered as Vasa oak wood-PEG composite specimens, are calculated as ratios between the weights of the water contained in each individual specimen at each weighing occasion and the dry weights of that specimen i.e. the sum of dry weights of the oak fibre- and the PEG content. The PEG content of the dry weights of the three specimens chosen were 34, 32, and 30% of the Vasa oak wood-PEG 4000, PEG 1500, and PEG 600 composite specimen, respectively.

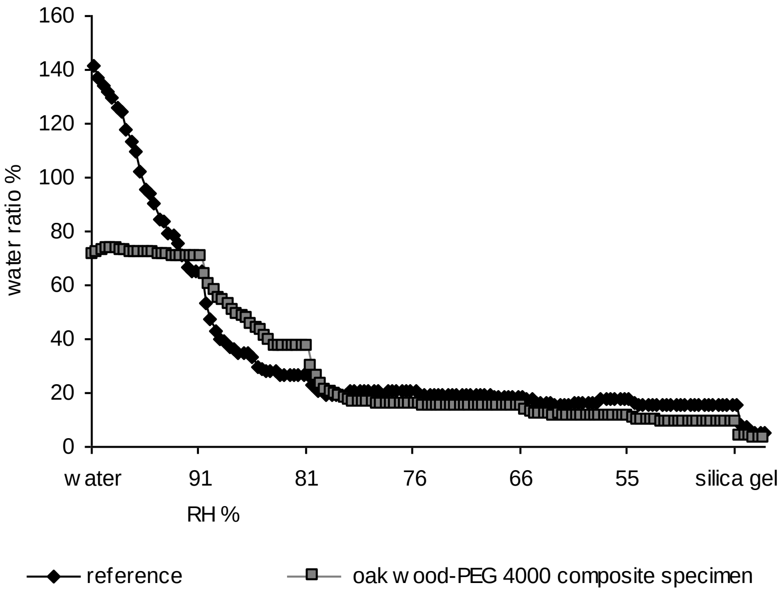

Figure 5-16. Water-ratio during the drying period of the specimen removed at the 5% level of the conservation programme (reference specimen with 0% PEG 4000), and the specimen removed at the 75% level (oak wood-PEG 4000 composite specimen with 34% PEG).

The reference specimen of the PEG 4000 series contained water equalling c. 140% water ratio but no PEG detectable with the method used, when removed from the conservation solution. During the first period of the drying programme when high humidity was produced by pure water in the bottom tank of the climatic chamber the reference specimen lost water equalling c. 75 percentage units water ratio and contained at equilibrium c. 65% water ratio. The Vasa oak wood-PEG 4000 composite specimen with its dry weight containing 34% PEG 4000 contained water equalling c. 70% water ratio calculated on its dry weight was very close to equilibrium with the atmosphere of the first step of the drying programme when it was removed from the conservation solution. Consequently it neither gained nor lost weight during that phase of the drying programme.

During the second phase of the drying programme with RH controlled at 91% the reference lost water equalling c. 40 percentage units water ratio and arrived at a water ratio of c. 25%. The test specimen lost water equalling c. 30 percentage units water ratio and arrived at c. 40% water ratio. During the third step of the drying programme with RH controlled at 81% the test specimen lost more water than the reference specimen and arrived at a water ratio value well below 20%, while the reference specimen arrived at an equilibrium at c. 20%. These equilibrium levels were continued during the fourth step of the drying programme with RH controlled at 76%. At the fifth step of the drying programme with RH controlled at 66% both of the specimens lost a couple of percentage units of water ratio. At the sixth period of the drying programme with RH controlled at 55% the test specimen dried to a water ratio equilibrium level of c. 10% while the reference specimen levelled out at c. 15% water ratio.

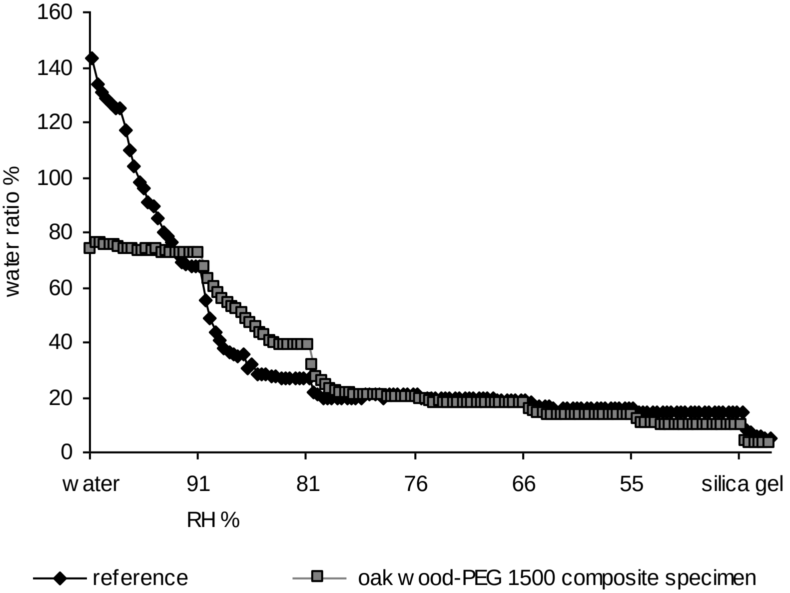

Figure 5-17. Water-ratio during the drying period of the specimen removed at the 5% level of the conservation programme (reference specimen with 1% PEG 1500), and the specimen removed at the 75% level (oak wood-PEG 1500 composite specimen with 32% PEG).

The reference and the test specimens of the PEG 1500 series respectively, had undergone the same treatment as the corresponding specimens of the PEG 4000 series. During the treatment the reference specimen of the PEG 1500 series had arrived at a PEG content of 1% of the dry weight of the specimen while the test specimen that had been removed at the end of the completed conservation programme contained 32% PEG 1500 of the dry weight.

The graphs of the drying procedure of the Vasa oak wood-PEG 1500 reference and test specimens show almost identical features as the graphs of the drying procedure of the Vasa oak wood-PEG 4000 reference and test specimens during the two initial steps of the drying programme. During the next two steps of the drying procedure the two diagrams ran almost on top of each other at 20% water ratio. At the 66% RH level the drying diagram of the composite specimen barely stepped down to a level below the drying diagram of the reference specimen. At the 55% RH level the drying diagram of the reference specimen remained at c. 15% while the drying diagram of the composite specimen ended up at c. 10% water ratio.

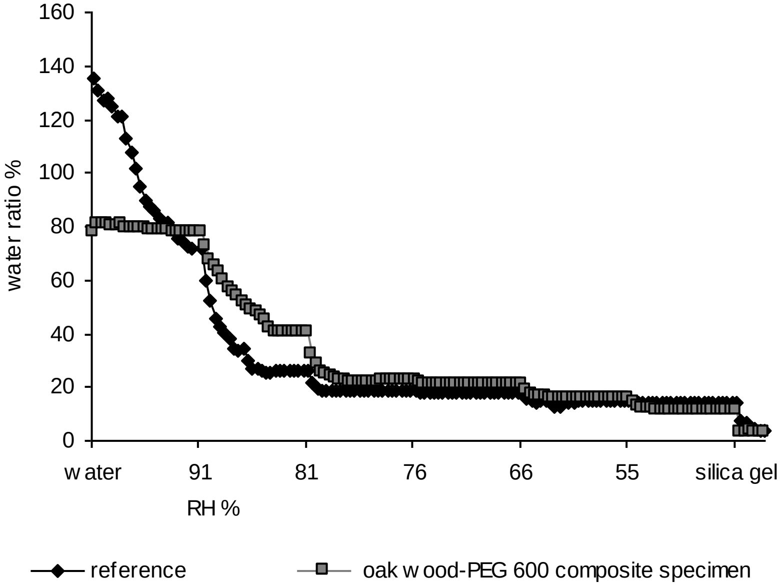

Figure 5-18. Water-ratio during the drying period of the specimen removed at the 5% level of the conservation programme (reference specimen with 2% PEG 600), and the specimen removed at the 75% level (oak wood-PEG 600 composite specimen with 30% PEG).

The reference and the test specimens of the PEG 600 series respectively, had undergone the same treatment as the corresponding specimens of the PEG 4000 and 1500 series. During the treatment the reference specimen of the PEG 600 series had arrived at a PEG content of 2% of the dry weight of the specimen while the test specimen that had been removed at the end of the completed conservation programme contained 30% PEG 600 of the dry weight.

The graph of the drying procedure of the Vasa oak wood-PEG 600 reference is almost identical with the graphs of the drying procedure during the two initial steps of the drying programme of the Vasa oak wood-PEG 4000 and 1500 reference specimens.

Similar to the corresponding specimens of the PEG 4000 and 1500 series the Vasa oak wood PEG 600 composite test specimen when placed in the climatic chamber with pure water as humidifying agent did neither gain nor loose weight but was quite stable. The equilibrium level of the PEG 600 composite test specimen, however, remained at 80% water ratio while the PEG 4000 and 1500 composite test specimens had stayed at c. 70% water ratio. During the second step of the drying programme when the RH was controlled at 91% the PEG 600 composite test specimen lost weight corresponding to 40% water ratio. With this the PEG 600 composite test specimen ended up at 40% water ratio, i.e. the same level as the PEG 4000 and 1500 composite test specimens.

During the steps of the drying procedure controlled at 81 and 76% RH respectively, the two graphs of the PEG 600 test and reference specimens came close to each other with the graph of the PEG 600 composite test specimen barely above the graph of the reference specimen at a level of 20% water ratio. At the 66% RH the drying graphs of the PEG 600 composite test specimen and its reference ran almost on top of each other at c. 17% water ratio. At the 55% RH level the drying graph of the reference specimen remained at c. 15% and while the drying graph of the composite specimen ended up, maybe at half a percentage unit lower level.

One conclusion to be drawn from the result of the drying procedure is that the rather high percentage of PEG 600 seems to have little influence on the hygroscopicity of the Vasa oak wood-PEG 600 composite material at the RH level considered for the Vasa museum. The two less hygroscopic PEG 4000 and 1500 produce composites that are markedly less hygroscopic than the very near to un-treated Vasa oak wood of the reference specimens.

Evaluation of the conservation result by the shrinkage characteristics

As shrinkage is the most important parameter for judging — in this context — the effectiveness of a conservation treatment, all the equilibrium levels of radial and tangential shrinkage obtained at experiment 2.3.4. are presented, for the PEG 4000 treated specimens (tables 5-V, 5-VI), for the PEG 1500 treated specimens (tables 5-VII, 5-

VIII), and for the PEG 600 treated specimens (tables 5-IX, 5-X). The specimens chosen as reference specimens are represented by the shrinkage figures in the first column of each pair of tables.

Drying programme	Fraction of PEG in the dry weight of the Vasa oak-PEG 4000 composite (%)							
	0	4	7	10	16	25	34	34
water	0.6	0.4	0.2	0.2	0.2	-0.2	-0.1	-0.1
91% RH	5.1	5.2	4.2	3.1	1.5	0.0	-0.2	0.2
81% RH	5.9	5.9	5.3	3.9	3.1	1.9	0.4	0.9
76% RH	5.9	6.0	5.6	4.5	3.2	2.6	0.4	1.3
66% RH	6.2	6.3	5.9	4.5	3.6	2.6	1.2	1.8
55% RH	6.4	6.4	5.9	4.8	3.9	3.0	1.7	2.3
silica gel	8.5	8.4	7.7	6.2	4.4	3.4	2.3	3.2

Table 5-V. Shrinkage in the radial direction of the wood structure of the Vasa oak wood-PEG 4000 composite specimens.

Drying programme	Fraction of PEG in the dry weight of the Vasa oak-PEG 4000 composite (%)							
	0	4	7	10	16	25	34	34
water	0.9	1.1	0.4	0.4	0.4	0.1	-0.5	-0.8
91% RH	11.6	11.4	6.9	5.2	2.1	0.1	-0.3	0.0
81% RH	12.3	11.9	8.5	6.6	5.3	3.1	2.0	1.9
76% RH	12.0	11.9	8.6	7.1	5.6	3.9	2.6	2.5
66% RH	12.0	12.1	8.7	7.1	6.1	4.2	3.5	3.4
55% RH	12.4	11.9	8.5	7.3	6.4	5.0	4.3	4.1
silica gel	14.2	14.0	10.2	8.1	6.8	5.9	5.5	5.2

Table 5-VI. Shrinkage in the tangential direction of the wood structure of the Vasa oak wood-PEG 4000 composite specimens.

Comparing the radial and tangential shrinkage respectively in the first column of each pair of tables that shows the measurements of the three specimens chosen for reference reveal a difference between those, especially during the initial drying phase where the high RH value of the drying atmosphere was produced with pure water. The radial shrinkage amounts to 0.6, 0.2 and 0.2% respectively of the PEG 4000, 1500, and 600 specimens that indicates a difference between the PEG 4000 specimens relative the two others. The tangential shrinkage amounting to 0.9 and 0.7% of the PEG 4000, and 1500 specimens respectively makes those specimens a pair with common reaction while the PEG 600 specimen quite contrary has swelled 0.1% in the atmosphere of the initial drying phase. Contrary to these three specimens the un-treated reference specimen of experiment 5.3. shrank 1.3% in the radial direction and 4.4% in the tangential direction during the initial phase of the drying programme.

The conclusion drawn from this is that the period of 3 weeks of treatment during which the PEG concentration of the conservation solution was raised from zero to 5% has resulted in PEG uptake by the secondary cell wall that has changed the reaction to high RH compared to un-treated Vasa oak cut from the same area of the hull.

Drying programme	Fraction of PEG in the dry weight of the Vasa oak-PEG 1500 composite (%)							
	1	4	10	11	18	29	32	34
water	0.2	0.3	0.2	0.2	0.1	0.0	-0.5	0.1
91% RH	4.8	4.5	3.7	2.5	0.8	-0.1	-0.3	0.0
81% RH	5.8	5.4	4.7	3.9	2.3	1.0	0.2	0.2
76% RH	5.9	5.8	5.0	4.1	2.6	1.4	0.4	0.3
66% RH	6.1	5.9	5.0	4.3	3.0	1.5	1.1	0.9
55% RH	6.3	6.1	5.1	4.4	3.5	2.2	1.6	1.4
silica gel	8.5	7.9	6.5	5.5	3.5	2.6	2.2	1.9

Table 5-VII. Shrinkage in the radial direction of the wood structure of the Vasa oak wood-PEG 1500 composite specimens.

Drying programme	Fraction of PEG in the dry weight of the Vasa oak-PEG 1500 composite (%)							
	1	4	10	11	18	29	32	34
water	0.7	0.7	0.4	0.4	0.1	0.3	-0.5	-0.2
91% RH	10.7	9.8	6.9	5.3	1.7	0.2	0.0	0.0
81% RH	11.6	11.1	8.3	7.5	5.7	2.1	1.0	1.0
76% RH	11.6	11.2	8.5	7.7	6.0	2.5	1.5	1.5
66% RH	11.7	11.8	8.1	8.2	7.0	3.4	3.2	2.9
55% RH	12.0	11.4	8.3	8.4	7.4	4.2	3.9	3.5
silica gel	14.0	13.0	9.4	9.3	7.9	5.3	4.8	4.6

Table 5-VIII. Shrinkage in the tangential direction of the wood structure of the Vasa oak wood-PEG 1500 composite specimens.

Studying the tables of the figures of radial and tangential shrinkage the minute shrinkage or even swelling is noted during the initial phase of the drying programme, when an equilibrium was established between an atmosphere with high RH produced by pure water is noted. The shrinkage figures at the different equilibrium levels, however, seem to have a connection to the PEG content of the dry matter of the specimens.

Considering the equilibrium shrinkage figures of the three Vasa oak wood-PEG composite specimen series when drying in the controlled RH atmospheres of 91 – 55% RH a strong similarity is observed between the series based on the three chosen PEG's respectively. The specimens of the series with growing PEG content of the dry matter show declining radial and tangential shrinkage values at each controlled RH level. However, considering the specimens of the two final conservation steps (tables 5-V – 5-X, last and second last column) there seem to be a limit to the amount of PEG in the dry matter as well as to the effectiveness of the PEG as shrinkage reducing substance.

Drying programme	Fraction of PEG in the dry weight of the Vasa oak-PEG 600 composite (%)							
	2	6	8	12	18	29	30	30
water	0.2	0.3	0.1	0.2	0.3	-0.2	-0.2	-0.2
91% RH	4.7	4.4	3.3	2.0	0.9	-0.2	-0.2	-0.2
81% RH	5.9	5.5	4.5	3.5	2.5	0.3	0.0	0.2
76% RH	5.9	5.6	4.8	4.0	2.7	0.6	0.1	0.2
66% RH	5.9	6.0	4.7	4.2	3.2	0.9	0.3	0.5
55% RH	6.3	6.0	4.9	4.3	3.6	1.4	1.0	0.5
silica gel	8.3	7.7	6.2	5.2	4.1	2.1	1.5	1.5

Table 5-IX. Shrinkage in the radial direction of the wood structure of the Vasa oak wood-PEG 600 composite specimens.

Drying programme	Fraction of PEG in the dry weight of the Vasa oak-PEG 600 composite (%)							
	2	6	8	12	18	29	30	30
water	-0.1	0.6	0.2	0.2	0.3	0.0	-0.2	-0.8
91% RH	10.8	9.7	6.0	4.0	1.4	-0.2	-0.2	-0.1
81% RH	11.8	11.1	8.3	6.6	5.5	1.3	0.4	0.1
76% RH	11.8	11.3	8.7	7.6	6.0	1.8	0.4	0.1
66% RH	11.8	11.7	8.4	7.6	7.1	2.5	1.7	1.1
55% RH	11.9	11.7	8.7	7.9	7.6	3.5	2.3	1.6
silica gel	13.9	13.3	9.6	8.3	8.3	4.8	3.8	2.9

Table 5-X. Shrinkage in the tangential direction of the wood structure of the Vasa oak wood-PEG 600 composite specimens.

Although the minute shrinkage or even swelling noted during the initial phase of the drying programme when an equilibrium was established between an atmosphere with high RH produced by pure water and the Vasa oak wood-PEG composite material it is its reaction to the museum climates considered feasible that must be the basis for evaluation of the effectiveness of the conservation treatment.

To enable thorough studying of the shrinkage procedure during the drying programme the graphs of the radial and tangential shrinkage respectively of the same three pairs of test and reference specimens as were used for the drying graphs are presented (figures 5-19 – 5-24).

Compared to the shrinkage measurements of the specimens of experiment 5.3., two circumstances are different at experiment 5.4. namely the fact that the reference specimens have been subjected to the initial heating procedure and the initial phase of the conservation procedure while those of experiment 5.3. were brought directly to the drying programme from storage in water at ambient laboratory temperature. This circumstance may account for the fact that contrary to the reference specimens of experiment 5.3. the reference specimens of the experiment at hand did not shrink noticeably during the first step of the drying programme when high humidity was produced by pure water in the bottom tank of the climatic chamber.

The main part of the shrinkage in both of the radial and tangential directions of the reference specimens occurred at the RH controlled at 91%. That means c. 5% in the radial direction and c. 11% in the tangential direction to be compared to 3 and 10% respectively in these directions of the transversely cut reference specimen of experiment 5.3. At the controlled climates of 81 and 76% RH respectively, the reference specimens of the present experiment shrank another percentage unit in the radial direction and another two percentage units in the tangential direction and levelled out shortly after being placed in the 81% RH climate. The reference specimen of experiment 5.3. levelled out with 4.5 and 13% shrinkage in the radial and tangential directions respectively.

The measurements of the reference specimens of experiment 5.4. remained at the level obtained at 81% RH during the rest of the drying programme while the radial and tangential measurements of the reference specimen of experiment 5.3. shrank another percentage unit at the RH level controlled at 55%.

The end result of the radial and tangential shrinkage of the reference specimens of the present experiment amounted to 6 and 13% respectively compared to 5.5 and 14% shrinkage of the reference specimen of experiment 5.3., i.e. the reference specimens are very close to each other concerning total shrinkage during the drying period. The only diverging behaviour may be the distribution over time, of shrinkage in the tangential direction of the totally un-treated reference specimen of experiment 5.3., where no shrinkage was noted during the drying phases at the 76 and 66% RH levels, but where shrinkage proceeded at an even pace during two thirds of the final phase, of the drying programme, the 55% RH level, before equilibrium was reached.

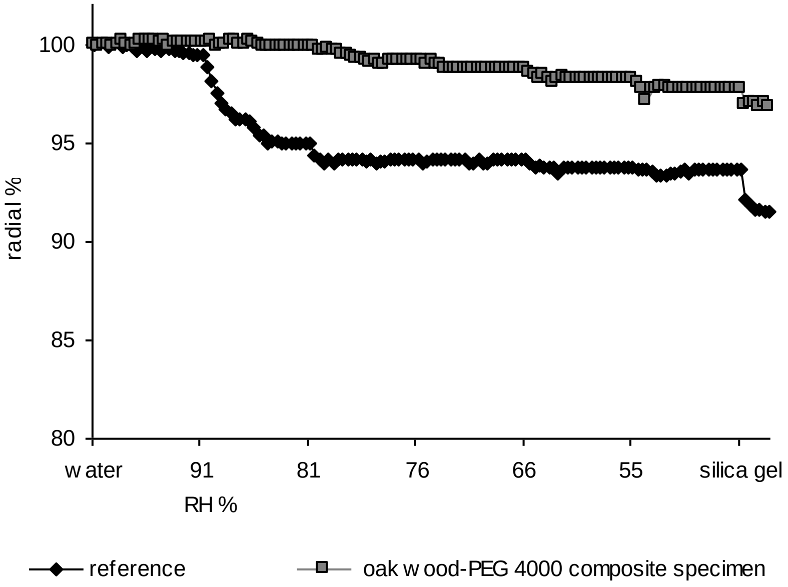

Figure 5-19. Radial shrinkage during the drying period of the specimen removed at the 5% level of the conservation programme (reference specimen with 0% PEG), and the specimen removed at the 75% level (oak wood-PEG 4000 composite specimen with 34% PEG).

As was the case with the Vasa oak wood-PEG 4000 composite specimen of experiment 5.3. (figure 5-7) the Vasa oak wood-PEG 4000 composite specimen of experiment 5.4. (figure 5-19) started to shrink in the radial direction during the phase of the drying programme when the RH of the atmosphere was lowered to 81%. The total of radial shrinkage obtained at the end of that drying period amounted to only c. 1%. During the drying phase at 76% RH the radial direction of the wood of the PEG 4000 composite specimen showed only slight further shrinkage. During the drying phases at the 66 and 55% RH levels, however, further shrinkage occurred that resulted in a total radial shrinkage of 1.8% and 2.3% at these RH levels respectively.

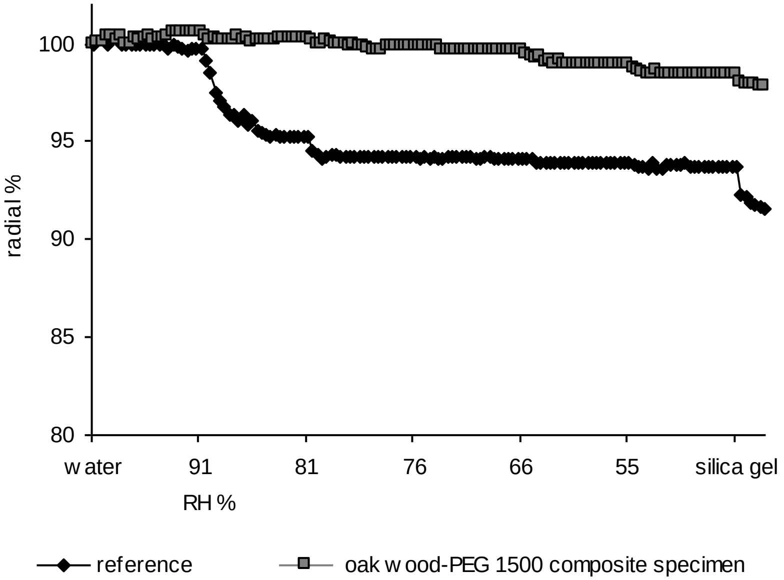

Figure 5-20. Radial shrinkage during the drying period of the specimen removed at the 5% level of the conservation programme (reference specimen with 1% PEG 1500), and the specimen removed at the 75% level (oak wood-PEG 1500 composite specimen with 32% PEG).

The radial direction of the wood of the Vasa oak wood-PEG 1500 composite specimen showed no shrinkage during the initial phases of the drying programme including the 76% RH atmosphere (figure 5-20). During the drying phase at the 66% RH level the PEG 1500 composite specimen shrank 0.8% in the radial direction and during the final phase of the drying programme, the 55% RH level, the PEG 1500 composite specimen shrank further in the radial direction to obtain a total shrinkage of 1.7%.

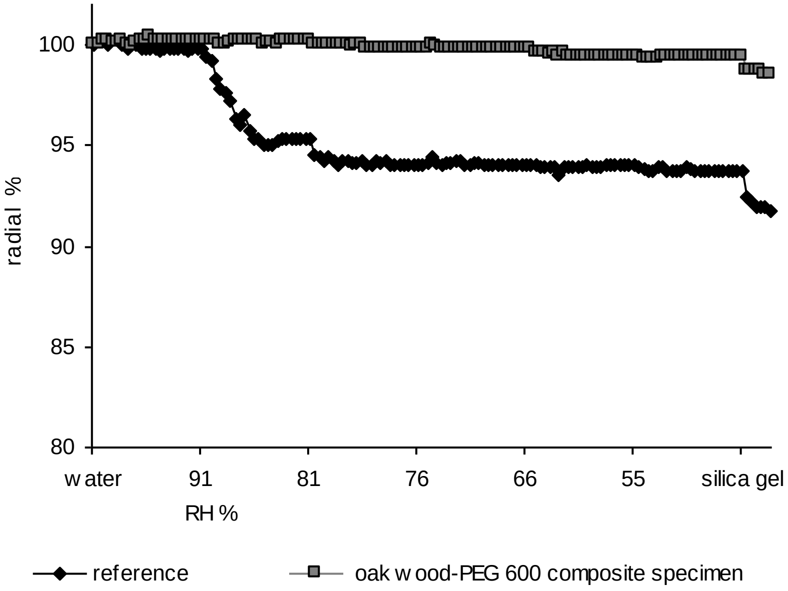

Figure 5-21. Radial shrinkage during the drying period of the specimen removed at the 5% level of the conservation programme (reference specimen with 2% PEG 600), and the specimen removed at the 75% level (oak wood-PEG 600 composite specimen with 30% PEG).

The radial direction of the wood of the Vasa oak wood-PEG 600 composite specimen like the radial direction of the wood of the PEG 1500 composite specimen did not shrink until the phase of the drying programme with 66% RH (figure 5-21) was introduced. At that level this specimen shrank 0.5% in the radial direction. During the final phase of the drying programme, the 55% RH level, the PEG 600 composite specimen showed no further shrinkage in the radial direction but ended up with a total shrinkage of 0.5%.

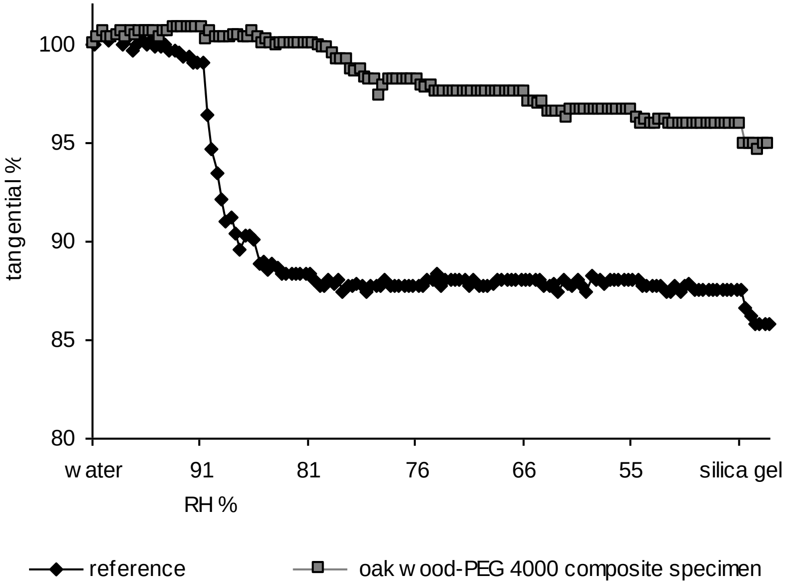

Figure 5-22. Tangential shrinkage during the drying period of the specimen removed at the 5% level of the conservation programme (reference specimen with 0% PEG) and the specimen removed at the level (oak wood-PEG 4000 composite specimen with 34% PEG).

As was the case with the Vasa oak wood-PEG 4000 composite specimen of experiment 5.3. (figure 5-8) the Vasa oak wood-PEG 4000 composite specimen of experiment 5.4.(figure 5-22) started to shrink in the tangential direction during the phase of the drying programme when the RH of the atmosphere was lowered to 81%. The total of tangential shrinkage obtained at the end of that drying period amounted to 1.8%.

During the drying phase at 76% RH, shrinkage in the tangential direction of the wood of the PEG 4000 composite specimen proceeded rather slowly and stabilized on a total shrinkage of 2.2%. Lowering the RH to 66% restarted shrinkage in the tangential direction and stabilized on a total shrinkage of 3.3%. During the final drying phase, at the 55% RH level, further shrinkage occurred that resulted in a total of tangential shrinkage of 4.2%.

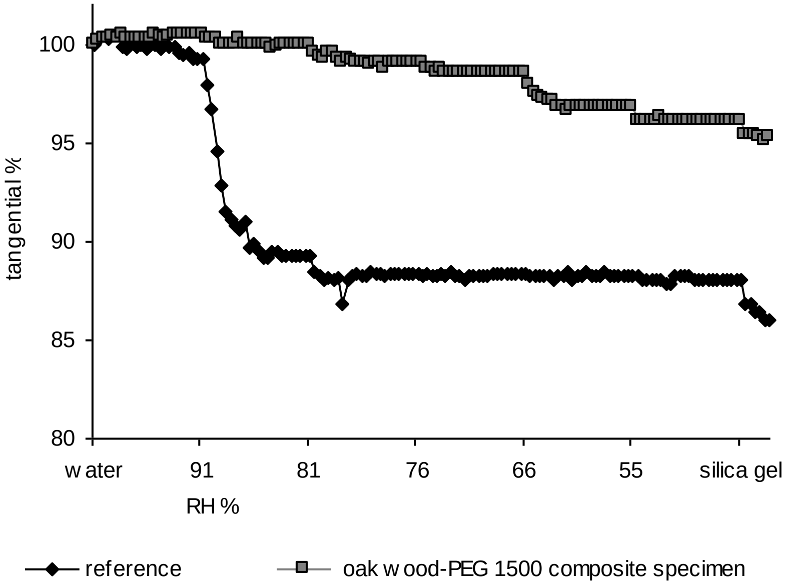

Figure 5-23. Tangential shrinkage during the drying period of the specimen removed at the 5% level of the conservation programme (reference specimen with 1% PEG) and the specimen removed at the 75% level (oak wood-PEG 1500 composite specimen with 32% PEG).

As was the case with the Vasa oak wood-PEG 4000 composite specimen (figure 5-22), the wood of the Vasa oak wood-PEG 1500 composite specimen started to shrink in the tangential direction during the phase of the drying programme when the RH of the atmosphere was lowered to 81% (figure 5-23). At equilibrium in that atmosphere the shrinkage in the tangential direction of the wood amounted to 0.8%.

During the subsequent phase of the drying programme when the RH of the atmosphere was lowered to 76% RH a minor shrinkage occurred that brought the total of tangential shrinkage to 1.3%. During the 66% RH phase a more pronounced shrinkage occurred that raised the total to 3.2%. This was about the same level of shrinkage as the Vasa oak wood-PEG 4000 composite specimen had shown. During the final phase of the drying programme, the 55% RH level, the PEG 1500 composite specimen shrank further in the tangential direction to obtain a total shrinkage of 3.8%.

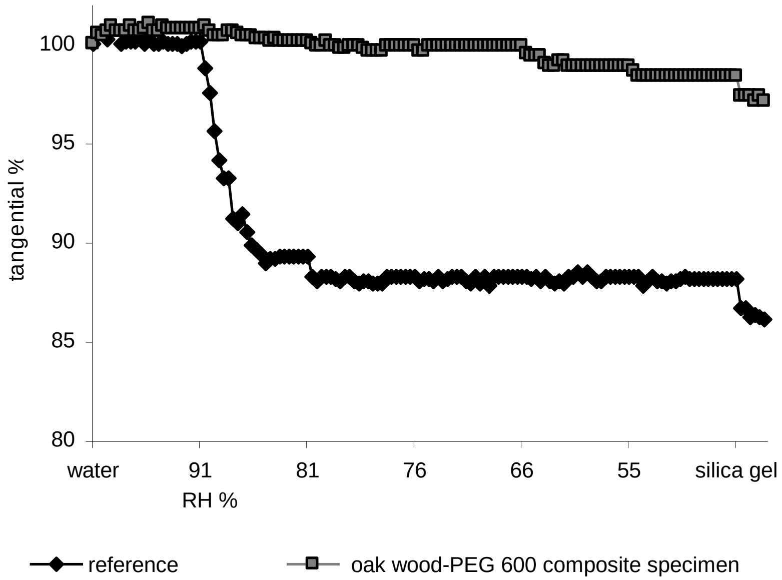

Figure 5-24. Tangential shrinkage during the drying period of the specimen removed at the 5% level of the conservation programme (reference specimen with 2% PEG) and the specimen removed at the 75% level (oak wood-PEG 600 composite specimen with 30% PEG).

The tangential direction of the wood of the Vasa oak-PEG 600 composite specimen showed no tangential shrinkage during the initial drying phases including the 76% RH atmosphere (figure 5-24). During the 66% RH phase the PEG 600 composite specimen shrank 1.2% in the tangential direction. During the final phase of the drying programme, the 55% RH level, the PEG 600 composite specimen showed only a slight further shrinkage in the tangential direction.

The reduction of shrinkage may be expressed by the ASE concept, as in the experiment 5.3. The ASE is calculated as the difference between the shrinkage of the reference specimen and the shrinkage of the test specimen taken as fraction of the shrinkage of the reference specimen. The specimen of the first conservation programme (the 0 – 5% PEG-programme) of each of the PEG 4000, 1500 and 600 series was chosen as reference of all the other specimens of that particular series. The ASE has been calculated for the shrinkage in the radial and the tangential directions of the Vasa oak wood-PEG 4000, 1500 and 600 composite series (table 5-IV) at 66 and 55% RH (figures 5-19 – 5-24).

To handle the ASE of the different anatomical directions and at the different RH of the equilibrium climates the designation of ASE is supplemented with R for radial, T for tangential and the RH level in brackets constituting the four different designations of ASE R(66), ASE T(66), ASE R(55) and ASE T(55).[125]

The two specimens that were preserved at the conservation programmes ending at 60 and 75% PEG concentration at each PEG molecular weight series, had reached a mean fraction of 30-34% PEG in their dry matter. The higher level of 34% PEG was found in the PEG 4000 composite and the lower level of 30% PEG was found in the PEG 600 composite with the PEG 1500 composite in between. With the conservation programme that ended at 45% PEG concentration the PEG fraction had reached from 25% for the PEG 4000 composite to 29% PEG for the composites with PEG 1500 and 600 respectively (table 5-IV).

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[125] Hoffmann, 1985, p 97.

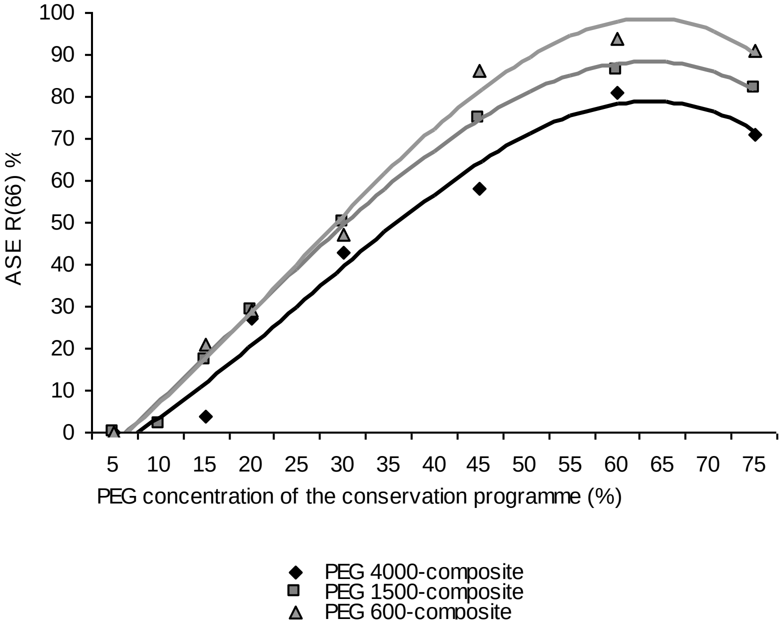

Figure 5-25. ASE at 66% RH in the radial direction of the Vasa oak wood-PEG 4000, PEG 1500 and PEG 600 composite specimens with the specimens removed at the 5% level of the conservation programmes as references.
Trend-lines; least square fittings.

The ASE-R values of the PEG 600 composite stays on top of the series with the PEG 4000 composite at the bottom and the PEG 1500 composite specimen in-between regardless of the fact that the fraction of PEG in their respective dry matter has the opposite ranking. Furthermore, the ASE-R values of the PEG 1500 and the PEG 600 composites follow each other closely until ASE-R values of 40% at 66% RH were reached. When the specimen was dried further at 55% RH the graphs of the PEG 600 and 1500 specimens started to diverge when ASE-R values of 30% were reached.

The ASE values presented below are mean values of the values obtained by the two specimens of each molecular weight PEG tested, that were preserved to an end concentration of 60 and 75%, respectively.

The maximum shrinkage reducing effect, 93% in the radial direction when the specimens were dried to equilibrium with a climate of 66% RH, was obtained by the PEG 600 composites. The corresponding values of the PEG 1500 and the PEG 4000 composites were 84 and 76%, respectively (figure 5-25). The highest ASE-T (66) value, 88%, was reached by the PEG 600 composite specimens while the ASE-T(66) values for the PEG 1500 and 4000 composite specimens amounted to 75 and 71%, respectively (figure 5-27).

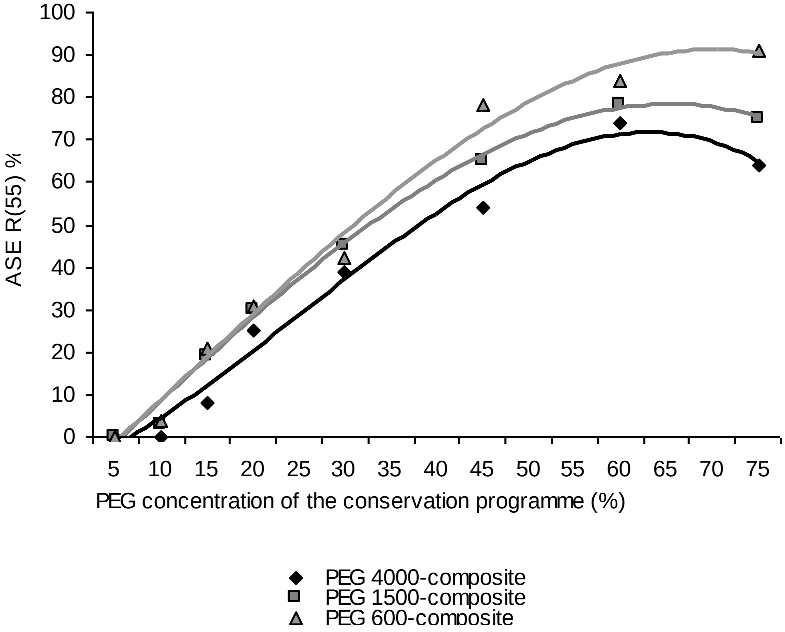

Figure 5-26. ASE at 55% RH in the radial direction of the Vasa oak wood-PEG 4000, PEG 1500 and PEG 600 composite specimens with the specimens removed at the 5% level of the conservation programmes as references. Trend-lines; least square fittings.

At equilibrium with a climate of 55% RH the ASE-R values reached by the specimens with a 30-34% PEG fraction of their dry matter showed the same ranking as at 66% RH but somewhat lower values, namely 88%, 77% and 69% for the PEG 600, 1500 and 4000 composite specimens respectively (figure 5-26).

As with the ASE-R values the ASE-T values of the PEG 1500 and 600 composite specimens stay close to each other at lower fractions of PEG in their dry matter both at climates with 66 and 55% RH.

At 55% RH the ASE-T values of the PEG 600, 1500 and 4000 composite specimens were 84, 69 and 67% respectively (figure 5-28).

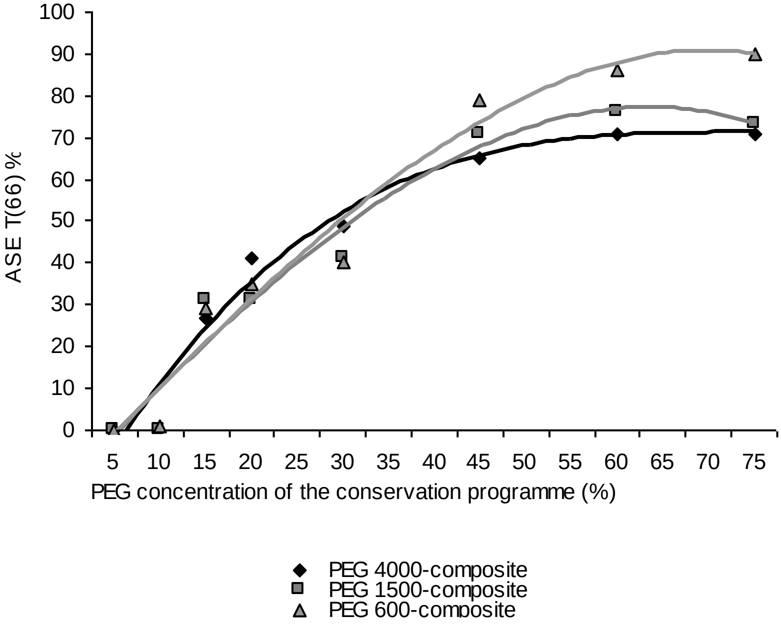

Figure 5-27. ASE at 66% RH in the tangential direction of the Vasa oak wood-PEG 4000, PEG 1500 and PEG 600 composite specimens with the specimens removed at the 5% level of the conservation programmes as references. Trend-lines; least square fittings.

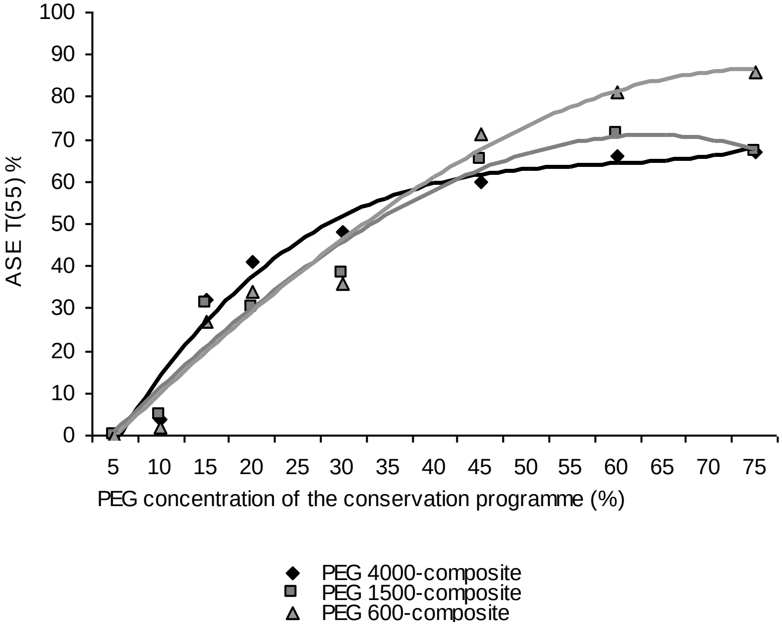

Figure 5-28. ASE at 55% RH in the tangential direction of the Vasa oak wood-PEG 4000, PEG 1500 and PEG 600 composite specimens with the specimens removed at the 5% level of the conservation programmes as references. Trend-lines; least square fittings.

The objectives of a dimension stabilising conservation project was defined as maintaining dimensions and shape of a wooden object. This would mean that ASE of 100% in both the radial and the tangential directions is the target. This experiment has shown that it is possible to get in reach of that goal.

The graphs of the diagrams (figures 5-25 – 5-28) show that the ASE increases with a growing fraction of PEG in the dry substance of the wood-PEG composite for all three tested PEG's, and that the increase of the ASE ceases when the fraction of PEG ceases to grow. This indicates that the shrinkage reducing effect is attributable to the PEG content. A difference in the shrinkage reducing capacity in favour of lower molecular weight PEG's also seems to be present.

5.5. Conclusions: Characteristics of the wood-polymer composite

In this section the wood-PEG composite has been considered. A number of 2.5 cm thick specimens were cut transversely from a deck-batten. This provided oak test specimens of 2.5 cm in the axial direction and a transverse surface of 9 by 9 cm. The short dimension in the axial direction was supposed to allow for an even distribution of PEG that would justify the characterisation of the preserved specimen as a Vasa oak wood-PEG composite with a defined fraction of PEG.

The transverse surface was equipped with 4 stainless steel nails for measurements in the radial and tangential directions.

The test specimens were preserved with PEG 4000 without showing any shrinkage during that procedure. The PEG-ratios obtained were as high as c. 65%. This meant that 40% of the dry weight of the wood-PEG composite consisted of PEG 4000. The radial and tangential measurements were performed during the drying programme. To calculate the effect of the PEG on the shrinkage behaviour the ASE (anti-shrink-efficiency) has been calculated for different RH values. The result in the axial, radial and tangential directions of 62, 63 and 61% ASE at 55% RH indicates that c. 60% of the shrinkage anticipated has been prevented.

Another experiment was performed with the same set-up and with the same type of specimens. In this experiment three series of eight specimens each were preserved with PEG 4000, 1500 and 600, respectively. From these conservation baths the test specimens were removed in succession at pre-chosen PEG-concentrations of the conservation programme. The test specimens removed were dried through the drying programme and eventually in vacuum with silica gel. This made possible calculations of PEG and water and also the ASE of the removed specimen.

The test specimens removed at 60 and 75% PEG-concentration of the conservation programmes had obtained dry weights with PEG-fractions of 30-34%. The ASE-R (55) values of the Vasa oak wood-PEG composites were 88, 77 and 69%, and the ASE-T (55) values were 84, 69 and 67% for the PEG 600, 1500 and 4000 respectively.

5. CHARACTERISTICS OF THE WOOD-POLYMER COMPOSITE

Evaluation of results is mainly connected to the comprehensive assumption expressed in section 2.5. of this dissertation, that polyethylene glycols (PEG's) are dimension stabilizing agents of wood from archaeological wet sites, meaning that PEG prevents or reduces shrinkage during the drying procedure of a PEG preserved piece of archaeological wood from a wet site, compared to an untreated sample of the same piece of wood.

The conclusion drawn is that the shrinkage reducing effect is attributable to the amount of PEG in the wood and that there is also an indication that lower molecular weight PEG's may have a higher shrinkage reducing effect. This may be explained by the size of the voids of the swollen secondary cell wall of the wood. The phenomenon has been investigated by Tarkow who found the upper limit of molecular size that could penetrate into the secondary cell wall of green Sitka spruce heart wood was the PEG 3000.[126]

The molecular mass distribution spectrum of the PEG's 4000, 1500 and 600 used for the conservation of the Vasa wooden material has been obtained for a surface sample of a plank from the upper gun-deck of the Vasa.[127] The figure shows that the PEG 4000 actually consists of a distribution of PEG's around the molecular weight of 3920 covering a range of ± c. 700 molecular weight units, the PEG 1500 has its centre molecular weight value at 1450 with a distribution covering a range of ± c. 500, and the PEG 600 has the molecular weight distribution of ± c. 500 around the centre molecular weight of 615. This gives a continuous molecular weight distribution from c. 100 to c. 2000 covered by the PEG 600 and 1500, then there is a gap of c. 1200 molecular weight units when the PEG 4000 starts at a molecular weight of c. 3200 and covers the range to the molecular weight of c. 4600.

If the internal voids of the capillary system of the secondary cell wall of the waterlogged Vasa oak are larger than those of the green Sitka spruce investigated by Tarkow larger molecules could penetrate into the cell wall material. This scenario might explain the effect of the PEG 4000 on the ASE values. Another possibility proposed by Tarkow is that the tertiary cell wall that forms a barrier for diffusion from the cell lumen into the

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[126] Tarkow, *et al.*, 1966, p 64.

[127] Sandström *et al*., 2003, figure 3, p 21.

secondary cell wall may be sensitive to temperature and permit larger molecules to pass through at elevated temperature.

Thus the result of the experiment does not contradict the assumption that polyethylene glycols (PEG's) are dimension stabilizing agents of wet site archaeological wood, meaning that PEG prevents or reduces shrinkage during the drying procedure of a PEG preserved piece of wet site archaeological wood compared to an untreated sample of the same piece of wood.

III: Implementation of the Conservation Programmes

Preparing for the housing of the Vasa hull and the salvaged material was the most urgent duty for the Board of the Vasa that in 1959 took over the responsibility for the Vasa project. As it soon was decided that the hull would be placed on a floating pontoon a suitable location had to be found. The chosen location was situated in the neighbourhood of the Naval dockyard and the present Vasa museum. The site was contracted for a period of 6-7 years. This was supposed to be enough time for the hull to be preserved and made ready for exhibition, and for a permanent Vasa museum to be ready to receive the Vasa hull.

The loose material was brought to the naval dockyard where it was kept in water tanks. A 700 m^2 building was constructed within the space of the Naval dockyard, equipped for the conservation of the loose wooden material, the metal, the textile and the leather from the Vasa. This building was ready at the beginning of 1962, and it was contracted for a period of 5 years.[128]

The Vasa hull

The purpose of the treatment of the Vasa hull with PEG-solution was to prevent or at least diminish the shrinkage of the wood when drying, that would be brought about by bringing an amount of PEG into the cell walls of the wood. This was planned to be achieved by a diffusion process that was to be started by bringing a conservation solution of a low PEG-concentration in contact with the waterlogged wood. This contact was intended to last until equilibrium was reached between the PEG-concentration of the conservation solution and the PEG solution forming inside the wood. At that point the PEG-concentration of the conservation solution was to be raised, which would restart the diffusion process. The cycles of raising the PEG-concentration of the

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[128] Claus, 1986, pp 137-155.

conservation solution followed by a suitable diffusion period were to be repeated until the desired level of PEG in the wood had been reached.[129]

Assessment of the results of the treatment with PEG is based on analyses of samples of wood cores drilled from the timbers of the Vasa hull at chosen points of time during the treatment and drying periods. Such samples have been taken from 1962 to 1992 from the units of planking and ceiling of the Vasa hull. In order to avoid too much influence from the annual cycles of temperature- and RH-values the core samples were drilled at the same time of the year, that happened to be at the end of the summer period.[130] For the assessment it is anticipated that the treatment of the ceiling was similar to that of the planking. From 1975 to 1992 core samples have been drilled also from the wales that are specially thick timbers of the planking. The wales have been treated in exactly the same way and by the same spraying equipment as the rest of the planking.

Oak wood was the main construction material of the Vasa hull. Pine wood was mainly used for sculptures and panelling. However, the foremost part of the rider construction, the so-called riding bitts,[131] for belaying the anchor cable was built from one large oak beam with a cross-section measuring c. 30x30 cm that had been reinforced by a beam made of pine with a half circular cross-section of a radius of c. 15 cm. This pine beam that is situated on the lower gun-deck represents the heavy pine material inside the Vasa hull, while the heavy oak material is represented by c. 10 heavy items from inside the Vasa hull.

However, two thirds of the planks of the orlop deck are made of pine wood, while one third is made of oak wood. The oak planks measures c. 60 mm in thickness while the pine planks are a little thinner and measures c. 55 mm. These two parts of the orlop deck represent constructive oak and pine material of minor dimensions inside the Vasa hull.

These circumstances provide an opportunity to compare the results of the conservation treatment with focus on the two wood species mentioned.

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[129] Håfors, 2001, chap. 4-6.
[130] Håfors, 2001, pp 101-104.
[131] Cederlund, 2006, p 478 (glossary).

The loose objects and construction timbers

The excavation of the Vasa hull together with the sculptures and large timbers that had disconnected from the hull and were salvaged separately from the Vasa underwater site provided a huge amount of wooden material for immersion conservation.[132] Some material, like the large middle timber of the main mast that was going to be treated by immersion had been removed from the hull before this was built into the pontoon super structure.

Since the immersion procedure meant that the wooden objects were surrounded by the conservation solution during the entire conservation treatment period this was considered more reliable than the spraying treatment. It was also supposed to produce a faster conservation process but how fast was not easy to be decided.

The laboratory experiments of PEG treatment in a solution that were started at the same time as the conservation treatment of loose wooden material provided a basis for successive development of the immersion conservation programme during the entire conservation period.

The immersion conservations period started in 1962, and it was finished in 1977. During that period 20 batches of wooden material were treated in two large steel tanks with usable volumes of 34 and 42 m^3, respectively, and one small tank of a volume of 2.5 m^3.

All objects and timbers that were placed in the conservation tanks were given a support made to fit the particular object. The supporting constructions were mostly made of pine wood. These had to be designed individually for each object in the tank which made starting a conservation batch rather time consuming. As it was important that the waterlogged wooden objects did not dry during the period of placing the objects in the tank water was always pumped into the tank to cover the material in the afternoons. In the mornings, the smallest volume of water was pumped away, to be able to proceed with the work.

Special concern was taken not to obstruct the flow of conservation liquid when placing the selected material in a conservation tank. This entailed

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[132] Håfors, 2001, pp 4-5.

the rather low fraction of c. 30% of the usable volume to be occupied by wooden objects for conservation including supporting material. This in turn entailed volumes of conservation solution of between 25 and 35 m^3 to be handled at each conservation procedure in the large tanks.

Management of the conservation treatment

Director General Luis Monreal in his speech at the ICOM 19th General Conference, devoted to the subject of museum management, recognises the team as the crucial unit in museum work. His keynote speech underlines that "…museums have not generally been characterized by their ability to form teams. The most obvious reason is that museums require a heterogeneous staff to accomplish its many functions, with professionals from diverse horizons and different interests working together. Communication difficulties between staff members are widespread, a situation which often is exacerbated by the difficult conditions under which they work, the lack of recognition for their work, professional jealousy, modest salaries, etc. An art historian, an economist, a chemist, a restorer, an educator, a fund-raising specialist, a photographer, etc., may have little in common, but nevertheless all these professionals, and doubtless a few others, may be working under the same roof".[133]

The role and significance of a museum collection is the most important parameter and guides all the work of the museum. It must be formulated in museological terms and authorized by the museum director to the guidance of the managers of the different fields of museum activities. Otherwise everyone of these may create their own image of the goal of the museum. This demands by necessity that the chief manager of the museum has a disciplinary specialization with focus on its collection. As expressed by Stephen Williams where natural history collections are the subject: "Finally, the management function requires competency in a disciplinary specialization involving the collection in question. This is essential for the sake of understanding the 'language', and the 'relationships' associated within the collection. Without this knowledge, activities such as information management, retrieval and replacement of

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[133] ICOM News, Newsletter of the international council of museums, volume 54, 2001, No. 3, p 14.

collection items, problem identification, and simple communication, are severely impaired."[134]

Although the need of academic competence in chemistry is generally recognized for the care of archaeological finds, it has been very hard to persuade a museum director that "conservation" might be an academic discipline as well as chemistry. Recognition of conservation as a discipline on its own in the academic world as is the case since 1985 in Sweden, might change this situation and gradually give the competence needed to accomplish conservation work. It might also prepare museums to take responsibility for continuing development of the competence of the conservation staff.

Not as much by own experience, as by talking to colleagues, this author has noted that conservation still in many cases is considered as activities performed in order to bring museum objects into presentable shape for an exhibition. As a result the conservation staff generally is not considered as a necessary part of the museum team, and sometimes is thought of as dispensable - at least for a time - if money has to be saved. This is, after all, more rare in museums where responsibilities lie within the archaeological and, especially the wet site archaeological field. However, when preserved archaeological finds come into the possession of a museum with a mixed collection of ethnographical and anthropological materials, it may happen that even for archaeological finds, there is no continuing surveillance by experienced senior conservation staff. This is, in the author's opinion, not acceptable. Managing conservation should be an integrated part of the work in every museum.

The work with spraying the hull and carrying through the immersion conservation programmes was the responsibility of the conservation department.

The work was to be done according to plans made up jointly with the other departments and the museum director. Two plans existed, one for the current year, and one for a longer period. Both of these plans were to be authorized by the museum director.

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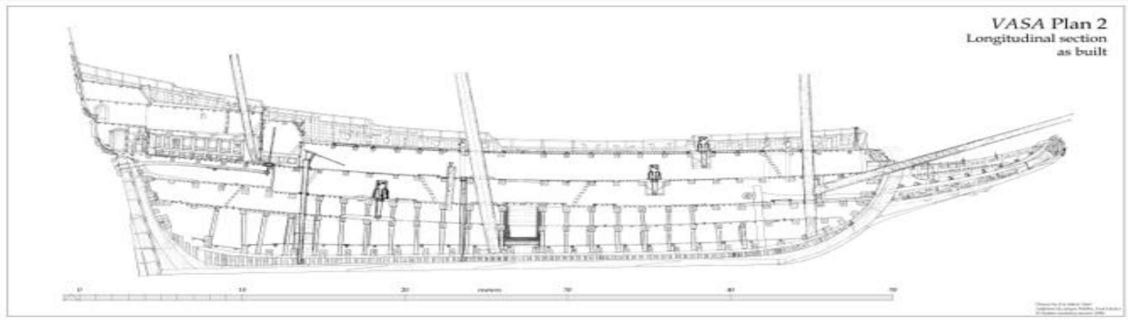
[134] Williams, 1999, pp 146-147.

The Vasa as built

As no construction plan had existed for building the Vasa, the present plan has been produced as part of the reconstruction work by careful measuring and drawing of construction parts and separate items since the hull was salvaged in 1961 until present days. This drawing is a result of the work.



6. The Vasa Wood

Anders Franzén, who relocated the Vasa based his opinion that the Baltic Sea would contain wooden shipwrecks in a good condition on the fact that the shipworm, *Teredo navalis*, did not exist in the Baltic.

The Vasa hull was built mainly of oak. This timber may reasonably have been procured from the oak forests in Sweden belonging to the Swedish Crown. Northern Europe was another provenance for timber for building of Swedish war-ships. According to the accounts of the Crown's dockyard in Stockholm,[135] that was charged with the construction of the Vasa, oak wood was bought from northern Europe through shipping ports in Holland, and from Königsberg and Riga.[136]

6.1. Strength of the Vasa wood

The strength of the wood was a necessary condition for the salvage operation. Therefore the initial concern about the Vasa wood was to answer the question whether it would have enough strength to withstand the impact of the forces of the lifting arrangements during the salvage procedure. The strength of the wet Vasa oak therefore had to be ascertained. In 1958 a piece of Vasa oak was sent to the Swedish Forest Products Research Laboratory for testing.[137] The strength parameters to be determined were:[138]

- Compressive strength in the grain direction (σ_t)
- Bending strength (σ_b)
- Hardness perpendicular to the grain ($H\perp$)
- Impact strength (A_B)

From the numerical values of these parameters, it appears that the compressive and bending strength of the Vasa oak was somewhat above half the standard values voiced in handbook literature for recent oak, and the impact strength was slightly above 25% of the corresponding value

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[135] Cederlund, 2006, p 39.
[136] Barkman, 1967, p 3; Håfors, 1987, pp 98 and 133.
[137] Claus, 1986, p 276.
[138] Barkman, 1967 pp 5-6; Barkman 1975, p 66.

for recent oak. The hardness of the wet Vasa oak was nearly two thirds of the same parameter for recent oak. The density (r_{ou}) of the Vasa oak was about 70% of the value of the same parameter for recent oak.[139] Since traces of fungi had been found only in the surface layer of the oak, Barkman ascribed this loss of matter to deterioration processes probably caused by bacterial and chemical decay, or other forms of corrosion.[140]

6.2. Macromolecular components of the cell wall of oak wood the Vasa

To proceed with the task of assessing the quality of the Vasa wood Barkman took six core samples from oak wood in different parts of the hull immediately after its salvage. Each sample was drilled right through the wooden member. The cores were sent for analysis to the Laboratory of the Swedish Cellulose Industries (Swe.: Svenska Cellulosaindustrins Centrallaboratorium, CCL) in Stockholm.

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[139] Barkman, 1967, p 5.

[140] Barkman, 1967 p 6; Barkman 1975, p 66.

Sample		Ash (%)	Lignin * (%)	Pentosane * (%)	Cellulose and other hexosanes (%)
From the "*Vasa*":					
	Surface	1.33	25.14	17.77	57.09
Hold	Middle	1.45	27.11	18.67	54.23
	Surface	1.41	26.65	18.00	55.35
	Surface	4.06	27.74	18.00	54.26
Lower gun-deck	Middle	1.74	27.07	18.50	54.43
	Surface	1.67	27.65	19.32	53.03
	Surface	1.32	22.65	17.77	59.58
Upper gun-deck	Middle	1.26	24.99	17.77	57.24
	Surface	1.51	23.01	19.40	57.69
	Surface	3.64	31.39	16.50	52.11
Wale No 6, BB, 6 m from the stern	Middle	7.16	26.06	17.10	56.84
	Surface	3.06	25.61	20.20	54.19
	Surface	2.90	27.23	17.70	55.07
Wale No 6, SB, 6 m from the stern	Middle	2.51	22.46	-	-
	Surface	2.42	22.23	19.20	58.57
	Surface	1.48	25.19	19.20	55.61
Keel, 3 m from the stern	Middle	1.11	23.56	21.20	55.24
	Surface	1.43	24.49	19.30	56.21
From "*Gröne Jägaren*":		2.13	39.28	9.53	51.19
Recent oak:		0.26	27.54	23.40	49.06

Table 6-I. Ash, lignin and pentosane in oak from different parts of the Vasa hull. Cellulose and other hexosanes are calculated as residues.
* = Calculated on ash-free weights.
Source: Laboratory of the Swedish Cellulose Industries, in Stockholm.

The substances chosen to give information about the deterioration pattern were ash, lignin and hemicelluloses represented by pentosane as its main constituent. Before analysis each core sample was cut into three portions. Two of these contained the surface layer of the wood that either had been exposed to the surrounding environment or remained hidden in the ship side construction, whereas the middle part had not been subjected to direct exposure to the environment. For comparisons were added one sample of recent oak and one sample of oak from another 1700th century shipwreck, "*Gröne Jägaren*", situated in the Stockholm archipelago at an under-water site with a higher velocity of water movement than at the Vasa wreck site.

As mentioned above there was a 30% loss in volumetric weight (r_{ou}) of the Vasa oak compared to recent oak. This implies that 30% of the wood substance had been lost during the more than 300 year submersion of the hull in the Stockholm harbour. This loss may have affected each of the macromolecular cell wall components either proportionally, or differently. Using as reference the sample of recent oak analysed together with the batch of samples from the Vasa hull and calculating the loss of each of the macromolecular fractions from the mean values of lignin and pentosane respectively of the analysed samples from the Vasa hull (published by Barkman),[141] and the loss in volumetric weight given above, the lignin fraction has lost 35%, the pentosane fraction has lost 44% and, the cellulose and other hexosane fraction has lost 21% of their original molecular materials respectively. If the loss in volumetric weight of the oak wood of the "*Gröne Jägaren*" would be of the same magnitude as the loss in volumetric weight of the Vasa oak the analysis would mean that no lignin had been lost but as much as 73% of the pentosane fraction and 25% of the cellulose and other hexosane fraction.

Analysis of the macromolecular components may provide information about the capillary system of the cell wall of the hydro-archaeological wood to be preserved. The state of the capillary system is decisive for the feasibility of using a bulking method for dimension stabilizing conservation, and if PEG is to be used, and even to predict which molecular weight PEG that will be the most suitable.[142]

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[141] Barkman, 1967, p 7.

[142] Hoffmann, 1982, pp75 and 83.

6.3. Old and new corrosion products in the Vasa wood

During the long period when the Vasa was resting on the seabed the iron bolts that had held the timbers together had rusted away.[143] Apart from the bolts there was a large amount of iron cannon balls that although their shape and dimensions were unchanged, sometimes had lost as much as 80% of their original weight. Part of the iron that had oxidised and dissolved eventually had precipitated on the wooden surfaces as stalactite- and stalagmite-shaped structures. These were removed mechanically from the surface of the wood during the cleaning procedure.[144] Some of the stalagmite/stalactite-shaped structures were, however, kept as documentation at the conservation laboratory.

In 1963 samples of the sail cloth that was found in the sail locker inside the Vasa hull were sent to the laboratory of the Geological Survey of Sweden (SGU; Sveriges Geologiska Undersökning) for analysis of some stains which should be removed before conservation of the sails. Along with the sail samples some samples of the stalagmite/stalactite-shaped structures were sent for analysis to gain knowledge of their chemical composition.[145]

The analyses made in 1962 by the CCL laboratory revealed a much higher ash content of the oak samples from the hull of the Vasa compared to the sample from recent oak (table 6-I). A large proportion of the ash consisted of iron salts.

The analyses were performed under personal guidance of Dr. A.M. Asklund, head of the chemical laboratory at SGU. In order not to change the minerals composing the corrosion products the choice was to use a dry method for analysis, why the samples were submitted to x-ray analysis. As the x-ray spectra were too diffuse to give any information of interest, the SGU laboratory went on instead to do chemical analyses. As it was observed that the structures consisted of a dark inner core surrounded by a brighter layer the structures were mechanically separated into core and outer layer materials respectively, making two different samples. A portion of each sample then was dried at 110 °C and analysed in accordance with the classical analytical procedure. The

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[143] Håfors, 2001, p 16.
[144] Håfors, 2001, pp 122-123.
[145] Barkman, 1967, p 20.

analyses showed that both samples contained iron salts but with a significant difference between the dark core and the light coloured surface material regarding the proportions between 3-valenced (ferric-) and 2-valenced (ferrous-) iron-ions. The core material showed a ferric- to ferrous-ion proportion of 7 to 3 whereas this proportion was 9 to 1 in the surface material.

The rather high proportion of ferrous-iron in the samples of core material led to an assumption that metallic iron might also be present, so these samples were tested with a magnet. This test separated a strongly magnetic phase which proved to be magnetite (Fe_3O_4) from the core material. The analyses showed that the core also contained iron sulphides (FeS) and siderite ($FeCO_3$). The surrounding layer contained hydrated iron sulphates ($FeSO_4 \bullet x\ H_2O$) and some clay material. Asklund considered the crystallization of a magnetite at the defined pH- and redox-setting in the Vasa wreck during 300 years, in fact a kind of unintentional in situ laboratory experiment, to be of interest for understanding the formation of iron ore.[146]

Spots of precipitate were, however, observed to develop on the surfaces of several of the Vasa sculptures unearthed during the excavation of the Vasa hull in 1961. Most of these spots were white in colour and easily dissolvable in water. Sometimes though, there was an accompanying phase of darker material which was not possible to be dissolved in water.

In July 1963 Barkman sent samples of the newly identified white precipitate from four sculptures and a sample of corrosion products taken from a bolt hole for X-ray diffraction analysis.[147] Analysis of the precipitate from the sculptures showed that the easily dissolvable part consisted of hydrated ferrous sulphates ($FeSO_4 \bullet 4\ H_2O$ and $FeSO_4 \bullet 7H_2O$), in some cases accompanied by a grey or brown phase that was identified as ferric oxide (Fe_2O_3). The sample of corrosion products from the bolt hole was separated into a yellowish and a brownish part that were identified as ferrous carbonate ($FeCO_3$) and hydrated ferric oxide ($Fe_2O_3 \bullet H_2O$), respectively.

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[146] SGU, Mineralkemisk undersökning UD4.
[147] KI, 1963 07 19.

In contrast to the old rust the new precipitate was easily dissolvable in water so it could be removed from the wooden surfaces whenever it made its appearance and therefore no special measure was taken against it.

However, salt infestations were reported during the period as a severe problem by conservators. In 1981, at the WOAM meeting in Ottawa, Jacqui Watson, conservation officer at the Ancient Monuments Laboratory in London, said during a discussion about the use of pre-treatment of archaeological wood from wet sites with EDTA to remove iron in order to enhance penetration of PEG into the wood during conservation: ”I have found with the surfaces of many of my artefacts that they are actually becoming minerally replaced with some of these iron salts, and if I start taking them out after treatment a lot of surface detail is lost.”[148]

At the joint meeting of the ICOM-CC working groups on wet organic materials and metals in 1987 in Fremantle a report was given by conservator Kirsten Jespersen about outbursts of white precipitate on the PEG treated oak wood of the Viking ships in the museum of Roskilde.[149] Investigation led to the conclusion that the white precipitate consisted of tetra-hydrated ferrous sulphate ($FeSO_4 \bullet 4\ H_2O$). Jespersen assumed that pyrite was the origin of the sulphates. She pointed out that the volume of the resulting sulphates is three times that of pyrite, implying that the transformation might mechanically damage the wood. She referred to a report by Francis Howie at the Natural History Department of British Museum saying that pyrite material would be stable only below 60% RH. So she deduced the cause for the outbursts to the fact that the RH in the museum had been allowed to fluctuate with greater amplitude than earlier, at the time when the outbursts had first been observed. The remedy applied was to lower the RH to 50 – 55% in the museum instead of the 60 – 65%-interval that had been the control values earlier, and which is considered as the most suitable RH-interval for wood treated with PEG 4000.

At the time when Jespersen presented her report about the salt outbursts on the Viking ships the Vasa still was slowly drying in the pontoon super structure at an atmosphere with RH mean values of 65% and higher.[150]

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[148] Proceedings of the ICOM Waterlogged Wood Working Group Conference, Ottawa 1982, p 284.

[149] Jespersen, 1989, pp 141-150.

[150] Håfors, 2001, pp 101-107.

No salt outbursts had occurred so far on the Vasa hull. As to the immersion treated loose finds that had been slowly dried in the climatic storage rooms, salt precipitation had arrived on to the wooden surface. These precipitations had been removed in a manual cleaning procedure. This was repeated several times as the dissolved salt arrived at the wooden surface where it precipitated when the water evaporated. The Vasa conservation laboratory had not until then considered this a cause for alarm.

However, in the autumn of 2000 a growing amount of white and yellowish spots were observed on the timbers of the Vasa hull.[151] Investigation as to the nature of the spots revealed that they were sulphate salt precipitations mostly of high acidity ($pH < 2$).[152] The pH value reported from the outbursts on the Viking ships was 3.5.[153] Analysis made clear that the salt precipitations on the Vasa contained sulphuric acid that was the reason for the low pH values. The high acidity may have caused damage to the wood by acidic hydrolysis of the wood macromolecular components.[154]

The origin of the sulphates in the Vasa wood have been traced to the circumstances at the Vasa under water site in the Stockholm harbour. Here sulphates dumped as garbage have been reduced and transformed into hydrogen sulphide that has penetrated into the wood of the Vasa. Inside the wood the sulphide has been oxidized to elemental sulphur. When the Vasa wood that contained the elemental sulphur came into contact with the oxygen of the atmosphere the oxidation of the elemental sulphur started.[155] The formation of sulphuric acid and sulphate salts with iron or other cat-ions e.g. ferrous sulphates ($FeSO_4 \bullet x\, H_2O$) is the ultimate result of the oxidation process. The formation of sulphates that usually crystallize in hydrated forms is resulting in the elemental sulphur replacement by molecules at least three times as large. This also means that beside acidic deterioration there might be a mechanical damage, when the crystallization occurs inside the wood.

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[151] Sandström, M., *et al*., 2003, p 22.
[152] Fors, 2002, p 1.
[153] Jespersen, 1989, p 145.
[154] Fors, 2002, p 9.
[155] Sandström, M., *et al*., 2003, pp 43-44.

The oxidation might proceed until all elemental sulphur is consumed. As the rate of formation of spots on the Vasa accelerated there was a need to find a remedy to counteract this process. Jespersen had found that in the case of the Viking ships the salt formation on the wood had been slowed down by lowering the RH of the exhibition hall of the Viking ships.

The RH and temperature values of the Vasa museum exhibition hall have been thoroughly monitored, continuously since the opening of the museum in 1990, initially with the thermo-hygrographs brought with the hull from the pontoon super structure,[156] and from the autumn of 1991 with a computerized system in the permanent Vasa museum (figures 6-1, 6-2). At the outburst of spots in 2000 there had been values of 65% RH and higher during most part of July and August, that year,[157] when the climate should have been controlled at 60% RH.[158]

RH-values have been registered since the opening of the Vasa museum (figures 6-1, 6-2). The diagrams show the mean RH-values at three levels close to the outside of the Vasa hull, and at four levels inside the Vasa hull during a period of eight years. From 1994 when the climate seems to have stabilised the mean RH-values of measurements outside the Vasa hull at the level marked ”high” did not exceed 60% at any time. At the intermediate level the mean RH-values exceeded 60% during each of the four later years of the period and at the level marked “low” the mean RH values exceeded 65% during each of the two years in the middle of the period of the study.

The difference between RH values measured during the summer period at low and intermediate levels in the Vasa museum amounted to c. 5 percentage units during each of the four years of the early part of the period of the study (figure 6-1).

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[156] Håfors, 2001, pp 97-99.
[157] Sandström, T. *et al.*, 2002, p 62.
[158] Håfors, 2001, p 96.

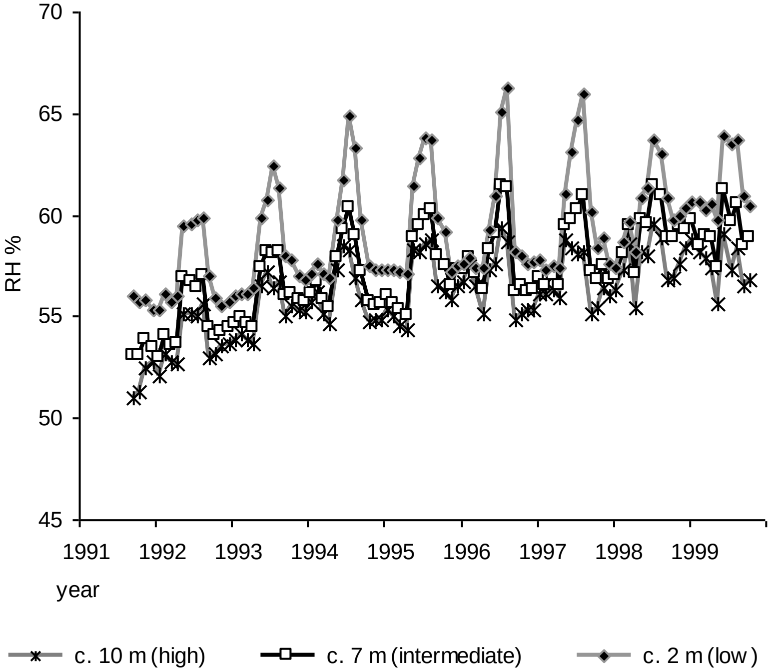

Figure 6-1. Mean RH values (%) in the Vasa museum close to the outside of the Vasa hull at c. 2 m (low), at c. 7 m (intermediate), and at c.10 m (high) above the keel level.

Inside the Vasa hull the RH-values registered in the hold resemble the low values from the outside but remained at c. 2 percentage units higher level than those. The same applies to the RH-values registered in the lower-gun-deck compartment compared to the RH-values registered at the intermediate level on the outside of the Vasa hull despite the fact that the atmosphere of the lower gun-deck through the gun-ports was in direct contact with the atmosphere of the museum.

The RH-values registered on the upper deck, however, are practically identical with the RH-values registered at the 10m level ("high") at the outside of the Vasa hull. Both series remain at a c. 2 percentage units lower RH-level than the current control values. The RH-values registered on the poop deck, that represent a still higher level of the museum atmosphere, remain at a c. 5 percentage units lower level than the current control values.

Like Jespersen the management of the Vasa museum decided to choose lower RH- and temperature levels for the museum atmosphere. The control value of the RH was lowered to 55 ± 4% to be kept all through the year, and the temperature level was to be kept below 20°C.[159] Some redesigning of the air-conditioning plant was also performed.

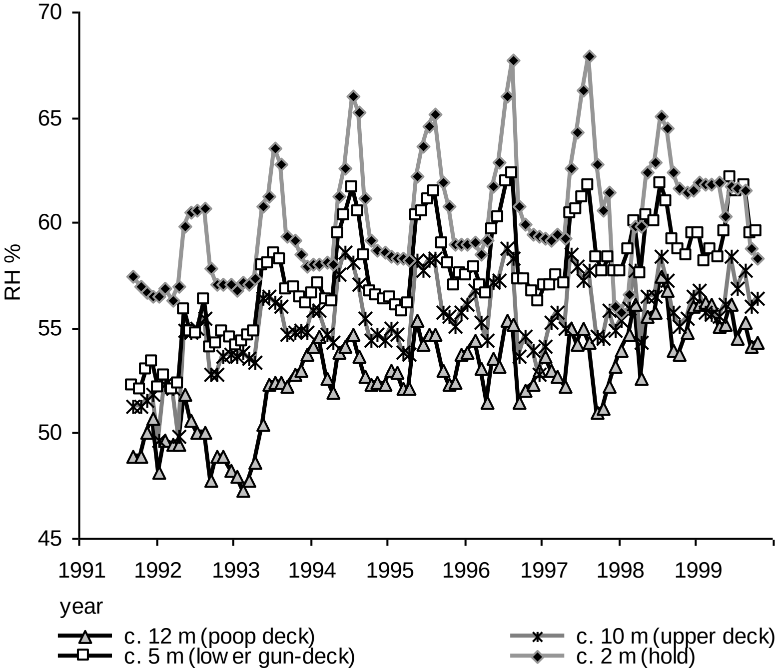

Figure 6-2. Mean RH values (%) inside the Vasa hull at c. 2m (hold), at c. 5m (lower gun-deck), at c. 10m (upper deck), and at c. 12m (poop deck) above keel level.

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[159] Sandström, T., *et al.*, 2002, p 65.

Beside the salt infestation there is the problem of the high acidity of the Vasa wood and some related hydro-archaeological finds. The intent to find a suitable way of neutralizing the sulphuric acid has been established as a most important item on the joint agenda of the Vasa museum and the other museums having the same problem.[160] Two methods have been tested, namely: sodium hydro-carbonate solution in water on the Vasa wood,[161] and ammonia in gas-phase on wood from the Batavia.[162] The effect of the borate in the spraying solution used on the Vasa hull as a neutralizing agent has also been evaluated.[163]

Jespersen stated that the PEG was not affected but was displaced by the ferrous sulphate formed in the oxidation process. The salt crystals were observed to have a pH value of 3.5.[164] In 1967 the conservation solution sprayed on the Vasa hull had raised the pH value of the oak of the keel to 4.5 in the surface to a depth of 38 mm according to one core sample. Another core sample showed a pH value of 4 to a depth of 105 mm. No lower pH-value than 2.5 was registered at the investigation (figure 6-3).

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[160] Hall Roth and Malmberg, 2005, p 172.
[161] Fors, 2002, p 30.
[162] Conservation of Wet Wood and Metal, Fremantle 1987, Western Australian Museum 1989, p 151.
[163] Sandström, M., *et al*., 2003, pp 39-41.
[164] Jespersen, 1989, p 145.

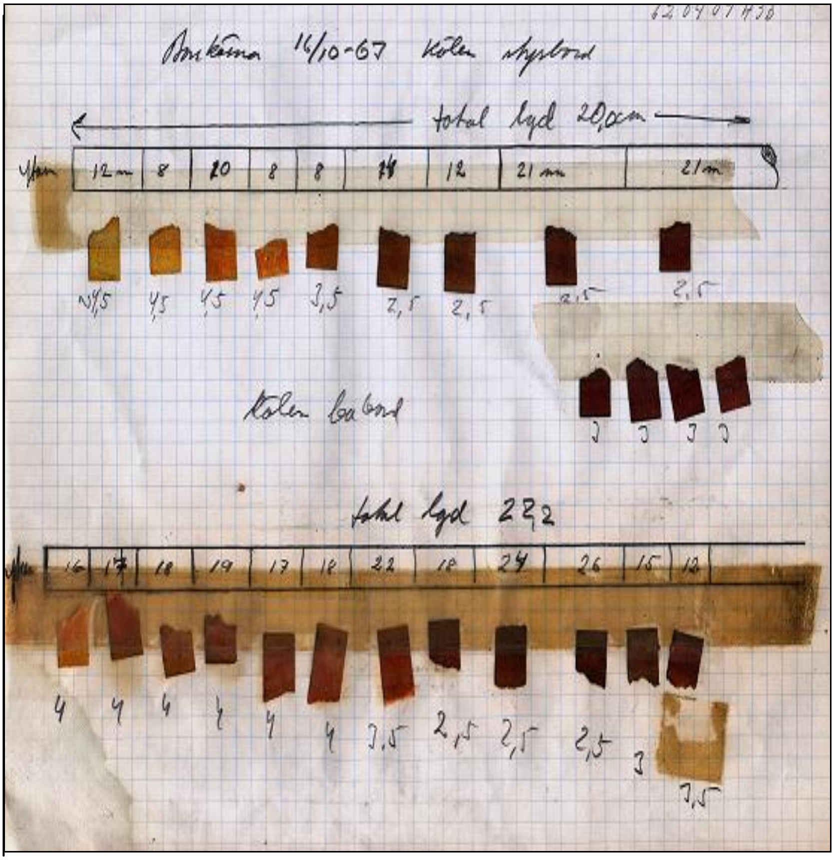

Figure 6-3. The liquid in each piece of two core samples from the keel of the Vasa was squeezed into pH test paper in a carpenter's bench. The pieces of pH test paper have been mounted on to a paper sheet with sketches of the wood cores and with the pH readings made at the time of the experiment.[165]

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[165] Experiment and collage was performed by Lars Barkman, 1967, The Archives of the Swedish Maritime Museums.

Two drawbacks have been introduced to PEG treatment of hydro-archaeological wood by a simultaneously on-going sulphur oxidation process. The first is that if the H_2SO_4 molecule degrades the PEG molecule, there is a great disadvantage in using PEG as a bulking substance for dimension stabilizing of archaeological wood from wet sites.

The second is the circumstance that two museums have lowered the RH of their exhibition halls to control the oxidation of elemental or sulphide sulphur which is also a drawback to dimension stabilizing treatment with PEG, depending on that restrictions are imposed to the role of the RH as a dimension stabilizing factor of the wood-polymer composite.

However, a micrograph of oak wood from the Vasa hull prepared in 1994 with a special laser ablation technique showed a rather undamaged quality of the wood.[166]

The situation stresses the importance of making a thorough examination before salvage of wet archaeological wooden material. As a comparison, a few samples from the Swedish warship "*Kronan*" that have been analysed have shown a mean sulphur content in the wood of c. 1%.[167] The recommendation given by the experts is to postpone the salvage until satisfactory conservation treatment has been developed.[168]

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[166] Stehr, M., 1999, p 9, Figure 2.

[167] Sandström, M., *et al.,*2003, p 33.

[168] Sandström, M*., et al*., 2003, p 33.

7. Conservation of the Vasa hull

The Vasa hull has been subjected to spray treatment for a period of c. 18 years with a solution of PEG in water.[169] A climate with a high relative humidity during the conservation treatment, has been stressed as important for diffusion of the PEG molecule, and consequently it is important for developing the shrinkage controlling capacity of PEG.[170] However, there may have existed unintended differences of climatic parameters of the outside of the Vasa hull compared to the situation inside the hull. This may be due to the circumstance that the interior of the hull was more sheltered than the exterior and also more difficult to reach by air-conditioning measures. To assess possible differences in the diffusion situation of the PEG molecules in the planks of the ceiling of the Vasa hull, compared to the diffusion situation in the outside units of planking, the core samples taken in the ceiling and the planking, respectively have been evaluated separately.

The circumstance that the lower part of the interior of the hull had no direct communication with the surrounding climate of the museum while the upper part communicated with the museum climate through the gun-ports in addition to openings upwards through larger hatches in the gun-decks than deeper down into the hull, points to possible climatic differences between upper and lower parts of the interior of the hull. The height of the hull and the height from the hull to the ceiling of the exhibition hall indicate that climatic differences might prevail also for upper and lower parts of the planking. This observation initiated a decision to split the cores of each sample from the ceiling and the planking, respectively, into one group representing the upper, and another group representing the lower parts of the hull, resulting in four groups of samples from the ceiling and the planking together.

The core samples taken from the wales, that differed from the rest of the planks of the planking by being generally thicker, were likewise split into two groups, one from the upper part and one from the lower part of the planking. This produces another two groups of core samples that represent different thickness of timbers from the outside area of the hull.

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[169] Håfors, 2001, chapter 4.
[170] This dissertation, 3.3.

This enables a number of comparisons for the assessment to be made of the result of the treatment.

- comparison between the planking and the ceiling of the hull
- comparison between the upper and the lower parts of the hull
- comparison between units of timbers of different thickness in the same area of the hull

This makes possible comparisons of seven pairs of core sample series. Since each wood core was cut into a number of pieces, to enable assessment of the penetration of PEG, the seven sets of comparisons may be performed for as many levels in the wood as the number of pieces.[171]

The parameters investigated were:

- the PEG concentration of an assumed PEG solution in the wood during the conservation process
- movement of water and PEG in the wood during the conservation process
- shrinkage during the conservation process
- PEG concentration in the wood at the end of the conservation process

7.1. Monitoring the conservation procedure

The conservation procedure was monitored at regular intervals by measurements with a vernier calliper in order to observe movements of the wood. [172] To investigate the amount of PEG in the wood, core sampling was performed at 33 instances during the conservation procedure.

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[171] Håfors, 2001, pp 110-111.

[172] Håfors, 2001, p 139.

Sources of data

At each core sampling occasion wood-cores were drilled from the planking and the ceiling. At a few occasions wood-cores were drilled also from the wales, the deck-planks, and the heavy timbers. The number of wood-cores of the different categories at each core sampling occasion are listed below (table 7-I).

The wood-cores

Each wood-core of the planking and the ceiling was drilled all through the plank and was cut into four sections, labelled from the outer surface, layer I, II, III and IV. In all cases the section I is 10 mm of length. What is left of the wood core after the 10 mm section I has been removed has been cut into three sections of equal length. This means that the lengths of the sections labelled II, III and IV, varies from minimum 9 to maximum 33 mm.

Each wood-core from the wales was drilled all through the timber (thick plank) and was cut into sections labelled from the outer surface, layer I, II …. . In all cases section I is 10 mm of length. Each of the following sections is cut to equal lengths with their neighbours, c. 20 mm. The number of sections depends on the length of the wood-core.

The wood-cores of the deck-planks were drilled all through the plank and were cut into 5 or 6 sections of c. 10 mm of length each. The sections were labelled I, II … from the upwards facing surface.

The wood-cores of the heavy timbers were drilled either all through the timber or to half the thickness of the timber, depending on the thickness of the timber. The wood-cores were cut into sections with the section labelled I representing the outer surface or the upwards facing surface. The section labelled I is cut to a length of 10 mm while the succeeding sections are cut to between 15 and 20 mm.

The PEG and the water of each section are considered to be distributed as a gradient throughout the section that is expressed by denominating the analytical values of these substances “mean values” of each section. An average value from several section with the same label (I, II etc.) is denominated a “grand mean”.

Months of the Vasa conservation project	Sampling No	Number of wood-cores													
		Planking		Ceiling		Wales		Deck-planks oak		Deck-planks pine		Heavy timbers oak		Heavy timbers pine	
		High level	Low level	High level	Low level	High level	Low level	High level	Low level	High level	Low level	High level	Low level	High level	Low level
13	1	3	3	4	2	-	-	-	-	-	-	-	-	-	-
18	2	9	7	2	2	-	-	-	-	-	-	-	-	-	-
24	3	17	13	12	18	-	-	-	-	-	-	-	-	-	-
37	4	17	13	12	18	-	-	-	-	-	-	-	-	-	-
49	5	18	12	12	18	-	-	5	5	-	1	-	-	-	-
61	6	18	12	12	18	-	-	-	-	-	-	-	-	-	-
79	7	18	12	12	18	-	-	5	5	-	1	-	-	-	-
98	8	18	12	12	18	-	-	-	-	-	-	-	-	-	-
105	9	6	2	4	4	-	-	-	-	-	-	-	-	-	-
109	10	17	13	12	18	-	-	-	-	-	-	-	-	-	-
118	11	17	13	12	18	-	-	-	-	-	-	-	-	-	-
125	12	4	4	4	4	-	-	-	-	-	-	-	-	-	-
127	13	4	4	4	4	-	-	-	-	-	-	-	-	-	-
131	14	6	4	8	6	-	-	-	-	-	-	-	-	-	-
139	15	14	6	14	6	-	-	5	5	-	1	-	-	-	-
152	16	14	6	14	5	-	-	-	-	-	-	-	-	-	-
154	17	6	4	6	4	-	-	-	-	-	-	-	-	-	-
155	18	6	4	6	4	-	-	-	-	-	-	-	-	-	-
156	19	6	4	6	4	-	-	-	-	-	-	-	-	-	-
157	20	6	4	6	4	-	-	-	-	-	-	-	-	-	-
158	21	6	4	6	4	6	4	-	-	-	-	-	-	-	-
161	22	5	5	6	4	-	-	-	-	-	-	-	-	-	-
162	23	6	4	6	4	-	-	-	-	-	-	-	-	-	-
164	24	6	4	1	4	-	-	-	-	-	-	-	-	-	-
166	25	5	8	13	-	1	-	-	2	-	-	1	4	-	-
168	26	10	10	11	5	-	-	-	-	-	-	-	-	-	-
173	27	10	10	12	9	-	-	-	-	-	-	-	-	-	-
177	28	10	10	11	9	-	-	-	-	-	-	-	-	-	-
181	29	10	10	11	9	-	-	4	3	-	-	9	8	1	-
188	30	5	5	5	5	-	-	-	-	-	-	-	-	-	-
190	31	10	10	11	9	6	4	3	3	-	-	9	8	1	-
201	32	10	10	11	9	6	4	5	5	-	2	10	8	1	-
215	33	10	10	11	9	6	4	5	5	-	2	9	8	1	-

Table 7-I. Number of wood-cores of the different categories drilled at the core-sampling occasions.

Analysis

Water and PEG in the wood-cores have been analysed, according to the “analytical programme for core samples 1962-1992”, as presented in the separate publication “Conservation of the Swedish warship Vasa from 1628”.[173]

To prepare for the analysis, the pieces of wooden cores were put into weighed specimen tubes at the site of sampling. The core samples were analysed for water and PEG. The water was determined quantitatively by weighing the sample before and after drying. However, because of the sensitivity of PEG to temperature the drying was performed at low pressure with silica gel (blue gel) as drying agent instead of the standard procedure of drying in an oven at 102°C or 105°C.

The methods developed earlier for the analytical determination of PEG needed rather large amounts of PEG to operate; thus, they could not be used for the small amounts of PEG in the small samples of the Vasa material. A method designed specially for the purpose was therefore developed by the Shell laboratories in Stockholm.[174] The principle was that the PEG was dissolved together with other water-soluble substances, by soaking the wood samples in water at room temperature. After evaporating the water, the PEG was dissolved from the residue, that had to be completely dry, by soaking in benzene for a short period of time. As there are few other water-soluble substances in archaeological wood known to dissolve in benzene, this sequence of activities separated the PEG from the rest of the substances. The final determination of the PEG in the benzene-solution was performed by spectrometric determination of the absorption at the wave-number 1107.5 cm^{-1}, which corresponds to a wavelength of 9.0 μm in the infrared region of the spectrum.

Calculations

To calculate the final results of all the analyses, the concept of moisture ratio was chosen as a model. Because the definition of moisture ratio is

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[173] Håfors, 2001, pp 113-114.

[174] The archives of the Swedish Maritime Museums.

water content in proportion to the dry fibre weight, it would be necessary to find the equivalent "dry fibre weight" for wood that was gradually being more and more filled with conservation substances. This ought to mean that the weight of preservatives had to be subtracted from the dry weight of each small piece of wood core. The conclusion was that to obtain any information from drying the samples, the preservatives in that particular sample had to be determined. Because an equilibrium had developed at an early date between the concentration of borates in the conservation solution at a mean level corresponding to about one per cent boric acid in the wood, the borates would not add continuously to the dry fibre weight. Thus the borates could be accepted as part of the dry fibre weight and the dry fibre weight for each piece of wooden core was determined as dry weight minus weight of extracted PEG. This is a stable reference at all times for the calculation of water ratio as the weight of water divided by the dry fibre weight, and PEG-ratio as the weight of PEG divided by the dry fibre weight. This way of calculation produces figures that can be used to describe the procedures over time.

Calculation of water-ratio and PEG-ratio, respectively:

water-ratio (%)

$$\frac{\text{weight of water} \times 100}{\text{dry weight - weight of PEG}}$$

PEG-ratio (%)

$$\frac{\text{weight of PEG} \times 100}{\text{dry weight - weight of PEG}}$$

Terminology used in this chapter

The term "water-ratio" denotes the ratio between the weight of the total amount of water in the piece of wood and the dry weight of the same piece of wood, less the weight of PEG of the piece of wood that contains this water (dry fibre weight).[175] Depending on the sensitivity of PEG to elevated temperature the drying was performed at low pressure with silica gel (blue gel) as drying agent instead of using the standard procedure of drying in a drying cabinet at 103 ± 2°C.

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[175] Håfors, 2001, p 115.

The term "PEG-ratio" denotes the ratio between the weight of the total amount of PEG in the wood and the dry weight of the piece of wood, less the weight of PEG (dry fibre weight) of the piece of wood that contains this PEG.[176]

The term "solution-ratio or (water + PEG)-ratio" denotes the ratio between the weight of the sum of the total amount of water and the specified preservative in the wood and the dry weight of the piece of wood, less the weight of PEG (dry fibre weight) of the piece of wood that contains the solution.

The term "PEG-concentration of assumed solution in the wood" denotes the ratio between the weight of the total amount of the specified preservative in a piece of wood as part of the sum of this weight and the weight of the total amount of water in the same piece of wood.

The term “mean value” is used to stress the fact that the values of each of the parameters “water-ratio, PEG-ratio, solution-ratio, and PEG-concentration of assumed solution in the wood” are distributed as a gradient in the piece of wood.

The term “grand mean” is used for the average values of the parameters “water-ratio, PEG-ratio, solution-ratio, and PEG-concentration of assumed solution in the wood” calculated layer by layer on all wood-core pieces belonging to a sample.

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[176] Håfors, 2001, p 115.

7.2. The PEG concentration of an assumed PEG solution in the wood during the conservation process

The PEG concentration of an assumed PEG solution inside the wood has been calculated for each of the six series of core samples representing the upper and lower areas of the ceiling, the planking, and the wales respectively for every batch of core samples procured during the conservation period.

Each one of the cores of the planking and the ceiling has been cut into four pieces. The mean PEG concentration of an assumed PEG solution inside the wood was calculated for each piece of wooden core. The calculation used the water and PEG quantities of the analyses as basis.[177] In order to protect the PEG in the samples from high temperature during the drying procedure this method of analysis has applied vacuum at low RH as a drying method instead of the standard drying method. This left a water residue in the wood compared to the standard drying method. By an experiment, performed at the Vasa conservation laboratory, this water residue was estimated to c. 1% water ratio. The PEG analysis calculates only unchanged PEG depending on the last extraction step with benzene that does not dissolve the more polar products that may have resulted from oxidation processes of PEG.

Depending on that the core samples were drilled all through the planks of the planking and the ceiling, the fourth piece of the cores represented the surface layer inside the construction of the ship's side. Since this layer was cut as one third of the core after a surface layer of 10 mm had been removed from the outer surface side, the two surface layers were not exactly matched. In order to study the gradient of PEG concentration in the wood, the graphs of PEG concentration of the outer surface layer of 10 mm, of the layer of c. 20 mm thickness beneath the surface layer, and of the layer of c. 20 mm thickness beneath this layer are presented in diagrams for the upper part of the planking, the lower part of the planking, the upper part of the ceiling, and the lower part of the ceiling respectively. The PEG concentration of the conservation solution is added to each diagram for comparison.

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[177] Håfors, 2001, pp 113 - 114.

The diagrams represent four successive periods of the treatment programme. The conservation parameters have been described in relation to these periods.

- The first period of the conservation treatment programme was characterized by spraying with rather dilute PEG solutions, starting with a period of hand spraying with a 15% PEG 4000 solution that lasted for c. three years, followed by a c. five year period of continuous automatic spraying with 10 and 15% PEG 1500. This eight year period ended in 1970 with a two step raise of PEG concentration of the conservation solution to 25% PEG 1500.

- The second period of the conservation treatment programme consisted of a three year period of continuous spraying with a 25% PEG 1500 solution.

- The third period of the conservation treatment programme started in 1973 with a raise of PEG concentration to 30% that was performed by adding PEG 600 to the conservation solution. Another raise of the PEG concentration of the conservation solution to 35% was made less than a year later. Reductions of the frequency of spraying rounds were also made at the beginning and the middle of this period that lasted for c. two years.

- The fourth period of the conservation treatment programme was started at the end of 1974 with a raise to 45% PEG concentration of the conservation solution. Reduction of the frequency of spraying rounds was continued to a minimum of between six and one rounds per day.[178]

Since samples were taken from the planking and the ceiling during all four periods of conservation treatment, but from the wales only at the end of the third and the fourth periods, a continuous mapping of the progress of the conservation can be performed only for the planking and the ceiling (figures 7-1, 7-2, 7-3 and 7-4).

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[178] Håfors, 2001, pp 65 - 68.

To enable comparisons between the ordinary planks of the planking and the ceiling and the wales the PEG concentration values of an assumed PEG solution inside the wood of each of the chosen groups of timbers have been recorded when each of the periods of conservation treatment that these groups had in common was completed. The trend-lines of the curves of PEG-concentration values are 4th degree polynomials (figures 7-1, 7-2, 7-3 and 7-4).

The upper part of the planking

The development of the PEG concentration of an assumed PEG-solution inside the oak wood at three consecutive levels, from the wood surface and into the depth of the wood, of the upper part of both of the starboard and the portside planking has been followed during the entire conservation period (figure 7-1).

The graph of layer I showed that from the middle of the treatment period with 15% PEG 1500 to the middle of the fourth treatment period the PEG concentration of the assumed PEG solution inside the surface layer was continuously increasing. During the first and the second periods there were enough spraying rounds to permanently keep a layer of conservation solution on the wood surface. This created an immersion-like conservation situation that may have promoted PEG to enter the wood by diffusion. At the end of the second period the PEG concentration of the surface layer was approaching the PEG concentration of the conservation solution.

During the third treatment period the concentration of the assumed PEG solution inside the surface layer approached the PEG-concentration of the treatment solution at both occasions of raises of the PEG-concentration of the treatment solution.

Half a year after the PEG-concentration raise from 35 to 45% of the conservation solution that started the fourth treatment period had been performed, the PEG-concentration of the assumed PEG solution in the surface layer exceeded the PEG-concentration of the treatment solution. The concentration of the assumed PEG solution inside the surface layer of the upper part of the planking of the Vasa hull amounted to 58% during the second half of the fourth treatment period.

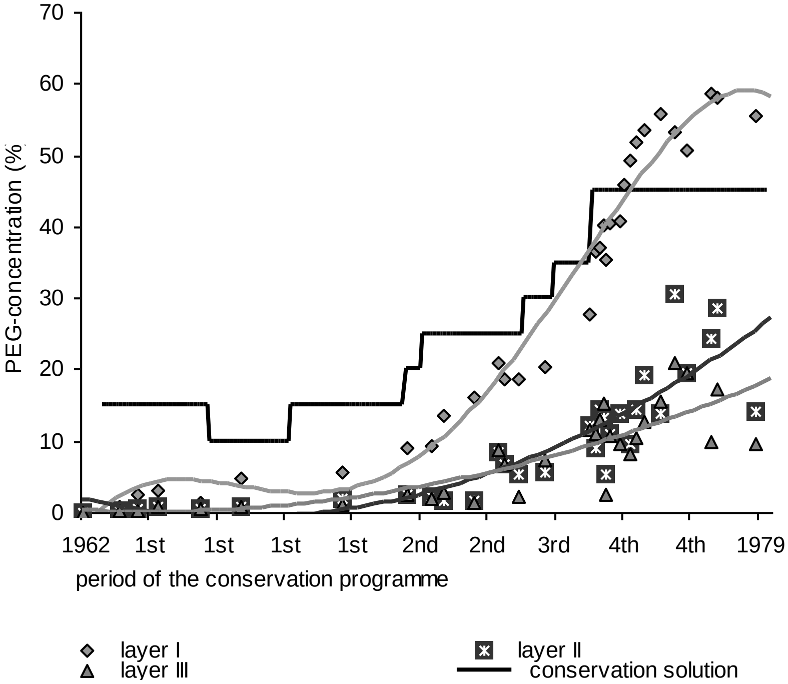

Figure 7-1. PEG-concentration of the conservation solution and mean values of the assumed PEG-concentration of the outer surface layer (layer I), the 1st layer beneath the surface layer (layer II), and the 2nd layer beneath the surface layer (layer III) respectively, of the upper part of the planking during the conservation period.
Trend-lines; least square fittings.

Like the situation inside the surface layer the PEG concentration of the assumed PEG solutions of the layers II and III was continuously increasing from the beginning of the second to the middle of the fourth treatment period.

The layers II and III showed equal levels of PEG-concentration from the start of the first to the end of the second treatment period. At the beginning of the third treatment period the PEG-concentrations of the two layers started to diverge and drifted apart until the gap stabilised at the level of c. 10 percentage units during the second half of the forth treatment period. The PEG-concentration of layer II remained higher than the PEG-concentration of layer III, during the remainder of the conservation period.

The gap between the PEG-concentrations of the two deeper layers and the surface layer widened continuously during the conservation period and terminated at c. 35 percentage units, at the end of the conservation period.

The concentration at the end of the conservation period of the assumed PEG solution inside the layers II and III amounted to 22 and 12% respectively, at the end of the conservation period.

The lower part of the planking

The development of the PEG concentration of an assumed PEG-solution inside the oak wood at three consecutive levels, from the wood surface and into the depth of the wood, of the lower part of both of the starboard and the portside planking has been followed during the entire conservation period (figure 7-2).

The graph of layer I shows that from the middle of the treatment period with 15% PEG 1500 to the middle of the fourth treatment period the PEG concentration of the assumed PEG solution inside the surface layer was continuously increasing. During the first and the second periods there were enough spraying rounds to permanently keep a layer of conservation solution on the wood surface. This created an immersion-like conservation situation that may have promoted PEG to enter the wood by diffusion. At the end of the second period the PEG concentration of the surface layer was approaching the PEG concentration of the conservation solution.

During the third treatment period the concentration of the assumed PEG solution inside the surface layer approached the PEG-concentration of the treatment solution at both raises of the PEG-concentration of the treatment solution.

Three quarters of a year after the PEG-concentration raise of the conservation solution from 35 to 45%, that started the fourth treatment period had been performed, the PEG-concentration of the assumed PEG solution in the surface layer exceeded the PEG-concentration of the treatment solution. The concentration of the assumed PEG solution inside the surface layer of the lower part of the planking of the Vasa hull amounted to 53% during the second half of the fourth treatment period.

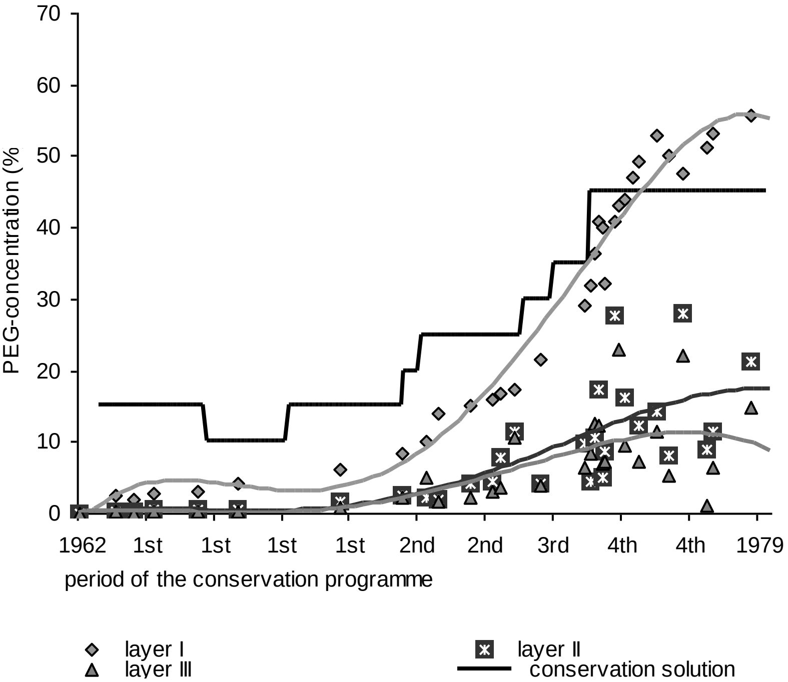

Figure 7-2. PEG-concentration of the conservation solution and mean values of the assumed PEG-concentration of the outer surface layer (layer I), the 1st layer beneath the surface layer (layer II), and the 2nd layer beneath the surface layer (layer III) respectively, of the lower part of the planking during the conservation period.
Trend-lines; least square fittings.

Like the situation inside the surface layer the PEG concentration of the assumed PEG solutions of the layers II and III was continuously increasing from the middle of the first to the middle of the fourth treatment period.

The layers II and III showed equal levels of PEG-concentration from the start of the first to the end of the second treatment period. At the beginning of the third treatment period the PEG-concentrations of the two layers started to diverge and drifted apart during the remainder of the conservation period. The gap between the PEG-concentration of the layers II and III reached 6 percentage units at the middle of the forth treatment period. The PEG-concentration of layer II remained higher than the PEG-concentration of layer III during the conservation period.

The gap between the PEG-concentrations of layer II and the surface layer widened continuously during the conservation period and terminated at c. 40 percentage units, at the end of the conservation period.

The concentration at the end of the conservation period of the assumed PEG solution inside the layer II and layer III amounted to 14% and 8% respectively at the end of the conservation period.

The upper part of the ceiling

The development of the PEG concentration of an assumed PEG-solution inside the oak wood at three consecutive levels, from the wood surface and into the depth of the wood, of the upper part of both of the starboard and the portside ceiling has been followed during the entire conservation period (figure 7-3).

The graph of layer I shows that from the middle of the treatment period with 15% PEG 1500 to the middle of the fourth treatment period the PEG concentration of the assumed PEG solution inside the surface layer was continuously increasing. During the first and the second periods there were enough spraying rounds to permanently keep a layer of conservation solution on the wood surface. This created an immersion-like conservation situation that may have promoted PEG to enter the wood by diffusion. At the end of the second treatment period the PEG-concentration of the surface layer was approaching the PEG-concentration of the conservation solution.

During the third treatment period the concentration of the assumed PEG solution inside the surface layer approached the PEG-concentration of the treatment solution at both occasions of PEG-concentration increase of the treatment solution.

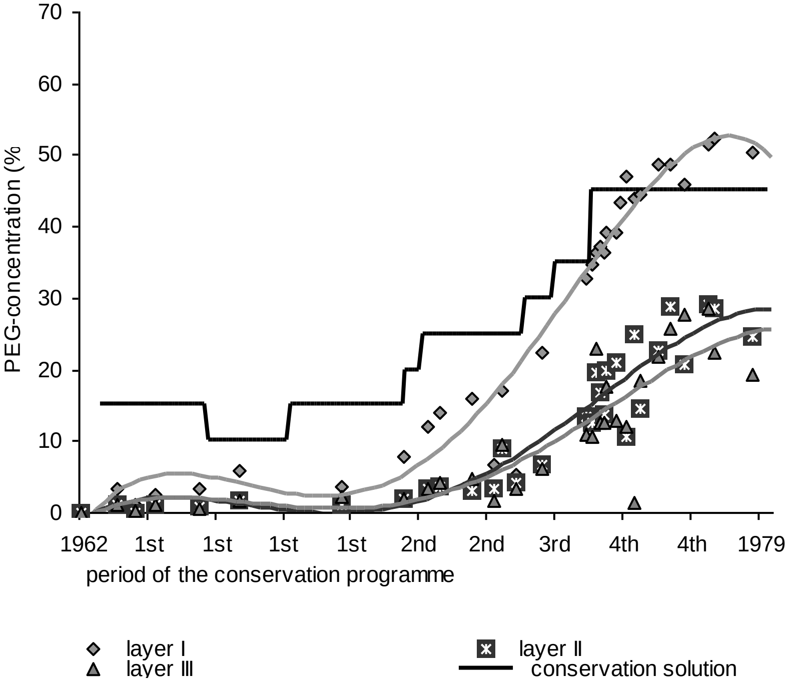

Figure 7-3. PEG-concentration of the conservation solution and mean values of the assumed PEG-concentration of the outer surface layer (layer I), the 1st layer beneath the surface layer (layer II), and the 2nd layer beneath the surface layer (layer III) respectively, of the upper part of the ceiling during the conservation period.
Trend-lines; least square fittings.

One year after the PEG-concentration increase from 35 to 45% of the conservation solution that started the fourth treatment period had been performed, the PEG-concentration of the assumed PEG solution in the surface layer exceeded the PEG-concentration of the treatment solution. The concentration of the assumed PEG solution inside the surface layer of the upper part of the ceiling of the Vasa hull amounted to 51% during the second half of the fourth treatment period.

Like the situation inside the surface layer the PEG-concentration of the assumed PEG solution of layer II was continuously increasing from the beginning of the second to the middle of the fourth treatment period. The graph of the PEG-concentration of layer III followed that of layer II closely as far as through the third treatment period but levelled out a year before the end of the full conservation period.

Layers II and III showed equal levels of PEG-concentration from the start of the first to the end of the second treatment period. At the beginning of the third treatment period the PEG-concentrations of these two layers started to diverge and drifted apart continuously with the gap growing to 4 percentage units at the middle of the fourth treatment period. The PEG-concentration of layer II remained higher than the PEG-concentration of layer III, during the remainder of the conservation period.

The gap between the PEG-concentrations of the two deeper layers and the surface layer widened continuously during the conservation period and ended up at c. 24 percentage units, at the end of the conservation period.

The concentration of the assumed PEG solution inside layers II and III amounted to 27 and 23% respectively, at the end of the conservation period.

The lower part of the ceiling

The development of the PEG concentration of an assumed PEG-solution inside the oak wood at three consecutive levels, from the wood surface and into the depth of the wood, of the lower part of both of the starboard and the portside ceiling has been followed during the entire conservation period (figure 7-4).

The graph of layer I shows that from the middle of the treatment period with 15% PEG 1500 to the middle of the fourth treatment period the PEG concentration of the assumed PEG solution inside the surface layer was continuously increasing. During the first and the second periods there were enough spraying rounds to permanently keep a layer of conservation solution on the wood surface. This created an immersion-like conservation situation that may have promoted PEG to enter the wood by diffusion. At the end of the second period the PEG concentration of the surface layer was approaching the PEG concentration of the conservation solution.

During the third treatment period the concentration of the assumed PEG solution inside the surface layer approached the PEG-concentration of the treatment solution at both occasions of PEG-concentration increase of the treatment solution.

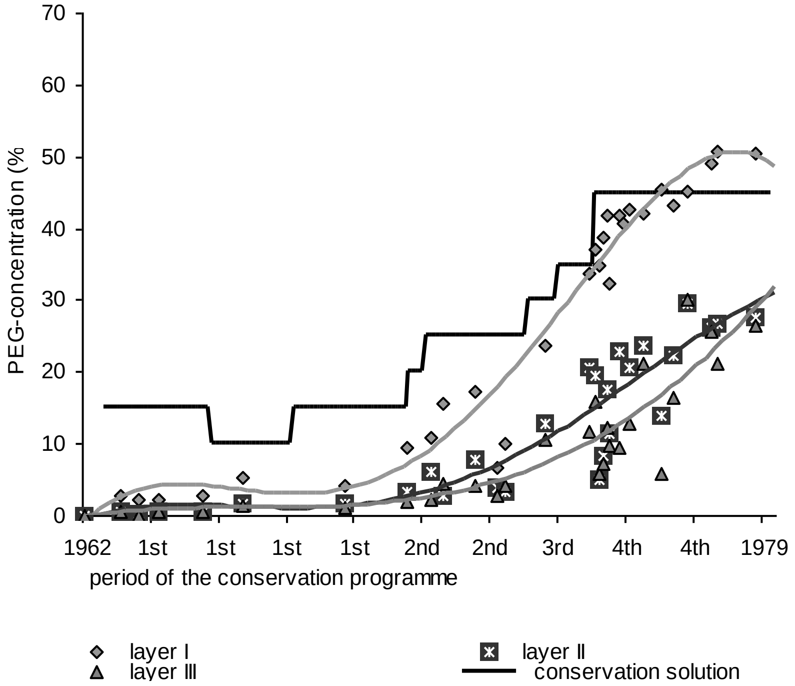

Figure 7-4. PEG-concentration of the conservation solution and mean values of the assumed PEG-concentration of the outer surface layer (layer I), the 1st layer beneath the surface layer (layer II), and the 2nd layer beneath the surface layer (layer III) respectively, of the lower part of the ceiling during the conservation period.
Trend-lines; least square fittings.

One and a half year after the PEG-concentration increase of the conservation solution from 35 to 45%, that started the fourth treatment period was performed, the PEG-concentration of the assumed PEG solution in the surface layer exceeded the PEG-concentration of the treatment solution. The concentration of the assumed PEG solution inside the surface layer of the lower part of the inner planking of the Vasa hull amounted to 50% during the second half of the fourth treatment period.

Like the situation inside the surface layer the PEG concentration of the assumed PEG solutions of layers II and III was continuously increasing from the middle of the first year to one year before the end of the fourth treatment period when the increase of PEG-concentration seemed to slow down and stop.

Layers II and III showed equal levels of PEG-concentration from the start to the middle of the first treatment period when the PEG-concentrations of the two layers started to diverge. During the remainder of the conservation period the PEG-concentration of the two layers slowly drifted apart. The gap between the PEG-concentration of layers II and III reached 1 percentage unit at the end of the forth treatment period. The PEG-concentration of layer II remained higher than the PEG-concentration of layer III during the entire conservation period.

The gap between the PEG-concentrations of layer II and the surface layer widened continuously during the conservation period and ended up at 23 percentage units, at the end of the conservation period.

The concentration of the assumed PEG solution inside the layer II and layer III amounted to 28% and 27% respectively at the end of the conservation period.

Evaluation of the PEG-concentration gradient of the “upper part of the planking”, the “lower part of the planking”, the “upper part of the ceiling”, and the “lower part of the ceiling”, respectively at the termination of the conservation treatment has been based on the mean values of the concentration during the latter half of the fourth period of the conservation programme.

Considerations on influence on diffusion process by climatic parameters and thickness of timbers

Beside differences of the thickness of the timbers in different parts of the Vasa hull there may be a possibility that differences of the climatic parameters during the conservation process might have influenced the diffusion of PEG and water in the wood. To investigate this assumption the temperature and RH-values are added to each of the four previously defined conservation treatment periods.[179]

- The first period of the conservation treatment programme was characterised in the region around the upper part of the planking by a temperature of 13°C and a RH-value of 92% RH. In the region around the lower part of the planking the temperature was 16°C and the RH-value 94%. There was no registration of temperature and RH inside the Vasa hull during the period.

- The second period of the conservation treatment programme is characterised in the region around the upper part of the planking by a raise of temperature from 13 to 14°C and a decrease of RH from 92 to 87%. In the region around the lower part of the planking the temperature was 16°C and the RH-value 84%. There was no registration of temperature and RH inside the Vasa hull during the period.

- The third period of the conservation treatment programme is characterised in the region around the upper part of the planking by a raise of temperature from 14 to 15°C and a decrease of RH from 87 to 78%. In the region around the lower part of the planking the temperature was 16°C and a decrease of the RH from 84 to 80%. There was no registration of temperature and RH inside the Vasa hull during the period.

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[179] Håfors, 2001, pp 101-103.

- The fourth period of the conservation treatment programme is characterised in the region around the upper part of the planking by a temperature of 16°C and a decrease of RH from 78 to 70%.
  In the region around the lower part of the planking the temperature was 16°C and a decrease of the RH from 80 to 75%.
  There was no registration of temperature and RH inside the Vasa hull during the period.

The core samples

The mean thickness of the planks of the upper part of the planking and the ceiling amounted to 64 and 65 mm, respectively, while the mean thickness of the planks of the lower parts of these constructional units were 83 and 82 mm, respectively. The mean thickness of the wales of the upper part of the planking amounted to 145 mm while the mean thickness of the wales of lower part of the planking was 182 mm.

The wood-cores were cut into four sections where the planking and the ceiling were concerned. As an exception, data on the layer III of the wales comprises a sum of several internal sections of the wood-core (table 7-II). Although the cores of the wales are cut into a greater number of pieces for analysis than the cores of the planking and the ceiling, these are presented in the tables as four layers. Layers I and II of the wales correspond exactly to the layers of the same designation of the planking and the ceiling while the third layer, called the middle layer in the tables, measured c. 100 - 120 mm and included several of the originally cut layers. The inner surface layer of the wales measured c. 20 mm like layer IV of the planking and the ceiling.

Since the wales were not incorporated into the core sampling until 1974, no figures of PEG-concentration are given for the endpoints of the 1st and the 2nd periods of the conservation programme. However, to facilitate reading the tables at comparisons between the planking and the wales all tables of PEG-concentration have been constructed exactly according to the same template.

	Layer I outer surface layer	Layer II 1st layer beneath the outer surface layer	Layer III 2nd layer beneath the outer surface layer	Layer IV inner surface layer
Planking:				
upper part	10	18	18	18
lower part	10	24	24	25
Ceiling:				
upper part	10	18	18	19
lower part	10	24	24	24
Planking:				
wales of upper part	10	24	90	20
wales of lower part	10	24	127	20

Table 7-II. Mean thickness (mm) of the sections into those the wood cores drilled from the planking, the ceiling and the wales of the Vasa hull for analysis of PEG and water content.

Comparison between the PEG-concentrations of the assumed PEG solutions of the upper and the lower parts of the planking, the ceiling and the wales

The assumption to be tested was the possibility that differences of the climatic circumstances, i.e. RH and temperature, at different situation and levels might have effected the diffusion of PEG into the wood differently. In order to investigate whether such differences were in existence tables of the PEG concentrations of assumed PEG solutions in the wood at the endpoints of each period of the conservation programme were composed (tables 7-III – 7-VI).

At the first major change of the conservation programme which has been denoted the endpoint of the 1st period of the conservation programme the diffusion of PEG 1500 had been promoted by continuous spraying with a 15% PEG solution for c. 5 years. The result of this was nearly 10% PEG concentration inside the exterior 10 mm of wood (outer surface layer) and a little lower PEG-concentration value inside the wood in the inner surface layer which may be explained by this being twice as thick as the pouter surface layer. The interior layers showed an even PEG-concentration of c. 2% (table 7-III).

	Layer I outer surface layer	Layer II 1st layer beneath the outer surface layer	Layer III 2nd layer beneath the outer surface layer	Layer IV inner surface layer
Planking:				
upper part	9.0	2.0	2.4	6.7
lower part	8.4	2.1	2.1	8.4
Ceiling:				
upper part	7.8	1.8	1.8	7.0
lower part	9.4	3.4	2.1	6.5
Planking:				
wales of upper part	-	-	-	-
wales of lower part	-	-	-	-

Table 7-III. PEG-concentration (%) of an assumed PEG solution inside the wood at the end of the 1st period of the conservation programme at two surface levels and two internal levels of the wood of the upper and lower parts of the planking and the ceiling.

The 2nd period of the conservation programme was finished after three years continuous spraying with a conservation solution with 25% PEG 1500. At that occasion the outer surface layers of the upper part of the planking showed a somewhat higher PEG concentration, 21%, than the corresponding layer of the lower part of the planking and both of the upper and lower parts of the ceiling which all showed a PEG-concentration of 17%. This difference was not at hand where the inner surface layer was concerned. The internal layers of both of the planking and the ceiling still resembled each other rather closely with c. 6% PEG concentration (table 7-IV).

	Layer I outer surface layer	Layer II 1st layer beneath the outer surface layer	Layer III 2nd layer beneath the outer surface layer	Layer IV inner surface layer
Planking:				
upper part	21	5.5	6.7	12
lower part	17	6.5	6.5	14
Ceiling:				
upper part	17	6.9	5.3	15
lower part	17	6.8	4.1	13
Planking:				
wales of upper part	-	-	-	-
wales of lower part	-	-	-	-

Table 7-IV. PEG-concentration (%) of an assumed PEG solution inside the wood at the end of the 2nd period of the conservation programme at two surface levels and two internal levels of the wood of the upper and lower parts of the planking and the ceiling.

The 3rd period of the conservation programme that lasted for c. 2 years was characterised by a conservation solution where the PEG concentration of the 25% conservation solution was raised at two occasions to 30 and 35%, respectively with additions of PEG 600. There was also a reduction of spraying rounds per time unit during the period.

Albeit this the PEG concentration of the assumed PEG solution inside the wood of the exterior surface layer still remained the same or a little lower than the PEG-concentration of the conservation solution used. There seemed also to have developed a slight PEG concentration difference between the layers II and III with lower concentration values in layer III.

Both of the groups of wales showed practically zero PEG concentration in the layers II and III. The outer surface layer of the wales of the upper part of the planking showed the same PEG concentration as the outer surface layer of the planks of the planking and the ceiling. The PEG concentration inside the wood of the outer surface layer of the lower situated wales seemed, however, to have lagged behind by a couple of percentage units (table 7-V).

	Layer I outer surface layer	Layer II 1st layer beneath the outer surface layer	Layer III 2nd layer beneath the outer surface layer	Layer IV inner surface layer
Planking:				
upper part	35	12	9.2	30
lower part	32	10	9.4	26
Ceiling:				
upper part	33	15	11	30
lower part	32	17	12	28
Planking:				
wales of upper part	34	0.5	0.0	19
wales of lower part	29	0.6	0.2	26

Table 7-V. PEG-concentration (%) of an assumed PEG solution inside the wood at the end of the 3rd period of the conservation programme at two surface levels and two internal levels of the wood of the upper and lower parts of the planking, the ceiling and the wales.

During the 4th period of the conservation programme the PEG concentration of the conservation solution was kept at 45% by only adding PEG 600 to the solution. The number of spraying rounds were reduced to a minimum of one double round per 24-hour period. The 4th period of the conservation programme lasted for c. 4 years.

The outer surface layer of the planking, the ceiling and the wales all showed PEG concentrations of the assumed PEG solution inside the wood of c. 50 – 58% which was well above the PEG concentration of the conservation solution. This showed that the surface layers that were exposed to the atmosphere had been drying during the terminating period of the conservation programme.

Considering the layers II and III the lag behind of the PEG concentration inside the wood of layer III was still more pronounced. There had also developed a distinct difference with higher PEG concentrations inside the wood of the upper parts compared to the lower parts of each of the construction units, the planking and the ceiling (table 7-VI).

This rather points to the conclusion that the diffusion situation may have been less favourable at lower levels. However, the thicker planks prevailing at lower levels may have had an unfavourable impact on the diffusion.

	Layer I outer surface layer	Layer II 1st layer beneath the outer surface layer	Layer III 2nd layer beneath the outer surface layer	Layer IV inner surface layer
Planking:				
upper part	58	22	12	44
lower part	53	14	8	34
Ceiling:				
upper part	51	27	23	43
lower part	50	27	25	40
Planking:				
wales of upper part	55	22	13	40
wales of lower part	49	5.5	0.3	31

Table 7-VI. PEG-concentration (%) of an assumed PEG solution inside the wood at the end of the 4th period of the conservation programme at two surface levels and two internal levels of the wood of the upper and lower parts of the planking, the ceiling and the wales.

Comparison between the wales and the ordinary planks of the upper part of the planking

The mean thickness of the wales of the upper part of the planking amounted to 145 mm while mean thickness of the planks of the upper part of the planking amounted to 64 mm (table 7-II).

The assumption to be tested was the possibility that the thickness of the timbers to be preserved is the most important characteristic to determine the diffusion of PEG into the wood. In this comparison the difference of thickness of the planks was greater than 50%. The difference of PEG concentration inside the wood of the ordinary planks of the upper part of the planking compared to the wales of the upper part of the planking was obvious in 1974 when the PEG concentration inside the wood of the wales was barely above zero, but was on its way to be obliterated in 1979 when the outer surface layers of both constructive timbers and the layer beneath that layer showed similar PEG concentrations of their assumed internal PEG solution (tables 7-V, 7-VI).

Comparison between the wales and the ordinary planks of the lower part of the planking

The mean thickness of the wales of the lower part of the planking amounted to 182 mm while mean thickness of the planks of lower part of the planking amounted to 83 mm (tables 7-II).

The assumption to be tested was the possibility that the thickness of the timbers to be preserved is the most important characteristic to determine the diffusion of PEG into the wood. In this comparison, like the previous one, the difference of thickness of the planks was more than 50%. The difference of PEG concentration inside the wood of the ordinary planks of the lower part of the planking compared to the wales of the lower part of the planking was obvious in 1974 when the PEG concentration inside the wood of the wales was barely above zero, a situation which still prevailed in 1979 despite the fact that the outer surface layers of both groups of constructive timbers showed similar PEG concentrations of their assumed internal PEG solution (tables 7-V, 7-VI).

An important main result is, that the investigation stressed the thickness of timbers as more important for the diffusion process than small differences in climatic parameters.

7.3. Movement of water and PEG in the wood during the conservation process

The movement of water and PEG in the wood during the conservation process has been evaluated by studying the development of the water-ratio and the ratio of the assumed PEG solution inside the wood. This investigation has been performed with the same six series of core samples as was used for calculation of the concentration of the assumed PEG solution inside the wood (7.2.). The same layers of the wood and the same division of the conservation treatment programme into periods have been used for presentation of the parameters in diagrams. 2nd degree polynomials have been chosen for the trend-lines of the ratios of the assumed PEG solution and the ratios of the water inside the wood (figures 7-5 – 7-20).

The upper part of the planking

The ratio of the assumed PEG solution inside the wood of the 10 mm surface layer of the upper part of the planking decreased during the first period of the conservation treatment programme from 150 to c. 120%. The values of this parameter continued to decrease to c. 100% during the second and third periods of the conservation treatment programme but came to a standstill at that level during the fourth period. The water ratio has been continuously decreasing creating a larger and larger gap between the graphs of the two parameters. This gap represents a growing PEG-ratio in the surface layer that amounted to c. 15% at the end of the first period, c. 40% at the end of the third period and c. 70% at the end of the treatment programme (figure 7-5).

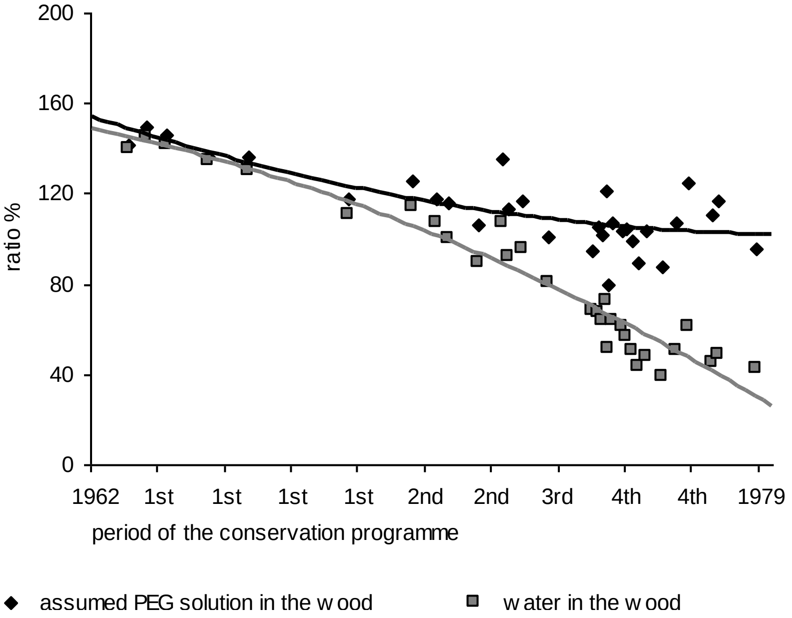

Figure 7-5. The ratio of assumed PEG solution and the ratio of water of layer I of the *upper* part of the planking during the conservation period; analytical results and trends. Trend-lines; least square fittings.

Layers II and III, deeper inside the wood, are represented by the graphs of figures 7-6 and 7-7. In both layers the graph of the ratio of the assumed PEG solution inside the wood and the graph of the water-ratio run almost on top of each other to the end of the first period of the treatment programme (1970). This indicates that practically no PEG had diffused into those layers during the treatment with low PEG-concentrations (10 and 15%).

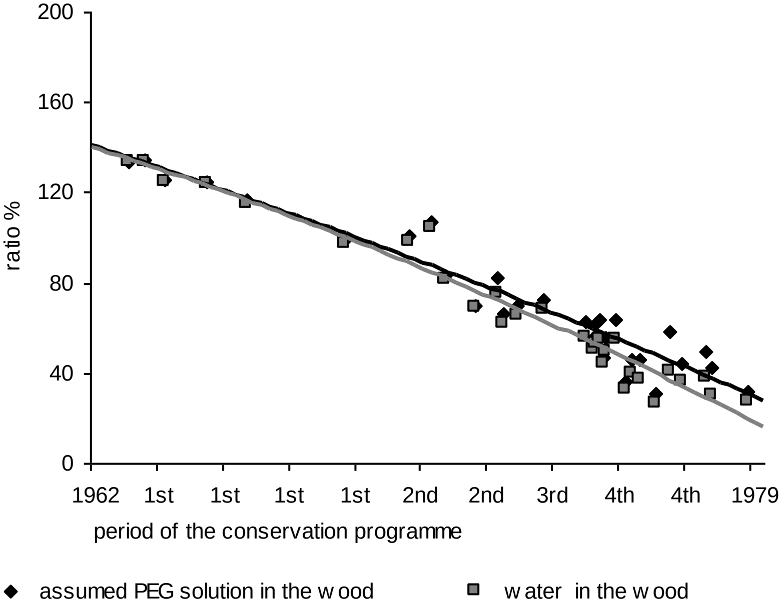

Figure 7-6. The ratio of assumed PEG solution and the ratio of water of layer II of the *upper* part of the planking during the conservation period; analytical results and trends. Trend-lines; least square fittings.

During the second period of the treatment programme when the PEG-concentration of the conservation solution was raised twice (20 and 25%) and further during the third period when the PEG-concentration of the conservation solution also was raised twice (30 and 35%), and in addition, the frequency of spraying rounds was lowered, eventually by half its original number a small gap developed between the graphs of the ratios of the sum of water and PEG and water respectively. This gap widened a little during the fourth period of the treatment programme indicating PEG ratios of c. 10%.

The water-ratio was declining at an even pace during the main part of the treatment programme. At the very end of the conservation programme, the water-ratios seem to have reached a standstill at c. 30%.

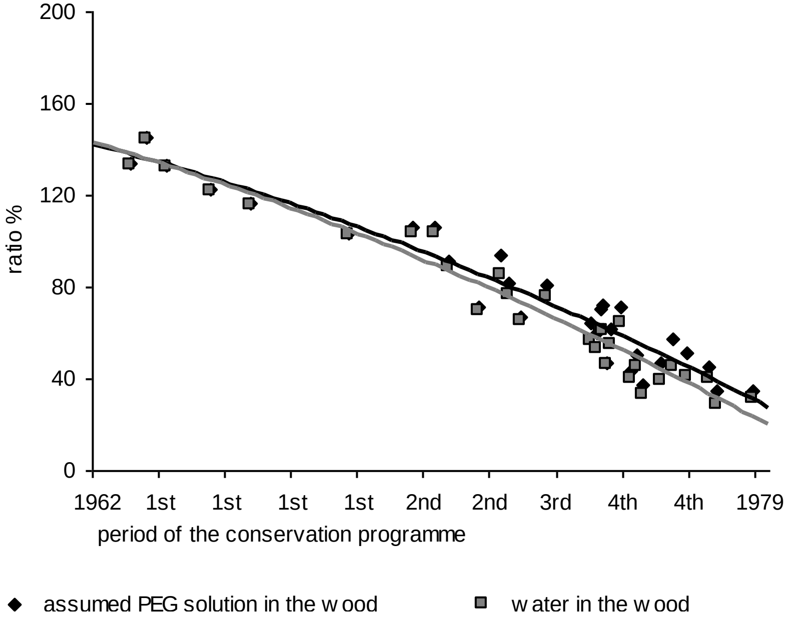

Figure 7-7. The ratio of assumed PEG solution and the ratio of water of layer III of the *upper* part of the planking during the conservation period; analytical results and trends. Trend-lines; least square fittings.

The ratio of the assumed PEG solution and the water-ratio in layer IV have been represented in a diagram (figure 7-8). Layer IV, that faces the inside of the ship's side construction has also been subjected to treatment by the conservation solution and may be regarded as a surface layer.[180] Layer IV is of the same thickness as the layers II and III, c. 20mm, and therefore, cannot be directly compared to the layer I that is only 10 mm thick. However, the graph of the ratio of the assumed PEG solution inside the wood of layer IV showed a similar declining tendency as the one of layer I. Like the situation in layer I this tendency levelled out and came to a standstill at c. 90% during the fourth period of the treatment programme. The graph of the water-ratio took a continuing

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[180] Håfors, 2001, p 62.

downward slope that ended at 40% water-ratio. This indicates a PEG-ratio of c. 50% in layer IV.

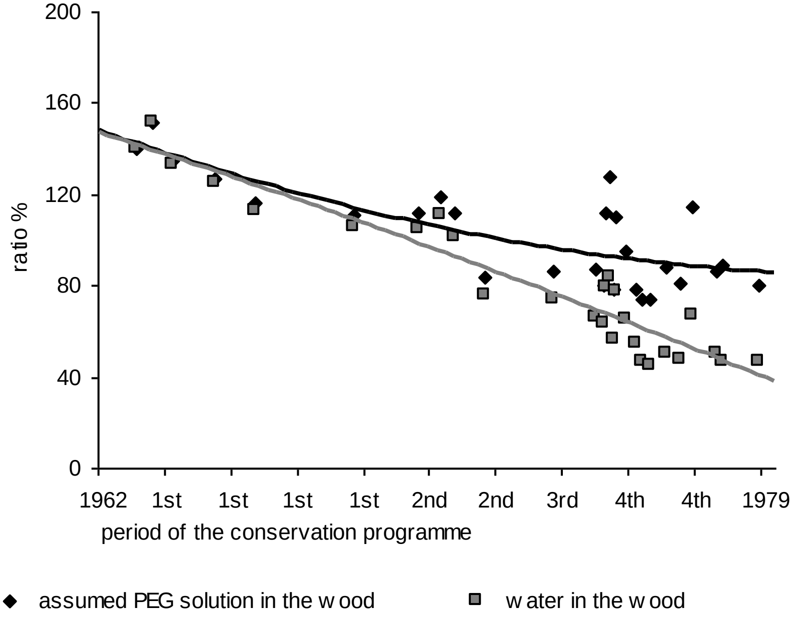

Figure 7-8. The ratio of assumed PEG solution and the ratio of water of layer IV of the *upper* part of the planking during the conservation period; analytical results and trends. Trend-lines; least square fittings.

The lower part of the planking

The ratio of the sum of water and PEG in the 10 mm surface layer of the lower part of the planking decreased during the first period of the conservation treatment programme from c. 170 to c. 115% (figure 7-9). The parameter remained at that value through the latter part of the first period, the second and third periods, and during half the fourth period of the conservation treatment programme. During the latter half of the fourth period there was an upwards movement that brought the ratio of the sum of water and PEG up to c. 130%. The water ratio has been continuously decreasing creating a larger and larger interval between the graphs of the two parameters. This interval represents a growing PEG-ratio in the surface layer that amounted to c. 15% at the end of the first period, c. 40% at the end of the third period and c. 60% at the end of the treatment programme.

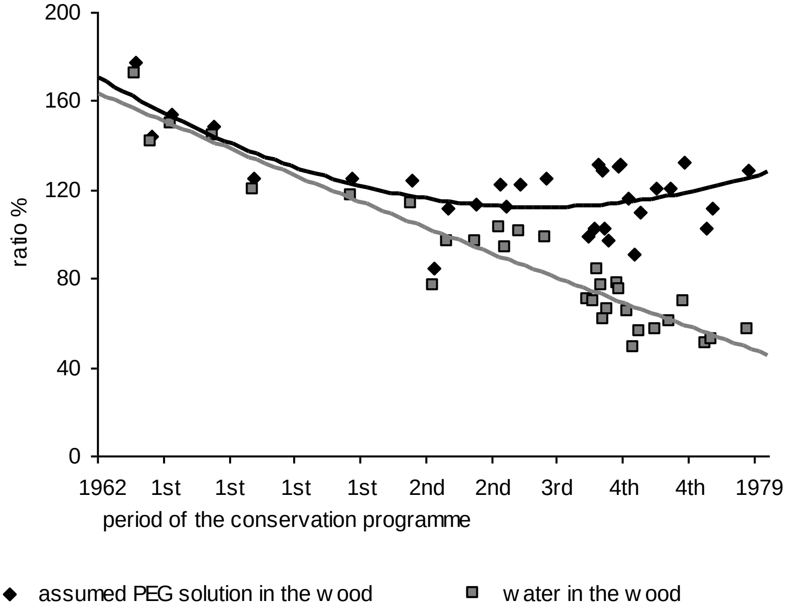

Figure 7-9. The ratio of assumed PEG solution and the ratio of water of layer I of the *lower* part of the planking during the conservation period; analytical results and trends. Trend-lines; least square fittings.

Layers II and III deeper inside the wood are represented by the graphs of the figures 7-10 and 7-11. In both layers the graph of the ratio of the assumed PEG solution inside the wood and the graph of the water-ratio run almost on top of each other to the end of the first period of the treatment programme (1970). This indicates that practically no PEG had diffused into those layers during the treatment with low PEG-concentrations (10 and 15%).

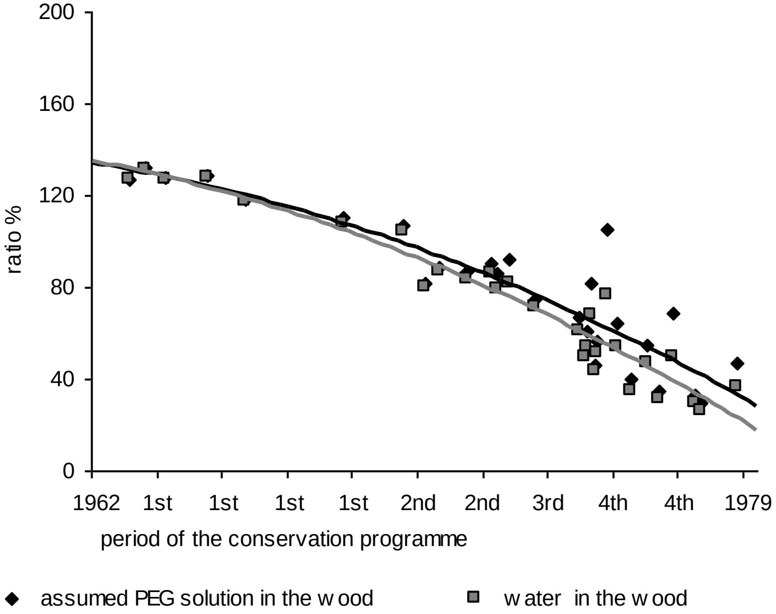

Figure 7-10. The ratio of assumed PEG solution and the ratio of water of layer II of the *lower* part of the planking during the conservation period; analytical results and trends. Trend-lines; least square fittings.

During the second period of the treatment programme, when the PEG-concentration of the conservation solution was raised twice (20 and 25%), and further during the third period when the PEG-concentration of the conservation solution also was raised twice (30 and 35%) and in addition the frequency of spraying rounds was lowered, eventually by half its original number a small interval developed between the graphs of the ratios of the assumed PEG solution and water respectively. This interval widened a little during the fourth period of the treatment programme indicating PEG ratios of c. 10 and 5% of layers II and III respectively.

The water-ratio was declining at an even pace during the main part of the treatment programme. At the very end of the conservation programme the water-ratios seem to have reached a standstill at c. 30%.

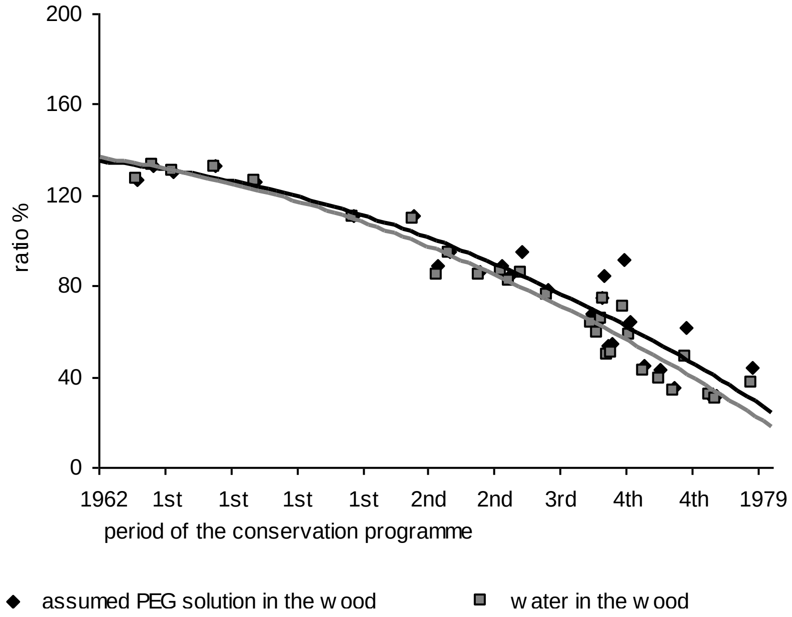

Figure 7-11. The ratio of assumed PEG solution and the ratio of water of layer III of the *lower* part of the planking during the conservation period; analytical results and trends. Trend-lines; least square fittings.

The ratio of the assumed PEG solution and the water-ratio in layer IV have been represented in graphs (figure 7-12). Layer IV, that face the inside of the construction of the ship's side has also been subjected to treatment by the conservation solution and may be regarded as a surface layer.[181] Layer IV is of the same thickness as layers II and III, c. 20 mm, and therefore cannot be directly compared to layer I, that is only 10 mm thick. However, the graph of the ratio of the assumed PEG solution inside the wood of layer IV, showed a rather faint but continuing declining tendency that did not stop before the end of the conservation treatment programme. At the final end of the treatment period the numerical value of the parameter was 80%. The graph of the water-ratio

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[181] Håfors, 2001, p 62.

took a continuing downward slope that ended at c. 40% water-ratio. This indicates a PEG-ratio of c. 40% in layer IV.

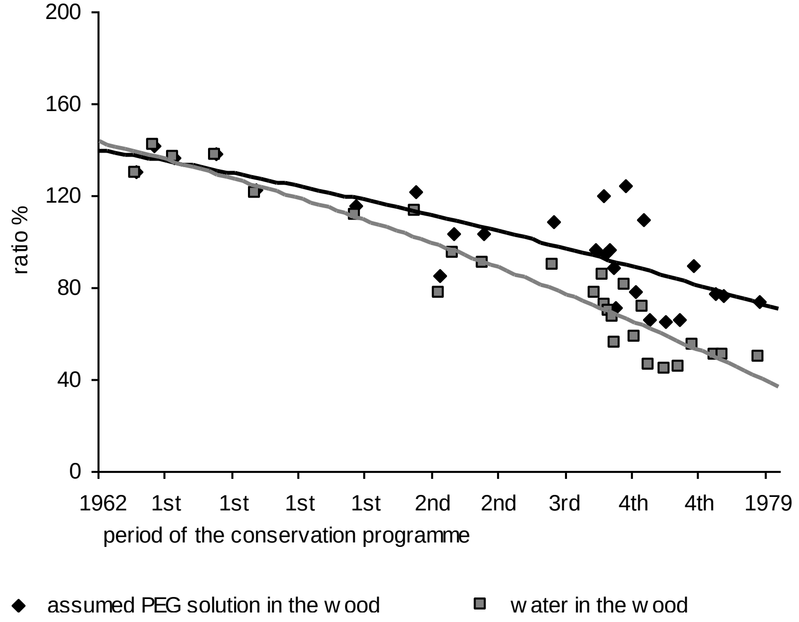

Figure 7-12. The ratio of assumed PEG solution and the ratio of water of layer IV of the *lower* part of the planking during the conservation period; analytical results and trends. Trend-lines; least square fittings.

The upper part of the ceiling

The ratio of the sum of water and PEG in the 10 mm surface layer of the upper part of the ceiling decreased during the first period of the conservation treatment programme from c. 200% to c. 130%. The parameter remained at that value through the latter part of the first period and the second period. During the third period the value started to increase and reached c. 135% at the middle of the fourth part of the conservation treatment programme. Towards the end of the fourth period there was a small decline that brought the ratio of the sum of water and PEG down to c. 150%.

The water ratio has been continuously decreasing creating a larger and larger interval between the trend-graphs of the two parameters. This interval represents a growing PEG-ratio in the surface layer that amounted to c. 15% at the end of the first period, c. 50% at the end of the third period and c. 75% at the end of the treatment programme (figure 7-13).

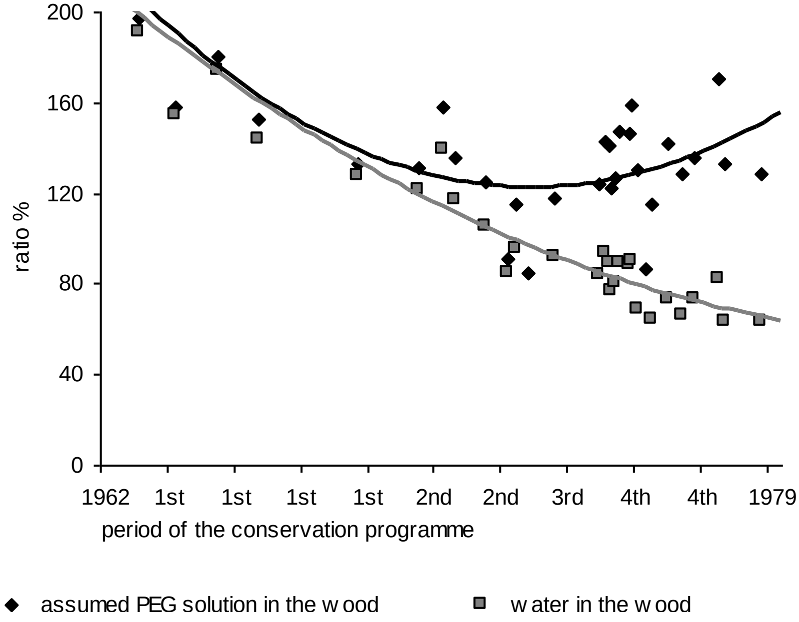

Figure 7-13. The ratio of assumed PEG solution and the ratio of water of layer I of the *upper* part of the ceiling during the conservation period; analytical results and trends. Trend-lines; least square fittings.

Layers II and III deeper inside the wood are represented by the graphs of the figures 7-14 and 7-15. In both layers the graph of the ratio of the assumed PEG solution inside the wood and the graph of the water-ratio run almost on top of each other to the end of the first period of the treatment programme (1970). This indicates that practically no PEG had diffused into those layers during the treatment with low PEG-concentrations (10 and 15%).

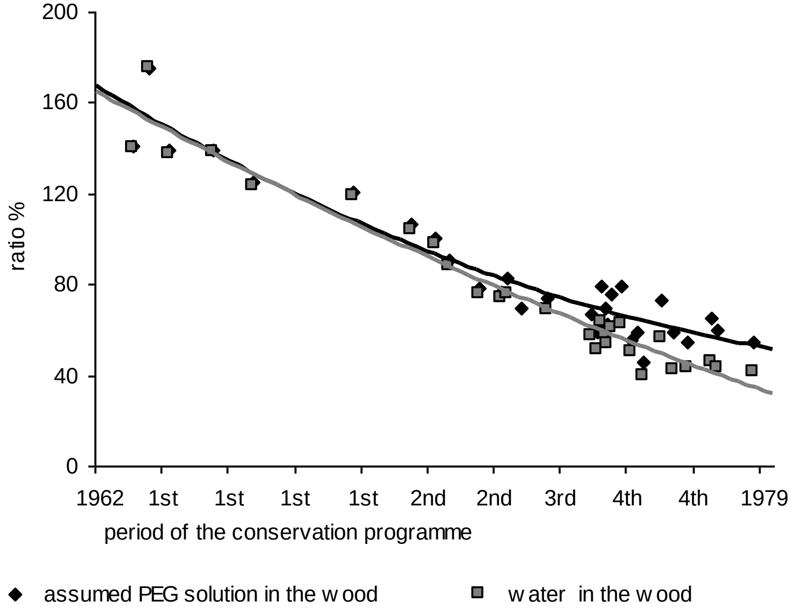

Figure 7-14. The ratio of assumed PEG solution and the ratio of water of layer II of the *upper* part of the ceiling during the conservation period; analytical results and trends. Trend-lines; least square fittings.

During the second period of the treatment programme, when the PEG-concentration of the conservation solution was raised twice (20 and 25%), and further during the third period, when the PEG-concentration of the conservation solution was also raised twice (30 and 35%), and in addition the frequency of spraying rounds was lowered, eventually by half its original number a small interval developed between the graphs of the ratios of the assumed PEG solution and water respectively. This interval widened a little during the fourth period of the treatment programme indicating PEG ratios of c. 20 % of layers II and III respectively.

The water-ratio was declining at an even pace during the main part of the treatment programme. At the very end the water-ratios seem to have reached a standstill at c. 40%.

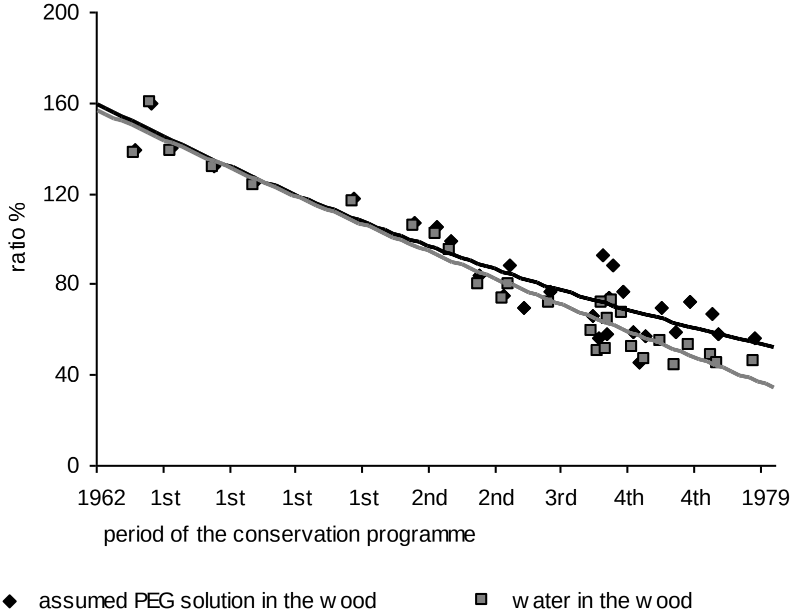

Figure 7-15. The ratio of assumed PEG solution and the ratio of water of layer III of the *upper* part of the ceiling during the conservation period; analytical results and trends. Trend-lines; least square fittings.

The ratio of the assumed PEG solution and the water-ratio in layer IV have been represented in graphs (figure 7-16). Layer IV, that faces the inside of the ship’s side construction has also been subjected to treatment by the conservation solution and may be regarded as a surface layer.[182]

Layer IV is of the same thickness as the layers II and III, c. 20 mm, and therefore cannot be directly compared to layer I that is only 10 mm thick. However, the graph of the ratio of the assumed PEG solution of layer IV first showed a similar declining tendency as the one of layer I. Like the situation in layer I, this tendency levelled out and came to a standstill at c. 95% at the beginning of the fourth part of the treatment programme. At the middle of the fourth period the values started to increase and climbed above the 100% level before the final end of the conservation treatment programme. The graph of the water-ratio took a continuing downward slope that ended at 50% water-ratio. This indicates a PEG-ratio of c. 50% in layer IV.

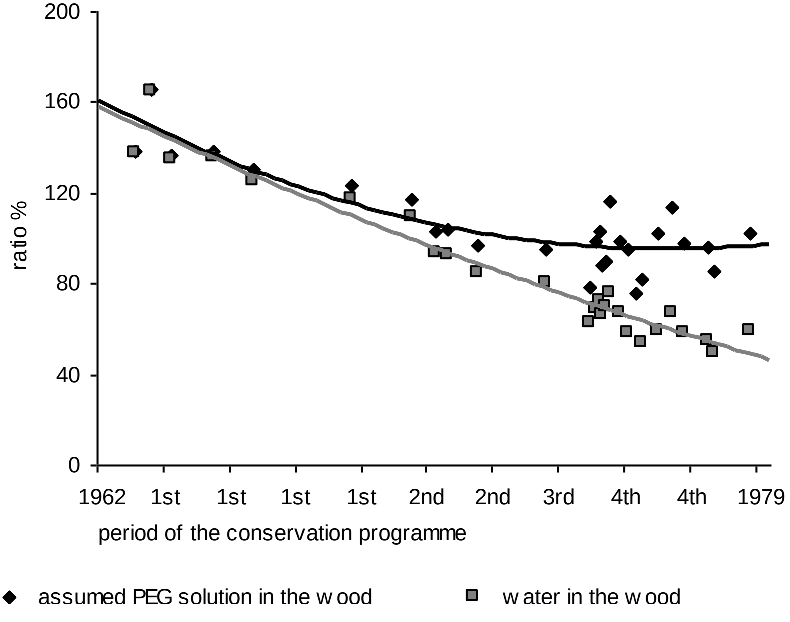

Figure 7-16. The ratio of assumed PEG solution and the ratio of water of layer IV of the *upper* part of the ceiling during the conservation period; analytical results and trends. Trend-lines; least square fittings.

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[182] Håfors, 2001, p 62.

The lower part of the ceiling

The ratio of the assumed PEG solution in the 10 mm surface layer of the lower part of the ceiling decreased during the first period of the conservation treatment programme from c. 160 to c. 120%.

The measurements of this parameter remained at that value through the latter part of the first period and all of the second period. During the third period the value started to increase and reached back c. 160% at the end of the fourth period. The water ratio was continuously decreasing creating a larger and larger interval between the graphs demonstrating the values of the two parameters. This interval represents a growing PEG-ratio in the surface layer that amounted to c. 15% at the end of the first period, c. 50% at the end of the third period and c. 80% at the end of the treatment programme (figure 7-17).

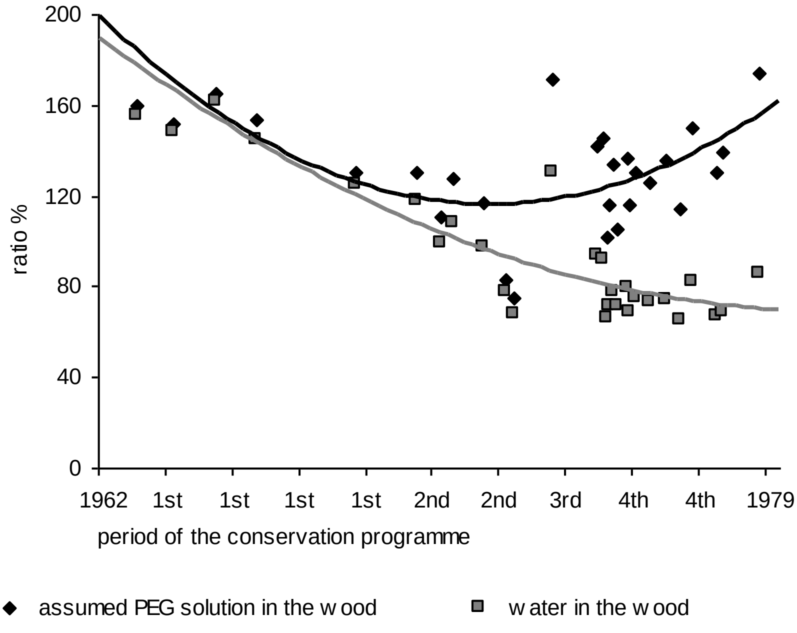

Figure 7-17. The ratio of assumed PEG solution and the ratio of water of layer I of the *lower* part of the ceiling during the conservation period; analytical results and trends. Trend-lines; least square fittings.

Layers II and III deeper inside the wood are represented by the graphs of the figures 7-18 and 7-19. In both layers the graph of the ratio of the assumed PEG solution inside the wood and the graph of the water-ratio run almost on top of each other to the end of the first period of the treatment programme (1970). This indicates that practically no PEG had diffused into those layers during the treatment with low PEG-concentrations (10 and 15%).

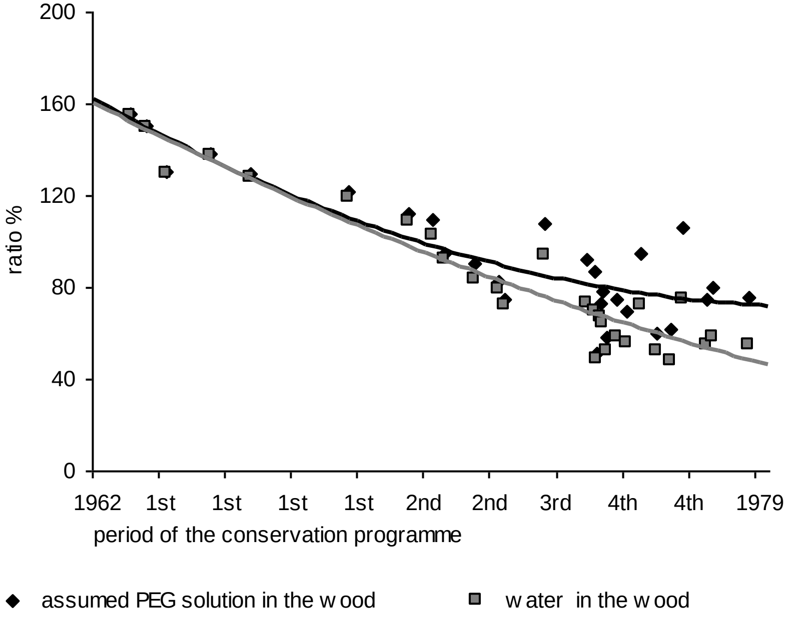

Figure 7-18. The ratio of assumed PEG solution and the ratio of water of layer II of the *lower* part of the ceiling during the conservation period; analytical results and trends. Trend-lines; least square fittings.

During the second period of the treatment programme, when the PEG-concentration of the conservation solution was raised twice (20 and 25%), and further during the third period, when the PEG-concentration was also raised twice (30 and 35%) and in addition the frequency of spraying rounds was lowered, eventually by half its original number an interval developed between the graphs of the ratios of the assumed PEG solution and water respectively. This interval widened during the fourth period of the treatment programme indicating PEG ratios of c. 15 % of layers II and III respectively.

The water-ratios of layers II and III were declining at an even pace during the main part of the treatment programme. At the very end of the conservation programme the water-ratios seem to have reached a standstill between 45 and 50%.

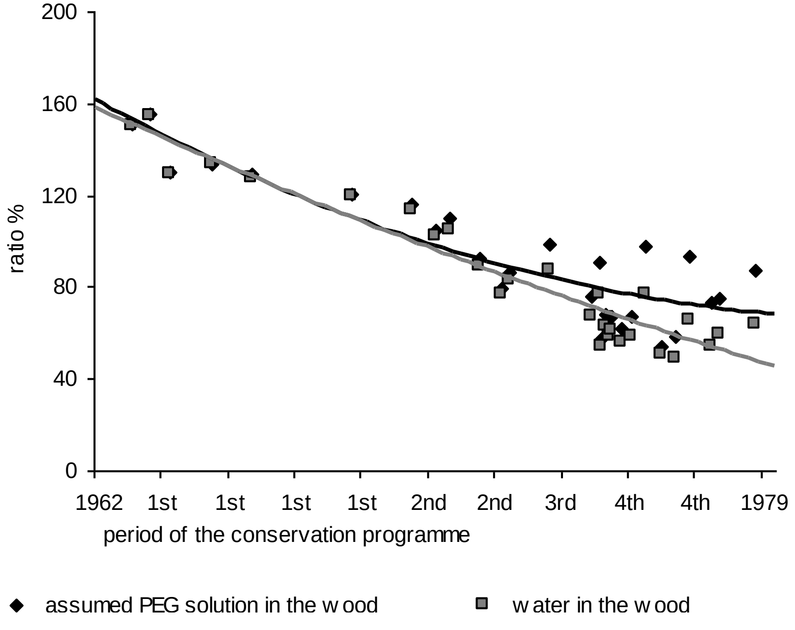

Figure 7-19. The ratio of assumed PEG solution and the ratio of water of layer III of the *lower* part of the ceiling during the conservation period; analytical results and trends. Trend-lines; least square fittings.

The ratio of the assumed PEG solution and the water-ratio in layer IV have been represented in graphs (figure 7-20). Layer IV, that faces the inside of the ship's side construction has also been subjected to treatment by the conservation solution and may be regarded as a surface layer.[183] Layer IV is of the same thickness as the layers II and III, c. 20 mm, and therefore cannot be directly compared to the layer I, that is only 10 mm thick. However, the graph of the ratio of the assumed PEG solution of layer IV first showed a similar declining tendency as the one of layer I. Like the situation in layer I, this tendency levelled out and came to a standstill at c. 95% at the beginning of the fourth period of the treatment programme. At the end of the fourth period the values started to increase and climbed above the 100% level before the end of the conservation treatment programme. The graph of the water-ratio took a continuing downward slope that ended at 55% water-ratio. This indicates a PEG-ratio of c. 45% in the layer IV.

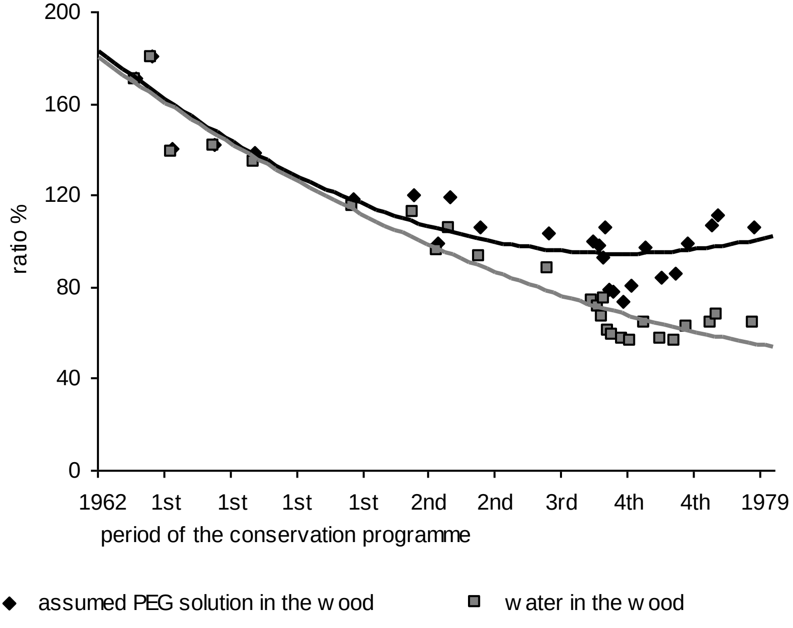

Figure 7-20. The ratio of assumed PEG solution and the ratio of water of layer IV of the *lower* part of the ceiling during the conservation period; analytical results and trends. Trend-lines; least square fittings.

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[183] Håfors, 2001, p 62.

Comparison of the grand mean of the water-ratio, the PEG-ratio and the ratio of assumed PEG solution inside the wood of the upper and the lower parts of the planking, the ceiling and the wales

To gain an over-view of the water and PEG content at different depths in the wood at different stages of the conservation programme the mean water-ratio and mean PEG-ratio of each defined level of the wood have been listed in tables at specified occasions during the conservation period. The starting-point is defined by the beginning of the hand-spraying activity in 1962. The water-ratio of the wood of the Vasa hull at that point of time was c. 150%.

Each of the cores of the planking and the ceiling were cut into four pieces while the thicker planks of the wales were cut into a larger number of pieces (table 7-II).

For comparison of the PEG penetration four levels of the wales have been selected; the 10mm surface layer in direct contact with the spray treatment and the museum atmosphere; the c. 20mm layer beneath the surface layer; the layer beneath, consisting of all the other layers except the inner surface layer; and the c. 20mm surface layer hidden in the hull side construction that had been subjected to a conservation solution that was deliberately leaked into it. This means that the third level of the wales which measures c. 90mm where the wales of the upper part of the planking are concerned and c. 125mm where the wales of the lower part of the planking are concerned will be compared to the c. 20mm thick layer of the third level of the planking.

The water-ratio

The first check-point of water-ratio is the end-point of the previously defined first part of the conservation programme ending in 1970, that is characterised by high frequency spraying with diluted PEG-solution.

At the first major change of the conservation programme which has been denoted the endpoint of the 1st period of the conservation programme the diffusion of PEG 1500 had been promoted by continuous spraying with a 15% PEG solution for c. 5 years.

At the termination of the 1st period of the conservation programme the water-ratio presents a rather uniform situation with c. 100% water-ratio inside the main part of the wood of the planking and of the ceiling. The water-ratio values inside the outer surface layer display a c. 10 percentage units higher water-ratio values compared to the main body of the wood. Considering the original water-ratio of 150% in the oak of the Vasa hull, this means that c. 1/3 of the original water content had left the wood of the Vasa hull during the hand spraying period and the 1st period of the conservation programme of the automatic spraying system, a period of c. 8 years (table 7-VII).

	Layer I outer surface layer	Layer II 1st layer beneath the outer surface layer	Layer III 2nd layer beneath the outer surface layer	Layer IV inner surface layer
Planking:				
upper part	111	92	94	100
lower part	104	98	103	103
Ceiling:				
upper part	117	97	100	100
lower part	110	100	104	104
Planking:				
wales of upper part	-	-	-	-
wales of lower part	-	-	-	-

Table 7-VII. Water-ratio (%) at the end of the 1st period of the conservation programme at two surface levels and two internal levels of the wood of the upper and lower parts of the planking and the ceiling.

The 2nd check-point of water-ratio took place at the end of the 2nd part of the conservation programme ending in 1972, characterised by high frequency spraying with 25% PEG solution.

The 2nd period of the conservation programme was finished after three years of continuous spraying with a conservation solution with 25% PEG 1500.

The main body of wood displayed a decrease of 18 percentage units of water-ratio since the previous check-point while the outer surface layer displayed a decrease of 15 percentage units water-ratio from the same occasion. There is still no considerable difference of water-ratio between the main body of wood and the surface layer (table 7-VIII).

	Layer I outer surface layer	Layer II 1st layer beneath the outer surface layer	Layer III 2nd layer beneath the outer surface layer	Layer IV inner surface layer
Planking:				
upper part	89	72	80	84
lower part	91	80	84	88
Ceiling:				
upper part	104	78	80	84
lower part	94	84	87	88
Planking:				
wales of upper part	-	-	-	-
wales of lower part	-	-	-	-

Table 7-VIII. Water-ratio (%) at the end of the 2nd period of the conservation programme at two surface levels and two internal levels of the wood of the upper and lower parts of the planking and the ceiling.

The 3rd check-point of water-ratio occurred at the end of the 3rd part of the conservation programme ending in 1974, characterised by raising the PEG concentration of the conservation solution using PEG 600 and cutting down on frequency of spraying rounds.

The 3rd period of the conservation programme that lasted for c. 2 years was characterised by a conservation solution where the PEG concentration of the 25% conservation solution was raised at two occasions to 30 and 35%, respectively with additions of PEG 600. There was also a reduction of spraying rounds per time unit during the period.

During the two years of the 3rd period of the conservation programme 26 percentage units water-ratio were lost from both of the outer surface layer and the main body of the wood. This time the water-ratio of the inner surface layer also seemed to have had a different development than the main body of wood and showed a loss of c. 22 percentage units water-ratio (table 7-IX) during the period.

During the two years the annual loss of water-ratio doubled compared to the situation during the previous periods of the conservation treatment.

	Layer I outer surface layer	Layer II 1st layer beneath the outer surface layer	Layer III 2nd layer beneath the outer surface layer	Layer IV inner surface layer
Planking:				
upper part	61	44	53	64
lower part	69	51	54	67
Ceiling:				
upper part	81	52	59	67
lower part	77	65	63	66
Planking:				
wales of upper part	68	51	57	57
wales of lower part	58	53	64	64

Table 7-IX. Water-ratio (%) at the end of the 3rd period of the conservation programme at two surface levels and two internal levels of the wood of the upper and lower parts of the planking, the ceiling and the wales.

The 4th and last check-point of water-ratio occurred when the conservation programme was terminated in 1979.

During the 4th period of the conservation programme the PEG concentration of the conservation solution was kept at 45% by only adding PEG 600 to the solution. The number of spraying rounds were reduced to a minimum of one double round per 24-hour period. The 4th period of the conservation programme lasted for c. 4 years.

On this occasion a different drying rate had been established between the outer surface layer where the annual drying rate was 6 percentage units water-ratio, and the main body of the wood, the layers II and III, where the annual drying rate was 5 percentage units water-ratio, and finally the inner surface layer where the annual rate of drying had been 4 percentage units water-ratio during the 4th period of the conservation programme (table 7-X).

	Layer I outer surface layer	Layer II 1st layer beneath the outer surface layer	Layer III 2nd layer beneath the outer surface layer	Layer IV inner surface layer
Planking:				
upper part	40	27	31	40
lower part	37	29	32	45
Ceiling:				
upper part	40	40	43	49
lower part	57	48	50	56
Planking:				
wales of upper part	47	32	32	44
wales of lower part	31	26	34	46

Table 7-X. Water-ratio (%) at the end of the 4th period of the conservation programme at two surface levels and two internal levels of the wood of the upper and lower parts of the planking, the ceiling and the wales.

The rate of drying during the 4th period of the conservation programme, thus, was comparable to the drying rate during the two initial periods of the conservation programme including the hand spraying period. However, the differences of water-ratio in various parts of the wood and in various construction units may have created tensions that may lead to checking and distortion of the wood or even to cracks.

Comparison of the water-ratio of wales and planks of the upper part of the planking

The mean thickness of the wales of the upper part of the planking amounts to 144 mm while the mean thickness of the planks of the upper part of the planking amounts to 64 mm (table 7-II).

The assumption to be tested was the possibility that the thickness of the timbers to be preserved was the most important characteristic that determined the rate of evaporation of water from the wood. In this comparison the difference of thickness between the planks was more than 50%. However, the water-ratio inside the wood of the planks and the wales of the upper part of the planking showed no significant difference (tables 7-IX, 7-X).

Comparison of water-ratio of wales and planks of the lower part of the planking

The mean thickness of the wales of the lower part of the planking amounts to 181 mm while the mean thickness of the planks of the lower part of the planking amounts to 83 mm (tables 7-II).

The assumption to be tested again was the idea that the thickness of the timbers to be preserved was the most important characteristic that determined the rate of evaporation of water from the wood. In this comparison, like the previous one, the difference of thickness of the planks was more than 50%. Contrary to what might be expected, in 1974, at the end of the third period of the conservation programme, layer II of the wales seemed to have dried somewhat faster than the corresponding layer of the planks. However, in 1979, at the final end of the conservation programme the water-ratio inside the wood of the planks and the wales of the lower part of the planking showed no significant difference (tables 7-IX, 7-X).

The investigation stressed climatic factors as important for the drying process and gave an indication that drying conditions varied with different regions of the Vasa hull.

The PEG-ratio

The assumption to be investigated was if the climatic circumstances, i.e. RH and temperature might have promoted diffusion of PEG molecules into the wood differently in different situations. Another question was if the width of the wooden members was of importance to the diffusion of PEG molecules.

At the first major change of the conservation programme which has been denoted, the endpoint of the 1st period of the conservation programme the diffusion of PEG 1500 had been promoted by continuous spraying with a 15% PEG solution for c. 5 years.

At this occasion a difference of PEG-ratio had already established itself between the outer and inner surface layers with c. 10% PEG-ratio and the layers II and III in between with c. 2% PEG-ratio (table 7-XI).

	Layer I outer surface layer	Layer II 1st layer beneath the outer surface layer	Layer III 2nd layer beneath the outer surface layer	Layer IV inner surface layer
Planking:				
upper part	10	3	6	6
lower part	10	2	2	9
Ceiling:				
upper part	8	0	0	10
lower part	10	3	1	8
Planking:				
wales of upper part	-	-	-	-
wales of lower part	-	-	-	-

Table 7-XI. PEG-ratio (%) at the end of the 1st period of the conservation programme at two surface levels and two internal levels of the wood of the upper and lower parts of the planking and the ceiling.

The 2nd period of the conservation programme was finished after three years continuous spraying with a conservation solution with 25% PEG 1500.

At this occasion a difference of PEG-ratio had been established also between the outer and inner surface layers with c. 20% and 15% PEG-ratio respectively in the outer and inner surface layers. The PEG-ratio in layers II and III was c. 6% (table 7-XII).

	Layer I outer surface layer	Layer II 1st layer beneath the outer surface layer	Layer III 2nd layer beneath the outer surface layer	Layer IV inner surface layer
Planking:				
upper part	24	5	5	16
lower part	23	6	5	15
Ceiling:				
upper part	21	5	8	16
lower part	8	8	4	12
Planking:				
wales of upper part	-	-	-	-
wales of lower part	-	-	-	-

Table 7-XII. PEG-ratio (%) at the end of the 2nd period of the conservation programme at two surface levels and two internal levels of the wood of the upper and lower parts of the planking and the ceiling.

The 3rd period of the conservation programme that lasted for c. 2 years was characterised by a conservation solution where the PEG concentration of the 25% conservation solution was raised at two occasions to 30 and 35%, respectively with additions of PEG 600. There was also a reduction of spraying rounds per time unit during the period.

At this occasion the difference of PEG-ratios between the outer and inner surface layers had grown. The PEG-ratio of the outer surface layer was double that of the inner surface layer showing c. 50 and c. 25% in these layers respectively. A small difference seemed also to have been established between the PEG-ratios of the layers II and III although the PEG-ratios in both of these were c. 10%.

The wales, which had been added to the wood-core sampling programme showed lower PEG-ratio compared to the corresponding part of the planking even in the outer surface layer. Practically no PEG seemed to have reached the inside layers (layers II and III) of the wales at the end of the 3rd period of the conservation programme (table 7-XIII).

	Layer I outer surface layer	Layer II 1st layer beneath the outer surface layer	Layer III 2nd layer beneath the outer surface layer	Layer IV inner surface layer
Planking:				
upper part	44	12	8	25
lower part	47	13	10	21
Ceiling:				
upper part	51	11	8	28
lower part	49	10	14	27
Planking:				
wales of upper part	36	4	0	11
wales of lower part	27	0	0	24

Table 7-XIII. PEG-ratio (%) at the end of the 3rd period of the conservation programme at two surface levels and two internal levels of the wood of the upper and lower parts of the planking, the ceiling and the wales.

During the 4th period of the conservation programme the PEG concentration of the conservation solution was kept at 45% by only adding PEG 600 to the solution. The number of spraying rounds were reduced to a minimum of one double round per 24-hour period. The 4th period of the conservation programme lasted for c. 4 years.

At this occasion a difference of PEG-ratios had developed between the outer surface layers of the planking and the ceiling. The PEG-ratio of the outer surface layer of the ceiling was c. 20 percentage units PEG-ratio higher than the PEG ratio of the planking showing c. 85 and c. 65% in these layers respectively. A difference seemed also to have been established between the PEG-ratios of the planking and the ceiling in both of the layers II and III, respectively. The difference in PEG-ratios amounted to 5 percentage units in layer II and 8 percentage units in layer III. The PEG-ratio level of the ceiling was c. 15% in both of the layers while the layer II and III of the planking displayed 12 and 7 % PEG-ratio respectively.

The wales, with one exception, still showed lower PEG-ratios compared to the corresponding part of the planking. The outer surface layer of the wales of the upper part of the planking showed 8 percentage units higher PEG-ratio than the outer surface layer of the planks in the planking. Still, practically no PEG seemed to have reached the inside layers (layers II and III) of the wales at the end of the 4th period of the conservation programme (table 7-XIV).

	Layer I outer surface layer	Layer II 1st layer beneath the outer surface layer	Layer III 2nd layer beneath the outer surface layer	Layer IV inner surface layer
Planking:				
upper part	62	13	9	37
lower part	62	11	5	25
Ceiling:				
upper part	74	15	15	40
lower part	74	19	15	43
Planking:				
wales of upper part	57	8	0	37
wales of lower part	39	0	0	23

Table 7-XIV. PEG-ratio (%) at the end of the 4th period of the conservation programme at two surface levels and two internal levels of the wood of the upper and lower parts of the planking, the ceiling and the wales.

Comparison of PEG-ratio of the wales and the planks of the upper part of the planking

The mean thickness of the wales of the upper part of the planking amounts to 144 mm while mean thickness of the planks of the upper part of the planking amounts to 64 mm (tables 7-II).

The middle layer of the wales of the upper part of the planking measuring c. 90 mm was cut into 5 pieces that have been compared with the c. 20 mm thick layer III of the planks of the same region.

The assumption to be tested was the idea that the thickness of the timbers to be preserved have determined the diffusion of PEG into the wood. In this comparison the difference of thickness of the planks was more than 50%.

Since there have been no core samples drilled from the wales during the first two periods of the conservation programme there are to be considered only the two PEG-ratio values from the end of the third and from the end of the fourth period of the conservation programme. These two values are similar in the outer surface layers but in the wales the layers beneath that layer have c. half the PEG-ratio values of the planks. The layer III and layer II of the planks have similar PEG-ratios while the middle layer of the wales is almost devoid of PEG (tables 7-XIII, 7-XIV; note that the values reported of the middle layer are median values).

Thus, this investigation seems to support the assumption that the thickness of the timbers is an important feature for determining the rate of diffusion of PEG molecules into the wood.

Comparison of PEG-ratio of the wales and the planks of the lower part of the planking

The mean thickness of the wales of the lower part of the planking amounts to 181 mm while mean thickness of the planks of lower part of the planking amounts to 83 mm (tables 7-II).

The middle layer of the wales of the lower part of the planking measuring c. 125 mm was compared with the c. 20 mm thick layer III of the planks of the same region.

Again, the assumption to be tested was the idea that the thickness of the timbers to be preserved is the most important characteristic to determine the diffusion of PEG into the wood. In this comparison, like the previous one, the difference of thickness of the planks was more than 50%.

Like in the previous investigation there are only PEG-ratio values from the end of the third and the fourth periods of the conservation programme to be considered. In the lower region even the outer surface layer of the wales show considerably lower PEG-ratio values compared to the outer surface layer of the planks from the same region. Moreover, both the layer beneath the surface layer and the middle layer of the wales show zero PEG-ratio meaning that no mean value of PEG-ratio of layer II nor the median PEG-ratio value of the middle layer have exceeded 0.4% (tables 7-XIII, 7-XIV).

This again supports the assumption that the thickness of the timbers is an important feature for determining the rate of diffusion of PEG molecules into the wood.

The assumption to be tested was the possibility that the climatic circumstances, i.e. RH and temperature at lower levels might have promoted diffusion of PEG molecules into the wood. On the contrary, the PEG content in the wood of the layer beneath the surface layer of the wales in the upper region demonstrate PEG-ratios of about the same size as in the layer beneath the surface layer of the planks in the same region. In the wales of the lower region there is no PEG at all inside the wood of the layer beneath the surface layer and further into the wood. Although the assumption could not be supported, the fact that the planks of the lower region are c. 25% thicker than those of the upper region should be weighed into the assessment. No final judgement of the impact of the climatic parameters could be reached.

The investigation stressed the thickness of timbers as more important for the diffusion process than small differences in climatic parameters. This ought to be kept in mind when planning a conservation treatment.

7.4. Comparison between the results of the spray treatment of oak and pine of minor dimensions in the Vasa hull

Since 1/3 of the orlop deck is constructed of oak wood while 2/3 of that deck is constructed of pine wood, and since the deck-planks of both these parts of the deck are of similar dimensions, and both parts of the deck have been subjected to the same atmosphere and the same conservation treatment there seem to be an ideal situation to ascertain whether these two different wood species react in the same way or differently to the same conservation situation.

One draw-back for the comparison is the fact that core-sampling of the deck-planks of the orlop deck had been performed during the conservation period only at 4 and 6 of the core-sampling opportunities for oak and pine planks, respectively. However, the distribution of core-sampling covered the conservation programme from the start of the automatic spraying which has enabled presentation of the results both in curves and in tables. The core-sample drilled at the occasion nearest to the end-point of each of the defined parts of the conservation programme has been taken to represent the conservation situation in the tables at that time of the procedure. This leaves out the 3rd part of the conservation period from the representation. The trend-curves chosen for the oak-samples are strait lines and those chosen for the pine-samples are 2nd degree polynomials.

Two wood-cores were drilled in each of the oak and the pine parts of the orlop deck at each core-sampling occasion. Each wood-core was cut into five pieces, each one c. 10 mm of length. Four of the pieces have been used for the investigation, leaving out the downward surface layer (figures 7-21 – 7-28, tables 7-XV – 7-XVII).

The oak part of the orlop deck

The ratios of an assumed PEG solution and of water in the separate layers of the oak cores from the orlop deck have been presented (figures 7-21 – 7-24). The oak part of the orlop deck may be compared to the lower part of the ceiling, layers I-III (figures 7-17 – 7-19), that has been subjected to the same treatment and belongs to the same climatic and treatment zone inside the Vasa hull as the orlop deck. The water-ratio of the surface layer at the first core-sampling of the orlop deck was as low as 100%, while the water-ratio of the surface layer of the ceiling was above 140% at the same core-sampling occasion. This may be due to the fact that the surface of the deck-planks lack the very deteriorated surface layer that constitutes a sometimes substantial part of the 10 mm thick layer I of the planks of the ceiling. In spite of this, according to the graphs of their water-ratios, the drying seems to be going on at the same pace in both cases, i.e. both have lost 80 percentage units of water during the conservation period, starting from the introduction of the automatic spray system.

The PEG-ratios may be derived from the gap between the graphs of the ratios of water and assumed PEG-solution. The PEG-ratio of layer I of the orlop deck has developed rather poorly, showing only two thirds as high PEG-ratio as layer I of the ceiling (figures 7-21, 7-17).

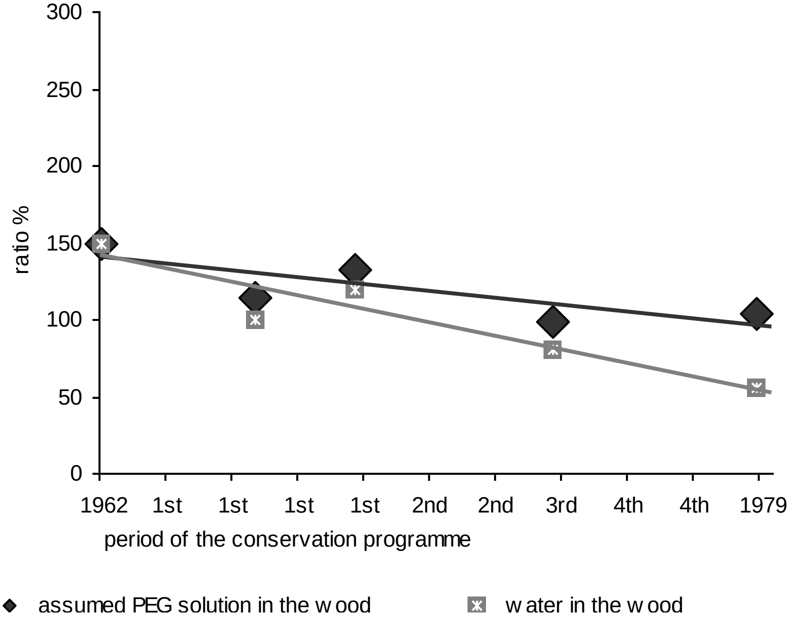

Figure 7-21. The ratio of assumed PEG solution and the ratio of water of layer I of the oak part of the orlop deck during the conservation period; analytical results and trends. Trend-lines; least square fittings.

The layers II and III of the orlop deck show similar drying patterns as the corresponding layers of the ceiling during the initial and the second periods of the conservation programme,[184] while the drying of the orlop deck proceeded faster during the third and the fourth periods of the treatment programme. The water-ratios of the oak part of the orlop deck, at the end of the conservation treatment programme, were c. 20 percentage units below the water-ratios of the corresponding layers of the ceiling.

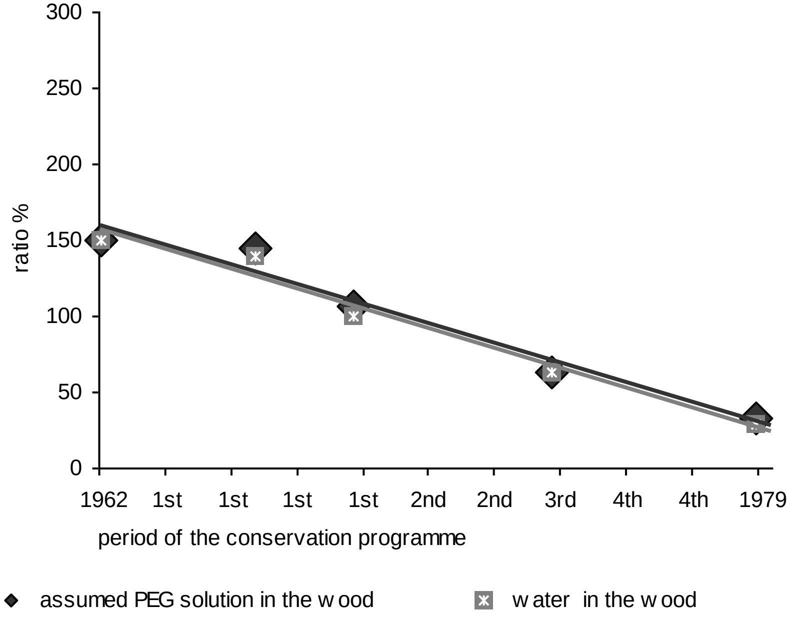

Figure 7-22. The ratio of assumed PEG solution and the ratio of water of layer II of the oak part of the orlop deck during the conservation period; analytical results and trends. Trend-lines; least square fittings.

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[184] This dissertation, 3.3.

Layer II of the orlop deck showed only traces of PEG, and layer III seemed to be totally devoid of PEG, while layer IV showed traces of PEG (figures 7-22 – 7-24).

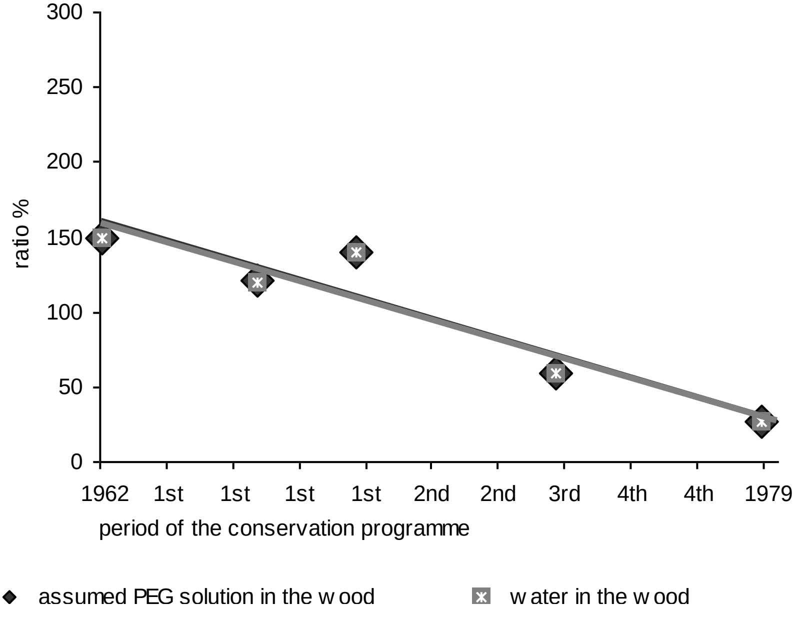

Figure 7-23. The ratio of assumed PEG solution and the ratio of water of layer III of the oak part of the orlop deck during the conservation period; analytical results and trends. Trend-lines; least square fittings.

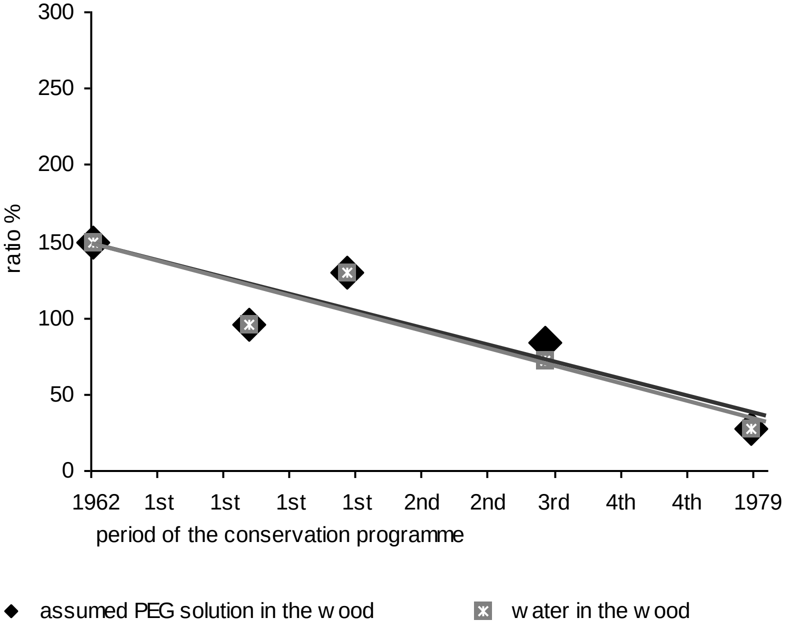

Figure 7-24. The ratio of assumed PEG solution and the ratio of water of layer IV of the oak part of the orlop deck during the conservation period; analytical results and trends. Trend-lines; least square fittings.

The pine part of the orlop deck

The ratios of an assumed PEG solution and of water in all of the separate layers of the cores from the part of the orlop deck that was made of pine wood have been presented (figures 7-25 – 7-28). The graphs of the water ratio show very similar tendencies at all levels of the wood-cores from the part of the orlop deck that was made of pine. At the first core-sampling the water ratios were between 120 and 140%. The graphs show a levelling out of the water ratios during the fourth period of the conservation programme. The decrease of water ratio during the conservation treatment period from the introduction of the automatic spraying system was c. 40% in all of the layers of the cores of the pine wood.

The ratios of assumed PEG solution did increase, especially during the fourth period of the treatment programme. This indicates movement of PEG molecules into the layers of the wood, and practically no water leaving the wood. As some drying occurred especially during the early periods of the conservation treatment programme, there may have been a combination of liquid transport as well as diffusion of PEG molecules from the treatment solution into the wood. Parallel to this process, water molecules may have been diffusing from the wood into the treatment solution, with a stable state concerning the water-ratio level in the wood forming during the fourth period of the conservation programme.

With a water-ratio in layer I of c.100% at the end of the conservation treatment period and a PEG-ratio of 100%, there is not much resemblance with layer I of the samples from the part of the deck that was made of oak. Instead, there is much more conformity with layer I of the lower part of the ceiling, with a water-ratio of c. 60% at the end of the conservation treatment programme and a corresponding PEG-ratio of 80% (figures 7-17, 7-25).

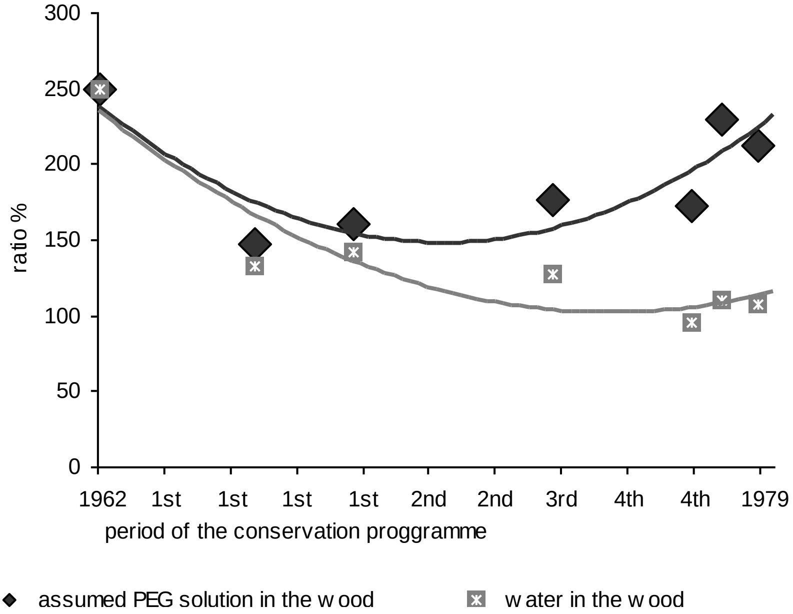

Figure 7-25. The ratio of assumed PEG solution and the ratio of water of layer I of the pine part of the orlop deck during the conservation period; analytical results and trends. Trend-lines; least square fittings.

The water-ratios of the layers II and III have also arrived at a stable state during the fourth period of the conservation treatment programme, with a corresponding increase of the PEG solution ratios, implying an increase of the PEG-ratios. Both the water- and the PEG-ratios were successively lower by just a few percentage units starting from the upwards surface and proceeding into the interior of the wood of the pine deck-planks. The water- and the PEG-ratios of layer II were c. 95% and 100% respectively. Both of the corresponding figures of layer III were c. 90%. The pine part of the orlop deck appeared extremely well preserved, compared to the oak part of the orlop deck, with c. 30% water-ratio and a negligible amount of PEG in the layers II and III.

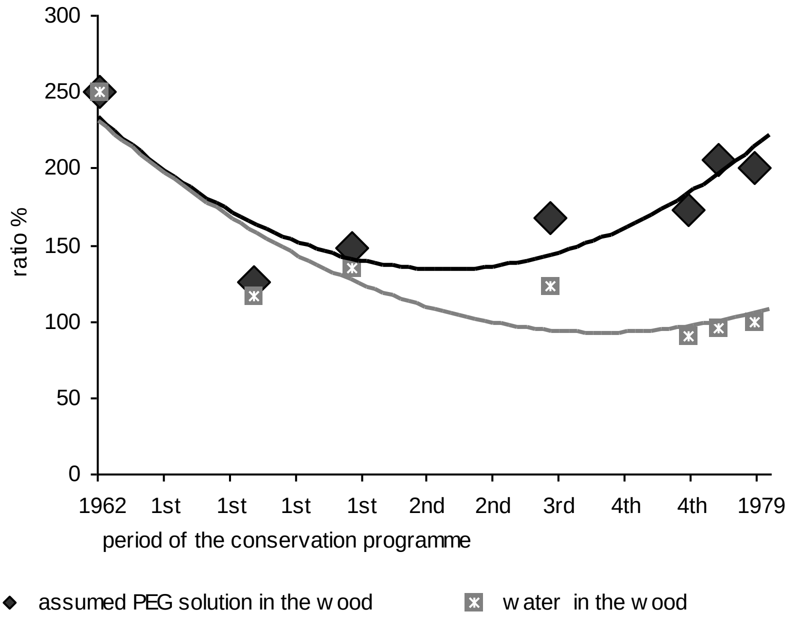

Figure 7-26. The ratio of assumed PEG solution and the ratio of water of layer II of the pine part of the orlop deck during the conservation period; analytical results and trends. Trend-lines; least square fittings.

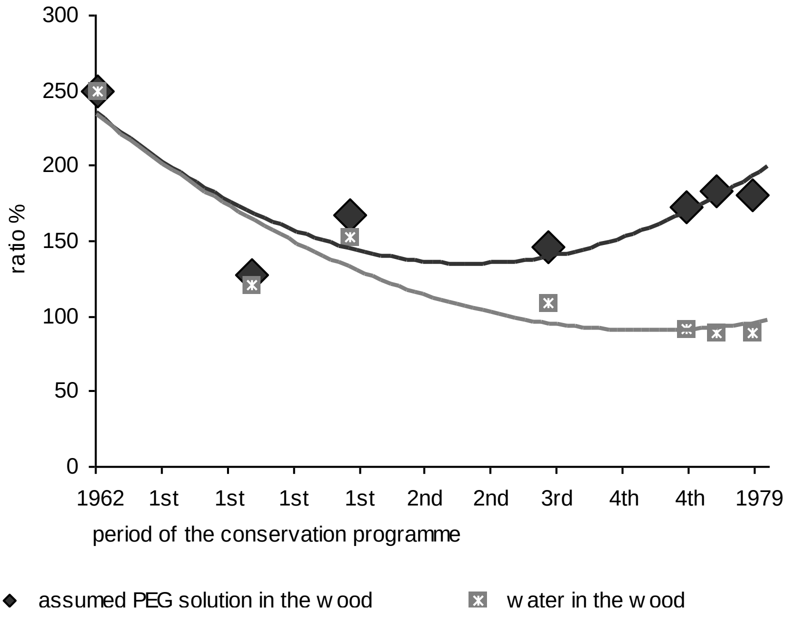

Figure 7-27. The ratio of assumed PEG solution and the ratio of water of layer III of the pine part of the orlop deck during the conservation period; analytical results and trends. Trend-lines; least square fittings.

Layer IV of the pine part of the orlop deck shows the same tendency as layers I, II and III of the pine part of the orlop deck, as regards the water- and the PEG-ratios. The water-ratio arrived at a steady state of diffusion of water molecules while the PEG solution ratio was increasing. This has resulted in a water-ratio of c. 80% and a PEG-ratio of c. 90% respectively, in the layer IV of the pine part of the orlop deck, at the end of the conservation treatment period.

The pine part of the orlop deck seems to have had a quite different ability to absorb PEG during the conservation period, even compared to the corresponding layers of the lower part of the ceiling, showing 45-50% water-ratios and c. 15% PEG-ratios.

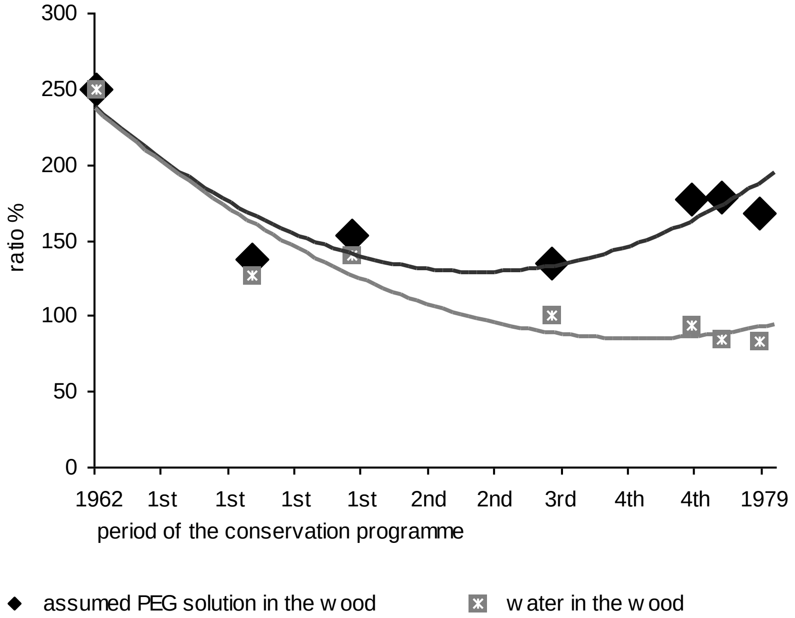

Figure 7-28. The ratio of assumed PEG solution and the ratio of water of layer IV of the pine part of the orlop deck during the conservation period; analytical results and trends. Trend-lines; least square fittings.

Comparison between the oak and the pine deck planks of the orlop deck

The first core-sample chosen as a check-point was drilled in 1970. This marks the change of the conservation programme which has been denoted the endpoint of the 1st period of the conservation programme. At that occasion the diffusion of PEG 1500 had been promoted by continuous spraying with a 15% PEG solution for c. 5 years.

The second core-sample chosen as a check-point was drilled in 1973 which marks the end-point of the 2nd period of the conservation programme. The period was terminated with a continuous spraying with a conservation solution with 25% PEG 1500. The duration of the period was three years which makes a total of eight years of continuous spraying up till that occasion.

The third core-sample chosen as check-point was drilled when the conservation programme was terminated in 1979. The changes observed at that occasion were due to what had happened during the 3rd and the 4th periods of the conservation programme. The PEG-concentration had been raised by adding PEG 600 to the conservation solution. This had been performed in steps of 5 percentage units from 25 to 35% and in one step of 10 percentage units to 45%, at the beginning of the 4th period.

During the 3rd period there was also a reduction of spraying rounds to 9 rounds per 24-hour period. The number of spraying rounds were reduced further to a minimum of one double round per 24-hour period during the 4th period of the conservation programme. This means that the third core-sample represented a six year period of cutting down of the spraying rounds from 32 to only one per 24 hour period and raising the PEG-concentration of the conservation solution from 25 to 45%.

The PEG-concentration of an assumed PEG solution inside the wood was chosen as monitoring parameter. The PEG- and the water-ratios have also been reported as conservation result (tables 7-XV – 7-XVII).

The PEG-concentrations of the layer I seem to be of the same magnitude in both of the ceiling and the oak part of the orlop deck, while the PEG concentrations of the assumed PEG solutions inside the layers II – IV of the wood-cores drilled from the oak part of the orlop deck show a markedly different pattern compared to the PEG concentrations inside the wood of the lower part of the ceiling. In the interior layers of the ceiling there is a steady increase in PEG-concentration while the figures of the corresponding layers of the oak part of the orlop deck are very low and irregular (figure 7-4, tables 7-XV, 7-III, 7-IV and 7-VI).

The concentrations of the assumed PEG solutions inside the layer I of the pine parts of the orlop deck of the Vasa were 2 to 5 percentage units higher than the concentration of the conservation solution on the occasions. The PEG-concentration inside the layer I of the oak part of the orlop deck was lower by 5 and 6 percentage units than the concentration of the conservation solution at the end of the 1st and the 2nd periods respectively. At the termination of the conservation programme the PEG-concentration inside the layer I of the oak part of the orlop deck corresponded to the concentration of the conservation solution. However, the concentration of the PEG solutions inside the oak part of the deck were lower by 4 to 9 percentage units, than the solutions inside the pine part at the corresponding occasions.

The assumed PEG solutions inside the wood of the layer II of the oak part of the deck show PEG concentrations that did not exceed 12%, while the PEG solution inside the layers II, III and IV of the pine part of the deck shows identical PEG-concentrations with the layer I during the 2nd and 4th periods of the conservation programme. Apart from the layer II, the interior of the oak part of the orlop deck show hardly detectable PEG concentrations (table 7-XV).

Orlop deck	Layer I upwards surface layer	Layer II 1st layer beneath the upwards surface layer	Layer III 2nd layer beneath the upwards surface layer	Layer IV 3rd layer beneath the upwards surface layer
oak part :				
PEG-concentration at				
end of 1st period	10	6.5	0.2	0
end of 2nd period	19	0.6	0.7	14
end of 3rd period	-	-	-	-
end of 4th period	46	12	1.5	0
pine part :				
PEG-concentration at				
end of 1st period	17	8.8	9.0	9.1
end of 2nd period	28	27	25	27
end of 3rd period	-	-	-	-
end of 4th period	50	50	50	51

Table 7-XV. PEG-concentration (%) of an assumed PEG solution inside the separate layers of the oak part and the pine part, respectively of the orlop deck at the end of the 1st, the 2nd and the 4th periods of the conservation programme at one surface level and three internal levels of the wood.

The Vasa pine material has been assumed to have had a maximum water-ratio of c. 250%, that is the water-ratio value chosen to be the initial water-ratio of the pine. The oak of the Vasa hull had a water-ratio of 150% according to analysis. During the first period of the conservation treatment programme, the drying proceeded uniformly at all levels of the wood in both of the oak and the pine parts of the orlop deck. At the end of the 2nd period there seems to have developed a water-ratio gradient between the surface layer and the other layers in the oak wood. This pattern was observed to have remained also at the end of the 4th period. Contrary to this situation the water-ratio of the pine wood remained uniformly distributed and at a high level until the end of the conservation treatment programme (table 7-XVI).

Orlop deck	Layer I upwards surface layer	Layer II 1st layer beneath the upwards surface layer	Layer III 2nd layer beneath the upwards surface layer	Layer IV 3rd layer beneath the upwards surface layer
oak part:				
H_2O-ratio at				
end of 1st period	120	100	140	130
end of 2nd period	80	63	59	72
end of 3rd period	-	-	-	-
end of 4th period	56	29	27	27
pine part:				
H_2O-ratio at				
end of 1st period	143	135	153	140
end of 2nd period	128	124	109	100
end of 3rd period	-	-	-	-
end of 4th period	107	100	90	83

Table 7-XVI. Water-ratio (%) of the separate layers of the oak part and the pine part, respectively of the orlop deck at the end of the 1st, the 2nd and the 4th periods of the conservation programme at one surface level and three internal levels of the wood.

The PEG-ratios of the layer I of both the oak wood and the pine wood was about equal in 1970, at the end of the 1st period of the conservation programme. In the oak wood the PEG-ratio of the surface layer remained at this level until the end of the 2nd period of the conservation programme. At that occasion the PEG-ratio of the layer I of the pine wood had more than doubled its PEG-ratio. At the end of the 4th period of the conservation treatment programme, the layer I of the oak part of the orlop deck had reached a PEG-ratio of 48% while the layer I of the pine part of the deck displayed a PEG-ratio value of above 100%. The deeper layers of the oak part of the deck seemed not to have absorbed any PEG after the 2nd period of the conservation programme. Contrary to the behaviour of the oak wood of the orlop deck the pine part of the deck has absorbed PEG nearly uniformly at all levels of the wood, and ended up with a PEG-ratio close to 100% at the end of the conservation period (table 7-XVII).

Orlop deck	Layer I upwards surface layer	Layer II 1st layer beneath the upwards surface layer	Layer III 2nd layer beneath the upwards surface layer	Layer IV 3rd layer beneath the upwards surface layer
oak part :				
PEG-ratio at				
end of 1st period	13	6.9	0.3	0
end of 2nd period	19	0.4	0.4	12
end of 3rd period	-	-	-	-
end of 4th period	48	4.0	0.4	0
pine part :				
PEG-ratio at				
end of 1st period	18	13	15	14
end of 2nd period	50	45	36	35
end of 3rd period	-	-	-	-
end of 4th period	106	101	91	85

Table 7-XVII. PEG-ratio (%)of the separate layers of the oak part and the pine part, respectively of the orlop deck at the end of the 1st, the 2nd and the 4th periods of the conservation programme at one surface level and three internal levels of the wood.

7.5. Comparison between the results of the spray treatment of heavy oak and pine timbers in the Vasa hull

The average thickness of the 10 items of heavy oak timbers inside the Vasa hull that were selected for core-sampling was c. 250 mm, and the thickness of the heavy pine timber amounted to 320 mm. No core-samples were drilled in heavy timbers inside the Vasa hull until 1975. This makes the occasions of core sampling during the conservation period too few, to allow for a basis for curves to be performed. The values of the mean PEG concentration, the mean water-ratio and the mean PEG ratio, respectively of each of the four 10 mm thick layers in succession from the upper surface to a depth of c. 40 mm into the wood of the objects have therefore been presented only in tables (tables 7-XVIII - 7-XX).

The two occasions for sampling have been the end of the 3rd and the end of the 4th periods of the conservation programme.

The 3rd period of the conservation programme that lasted for c. 2 years was characterised by a conservation solution where the PEG concentration of the 25% conservation solution was raised at two occasions to 30 and 35%, respectively with additions of PEG 600. There was also a reduction of spraying rounds per time unit during the period.

During the 4th period of the conservation programme the PEG concentration of the conservation solution was kept at 45% by only adding PEG 600 to the solution. The number of spraying rounds were reduced to a minimum of one double round per 24-hour period. The 4th period of the conservation programme lasted for c. 4 years.

The PEG-concentration of the assumed PEG solution inside the 10 mm thick surface layer of the oak and pine wood, respectively are found to be of the same magnitude for the two wood species both at the termination of the 3rd and at the termination of the 4th period. However, the PEG-concentration in the 10 mm thick layer beneath the surface layer was three times as high in the pine wood as in the oak wood at the end of the 3rd period. In the pine wood it was also nearly as high as in the surface layer. At the termination of the conservation programme, in 1979 the PEG-concentration had increased by c. 10 percentage units both in the oak and in the pine wood, and the PEG concentration in layer II of the pine wood was twice as high as the PEG-concentration of the corresponding layer of the oak wood. The rest of the gradient of the oak wood shows nearly identical PEG-concentrations both at the end of the 3rd and at the end of the 4th period. The PEG-concentration was only a few percentage units higher at the latter occasion. There was a declining gradient of PEG-concentration even in the pine wood, and in layer IV there seems not to have been much difference in PEG-concentration between the oak wood and the pine wood, neither at the end of the 3rd period nor at the termination of the conservation programme in 1979 (table 7-XVIII).

Heavy timbers inside the Vasa	Layer I upwards surface layer	Layer II 1st layer beneath the upwards surface layer	Layer III 2nd layer beneath the upwards surface layer	Layer IV 3rd layer beneath the upwards surface layer
oak timbers :				
PEG-concentration at				
end of 3rd period	40	12	6	7
end of 4th period	61	23	12	10
pine timbers :				
PEG-concentration at				
end of 3rd period	42	37	14	4
end of 4th period	61	48	29	14

Table 7-XVIII. PEG-concentration (%) of an assumed PEG solution inside the separate layers of the heavy oak timbers and the heavy pine timbers, respectively inside the Vasa hull at the end of the 3rd and the 4th periods of the conservation programme at one surface level and three internal levels of the wood.

The Vasa pine material has been assumed to have had a maximum water-ratio of c. 250%, that is the water-ratio value chosen to be the initial water-ratio of the pine. The oak of the Vasa hull had a water-ratio of 150%, according to analysis. At the end of the 3rd period, in 1975 the water-ratio gradient of the oak wood seems to have existed only between the surface layer and the rest of the layers. This pattern was maintained at a lower level also in 1979. The pine wood exhibits a gradient of the water-ratio between the layer II and the succeeding layers in 1975. This water-ratio gradient is somewhat unstable inwards into the wood both at the end of the 3rd period and at the end of the conservation programme in 1979 (table 7-XIX).

Heavy timbers inside the Vasa	Layer I upwards surface layer	Layer II 1st layer beneath the upwards surface layer	Layer III 2nd layer beneath the upwards surface layer	Layer IV 3rd layer beneath the upwards surface layer
oak timbers :				
water-ratio at				
end of 3rd period	59	45	45	44
end of 4th period	41	32	34	36
pine timbers :				
water-ratio at				
end of 3rd period	110	99	48	61
end of 4th period	59	76	49	77

Table 7-XIX. Water-ratio (%) inside the separate layers of the heavy oak timbers and the heavy pine timbers, respectively inside the Vasa hull at the end of the 3rd and the 4th periods of the conservation programme at one surface level and three internal levels of the wood.

The PEG-ratio of the oak wood surface layer showed rather high values both in 1975 and in 1979. In both years there was also a sharp demarcation to the PEG-ratios of layer II and the two deeper layers in the wood. In the pine wood the PEG-ratio of the surface layer was still higher than in the oak wood, and the PEG-ratio demarcation was between the layer II and the two deeper layers (table 7-XX).

Heavy timbers inside the Vasa	Layer I upwards surface layer	Layer II 1st layer beneath the upwards surface layer	Layer III 2nd layer beneath the upwards surface layer	Layer IV 3rd layer beneath the upwards surface layer
oak timbers :				
PEG-ratio at				
end of 3rd period	42	12	5	4
end of 4th period	69	16	9	13
pine timbers :				
PEG-ratio at				
end of 3rd period	80	59	8	3
end of 4th period	91	71	20	13

Table 7-XX. PEG-ratio (%) inside the separate layers of the heavy oak timbers and the heavy pine timbers, respectively inside the Vasa hull at the end of the 3rd and the 4th periods of the conservation programme at one surface level and three internal levels of the wood.

Conclusions

The results of the investigation, expressed as PEG-ratio, emphasize that the pine wood shows high PEG-ratios rather deep into the wood, and has responded better to the conservation treatment than the oak wood. This may depend on the circumstance that the higher content of water in the pine wood might have favoured the diffusion of PEG molecules, or that any hindrance to diffusion was present in the oak wood, depending on the difference in the anatomical structures of the softwood and the hard-wood species, respectively. This however, can not be decided upon in the present situation.

The result of the conservation treatment was that the heavy pine timber in the Vasa hull had obtained a high PEG-ratio to a depth of c. 20 mm while the heavy oak timbers had got half as high a PEG-ratio, and only to a depth of c. 10 mm. It has to be noted is that the heavy pine timber has as low PEG-ratio values deeper into the wood as the heavy oak timbers.

The improvement in PEG-ratios in both of the heavy pine and the heavy oak wood between 1975 and 1979 all through to the depth investigated, c. 40 mm, may suggest, that liquid transport may have taken place in the heavy timbers during this time interval.

7.6. Management of the conservation of the Vasa hull

When the Vasa hull had been raised the conservation experts of the Conservation Council and the conservation staff took over from the archaeologists, and acted as leaders of the project for a period of time. This leadership was restricted by an obligation that it was decided that the public should have access to the pontoon super structure in which the conservation of the Vasa hull went on. The condition was, however, that the conservation process would not be accepted to be disturbed in any way.

However, since there was no knowledge available about the processes of diffusion in archaeological wood with a high water content, the processes of conservation and drying were expected - even by experts on commercial wood impregnation - to proceed at much greater speed than was in fact the case. This situation caused some serious tension to develop between the groups of staff responsible for the conservation work and, on one hand those whose task it was to start restoration work and, on the other hand those who wanted to make exhibitions containing still not stabilized original objects. In these conflicts the goal of the project was brought up at meetings, and redefined differently by each of the conflicting parties.

A common goal description may have had eased clash of interests between these different fields of activities in the museum, where each such field would have had to formulate its specific objectives from the common one, as described by Director General Luis Monreal in his speech at the ICOM 19th General Conference.[185]

Management on the political level

A superior and partly political plan was introduced by the fact that the building for the conservation laboratories was placed at the disposal of the Vasa project for as short a period as 5 years and the location for the pontoon was placed at the disposal of the project until 1 April 1968, when the permanent Vasa museum was planned to be completed.[186]

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[185] ICOM News, volume 54, 2001, No. 3, p 14.

[186] Claus, 1986, pp 144-145.

The period of disposal of the conservation laboratories was later prolonged, and the building was used for the Vasa project until the year 2008. Since a political decision to finance the building of a permanent Vasa museum had to be taken, which issue came up on the political agenda several times starting in 1969, and finally in 1986 when an architect's competition for the design of a permanent Vasa museum was decided. The permanent Vasa museum was opened in 1990.

The uncertainty about how soon the permanent museum would be built affected the PEG-concentration raising programme. The suggestion in October 1969, from the conservation manager, Lars Barkman, that the PEG concentration level of the conservation solution should be raised from 15% , that had been the concentration level during a period of c. 3 years, to 20% was not approved by the Conservation Council. Despite this non-approval Barkman in January 1970, carried through the raise to 20% of the PEG-concentration of the conservation solution. Since the possibility that finance of a permanent museum would be provided came up every year, the conservation manager was pressed to accept a programme that would terminate the spraying of the Vasa hull with conservation solution at a fixed point of time. This situation eventually made the conservation manager leave his position.[187]

7.7. Swelling and shrinkage of the wood during the conservation process

In 1965, when the automatic spray system was started, some timbers in the Vasa hull were chosen for measuring movements of the wood.[188] These measurements have been performed both on the planks of the planking and the ceiling and on heavy timbers inside the hull (figure 7-29).

During the hand-spraying period a strain gauge measuring equipment had been in operation.[189] This measurement series had been terminated before the automatic spraying was introduced. The graphs of the shrinkage measurements have been represented together with the graph of the PEG concentration programme of the conservation solution

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[187] Håfors, 2001, pp 65-71.
[188] Håfors, 2001, p 139.
[189] Håfors, 2001, p 138.

(figure 7-29). The shrinkage is discussed for each of the previously defined periods of the conservation programme.[190]

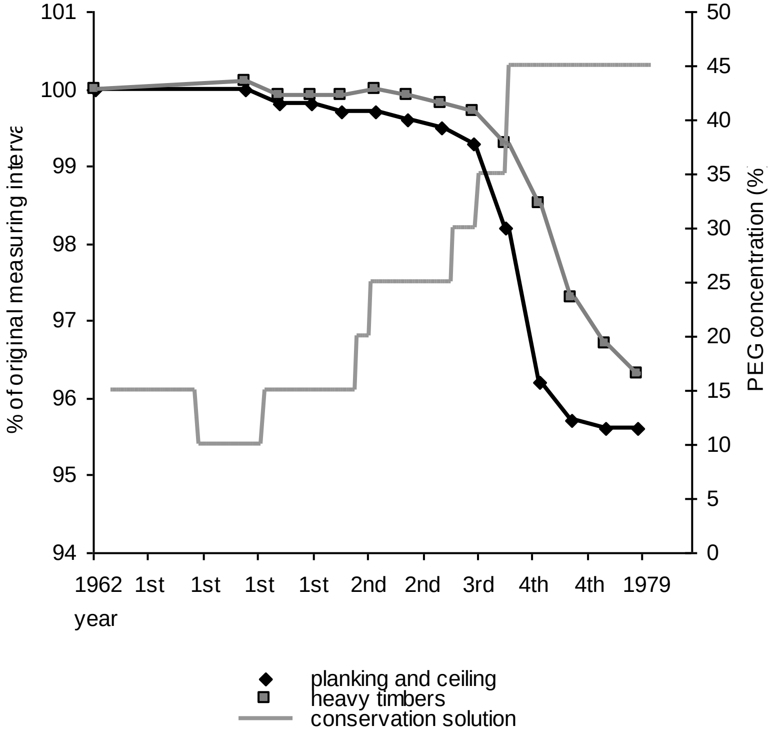

Figure 7-29. Shrinkage of the planks of the planking and the ceiling and the heavy timbers inside the Vasa hull.

During the first part of the conservation programme that was characterised by frequent spraying with PEG solution of low concentration the heavy timbers showed practically no movement. However, at the measuring points on the planks of the planking and the ceiling, however, movements were registered that at the end of that part of the programme showed a shrinkage of the planks of c. 0.3%.

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[190] This dissertation, p 140.

During the three years lasting, second part of the conservation programme when the spraying still was kept at the same high frequency as before but the PEG concentration of the conservation solution was raised from 15 to 25% the shrinkage of the timbers proceeded at a slow pace and reached c. 0.2 and c. 0.5% of the heavy timbers and the planks, respectively.

The third part of the conservation programme lasted for c. two years. During the first year the PEG concentration of the conservation solution was raised to 30% and the frequency of spraying rounds was cut down with c. 40%. During this first year the shrinkage went on much the same as before and had reached c. 0.3 and c. 0.7%, respectively of the heavy timbers and the planks when the PEG concentration of the conservation solution was raised to 35% and the frequency of spraying rounds was cut down to 50% of the original number. This seems to have accelerated the shrinkage of the rather thin timbers of the planks that brought the total shrinkage of these to c. 1.8%. However, the adjustment of the conservation programme seems not to have had a very profound effect on the shrinkage of the heavy timbers that ended up with c. 0.7% total shrinkage at the end of the third part of the conservation programme.

During the first year of the fourth part of the conservation programme the timbers of the planks shrank additionally 2 percentage units to a total of c. 3.8%. During the second year of the fourth part of the conservation programme the timbers of the planks shrank additionally 0.5% to a total of c. 4.3%. During the third and the fourth years of the fourth part of the conservation programme there was practically no additional shrinkage of the timbers of the planks. However, about half a year after the conservation had been stopped an additional shrinkage of the timbers of the planks amounting to c. 0.4% was registered.

The shrinkage of the heavy timbers was not as fast as the shrinkage of the thin timbers of the planks. During the first year of the fourth part of the conservation programme the additional shrinkage was 0.8 percentage units to a total of c. 1.5% and it was not until the end of the fourth part of the conservation period that the shrinkage of the heavy timbers had reached c. 3.7% i.e. about the same level of shrinkage as the thin timbers of the planks had reached at the end of the first year of the fourth part of the conservation programme.

The extent of shrinkage to be expected to happen after the treatment period before a stable situation has been established should also be taken into account at an evaluation of the conservation treatment.

7.8. Conservation of the Vasa hull: conclusions

The result anticipated from a bulking conservation treatment would be that an amount of preservative had been deposited in the wood. Therefore, the PEG content at the end of the conservation treatment should be the initial parameter to be investigated (table 7-XXI).

The PEG-ratios were rather high in the outer surface layer of all of the constructions investigated. The ceiling showed the highest values, c. 75% PEG-ratio while the planking stayed behind by more than 10 percentage units with c. 62% PEG-ratio. The PEG-ratios obtained in the upper and the lower parts of both of the planking and the ceiling are similar to each other. This, however is not the case where the wales are concerned. The outer surface layer of the group of higher situated wales show c. 5 percentage units lower PEG-ratio level than the outer surface layer of the planks of their corresponding zone of the planking while the group of lower situated wales show PEG-ratio values that are more than 20 percentage units lower than the PEG-ratio level of the planks of their corresponding zone of the planking.

In layer II of the planking the PEG-ratios of the upper and the lower parts, respectively are rather similar and rather low, just above 10%. In layer III the PEG-ratios were below 10% and the divergence of PEG-ratios had increased between the upper and lower parts. Layers II of the ceiling, however, show PEG-ratio values of 15% in the upper parts and as much as 19% at the lower level. Both of the levels of layer III show 15% PEG-ratio. Layer II of higher situated wales was the only internal layer of the wales that showed measurable PEG-ratio values.

The inner surface layer of all constructions investigated are facing each side of the ribs and thus are situated only at a very short distance from each other. The space has been accessible to conservation solution but it is rather poorly ventilated which means that the possibility of microclimate formation cannot be ruled out. This means that condensation of water may have occurred and diluted the conservation solution in that area. However, layer IV of the upper parts of both the planking and the ceiling and the wales have obtained PEG-ratios of c. 40%. Layer IV of the lower part of the ceiling shows equal PEG-ratio level as the upper part of the same constructional unit. Layer IV of the lower part of the planking arrived at the same PEG-ratio as layer IV of the wales, c. 25%.

As a summary may be noted, that:

- the thicker timbers, the wales, have obtained a lower degree of conservation (lower PEG-ratios) than the thinner planks in the same area, and
- the planks of the ceiling, have received a higher degree of conservation (higher PEG-ratios) than the planks of the planking on a corresponding level in the pontoon super structure.

	Layer I outer surface layer (0-10 mm)	Layer II 1st layer beneath the outer surface layer (11-30 mm)	Layer III 2nd layer beneath the outer surface layer	Layer IV inner surface layer
Planking:				
upper part	62	13	9	37
lower part	62	11	5	25
Ceiling:				
upper part	74	15	15	40
lower part	74	19	15	43
Planking:				
wales of upper part	57	8	0	37
wales of lower part	39	0	0	23

Table 7-XXI. PEG-ratio (%) at the end of the conservation period at two surface levels and two internal levels of the wood of the upper and lower parts of the planking, the ceiling and the wales.

Comparing the figures presented in the table with the generally accepted water-ratio of 150% of the Vasa oak-wood in the waterlogged situation gives the information that the Vasa oak wood had dried, loosing between c. 80 and 120 percentage units of water in the inside layers during the conservation period (table 7-XXII).

The outer surface layer of both of the ceiling and the lower part of the planking seems also to have had an initial water-ratio of c. 200%. This may be attributed to the original burial of the hull into the bottom sediments at the wreck-site, giving protection to mechanical wear of its wooden surface (figure 7-9).

	Layer I outer surface layer (0-10 mm)	Layer II 1st layer beneath the outer surface layer (11-30 mm)	Layer III 2nd layer beneath the outer surface layer	Layer IV inner surface layer
Planking:				
upper part	40	27	31	40
lower part	37	29	32	45
Ceiling:				
upper part	40	40	43	49
lower part	57	48	50	56
Planking:				
wales of upper part	47	32	32	44
wales of lower part	31	26	34	46

Table 7-XXII. Water-ratio (%) at the end of the conservation period at two surface levels and two internal levels of the wood of the upper and lower parts of the planking, the ceiling and the wales.

To assist investigation into the conservation situation, the sums of water and PEG of the same units and levels as before are considered (table 7-XXIII).

	Layer I outer surface layer (0-10 mm)	Layer II 1st layer beneath the outer surface layer (11-30 mm)	Layer III 2nd layer beneath the outer surface layer	Layer IV inner surface layer
Planking:				
upper part	105	40	40	89
lower part	103	40	37	77
Ceiling:				
upper part	128	55	58	101
lower part	140	67	65	97
Planking:				
wales of upper part	120	40	32	80
wales of lower part	73	26	34	76

Table 7-XXIII. (PEG + water)-ratio (%) at the end of the conservation period at two surface levels and two internal levels of the wood of the upper and lower parts of the planking, the ceiling and the wales.

In order to learn how much of the water, initially in the waterlogged oak-wood, had been replaced by PEG, a calculation of the fraction of PEG related to the initial quantity of water has been performed (table 7-XXIV).

	Layer I outer surface layer (0-10 mm)	Layer II 1st layer beneath the outer surface layer (11-30 mm)	Layer III 2nd layer beneath the outer surface layer	Layer IV inner surface layer
Planking:				
upper part	43	9	6	33
lower part	33	7	3	21
Ceiling:				
upper part	44	10	10	35
lower part	42	13	10	27
Planking:				
wales of upper part	49	5	0	24
wales of lower part	28	0	0	20

Table 7-XXIV. Fraction (%) of original content of water that has been exchanged for PEG inside the wood at the end of the conservation period at two surface levels and two inside levels of the wood of the upper and lower parts of the planking, the ceiling and the wales.

As basis for the calculation of the fraction of the original quantity of water inside the separate layers of wood that has been exchanged for PEG, an original water-ratio of 150% has been assumed for all layers except the outer surface layer of the ceiling, that has been assumed to have had an original water-ratio of 200% (figures 7-13, 7-17). The reason for this high water-ratio might be that the outer surface layer of the ceiling that is defined as the initial 10 mm of the wood-cores for analysis contains a larger part of the very deteriorated, soft surface layer than is the situation of the initial parts of the corresponding wood-cores of the planking. The basic idea of this interpretation is that the more sheltered situation inside the hull, with less mechanical wear of the surface, has retained more of the deteriorated surface than the outside of the hull.

The calculation shows that a rather low percentage of the original water quantity has been substituted with PEG in the inside layers of the wood.

However, the ceiling seems to have been more evenly preserved than the planking. A possible reason for this may have been the calmer climatic situation inside the hull, and also that the conservation solution might have remained on the surfaces for longer periods, depending on the shape of the inside.

As the measurements of movement had shown (section 7.7., figure 7-29) there had been a tendency of shrinkage of the planks of the planking and the ceiling as early as at the end of the 1st period of the conservation programme. The shrinkage of both of the heavy timbers and the planks then proceeded through the 2nd period of the conservation programme at the same rate as that of the planks during the 1st period of the conservation programme.

The internal layers of the planks of the ceiling of the Vasa hull seemed to immediately have started drying despite the continuous spraying with a rather dilute PEG solution. The water-ratio of the planks of the planking and the ceiling had fallen to c. 100% at the end of the 1st period and had proceeded to c. 75% at the termination of the 2nd period of the conservation programme (section 7.3., tables 7-VII, 7-VIII). The PEG-ratio of the internal layers of the planks increased slowly to c. 2% at the end of the 1st period and to c. 5% at the end of the 2nd period of the conservation programme (section 7.3., tables 7-XI, 7-XII).

The water-ratio proceeded decreasing by another 20 percentage units during the 3rd period of the conservation programme, which ended with a shrinkage of c. 2%. During the second half of the 4th period of the conservation programme the shrinkage had a standstill c. 4%, for c. 1.5 years, at a water-ratio of 40-35% (section 7.3., tables 7-IX, 7-X). The PEG-ratio increased during the 3rd and the 4th period of the conservation programme to c.10 and c. 15% (section 7.3., tables (section 7.3., tables 7-XIII, 7-XIV).

The shrinkage of the heavy oak timbers followed the shrinkage of the planks with some delay. The water-ratio at the termination of the 3rd and the 4th periods of the conservation programme were 45 and 35%, respectively. The PEG-ratio at the same occasions were 12-5% and 16-9% with the somewhat higher value in the layer II and the lower value in the layer III (tables 7-XXI - 7-XXIV).

- The main conclusion will be, that the conservation treatment has not been able to prevent shrinkage even during the treatment period.

With the PEG-ratio obtained at the end of the conservation period, the ASE at 55% RH would be c. 30% in both of the radial and the tangential directions of the wood for both of PEG 600 and 1500 (section 5.4., figures 5-26, 5-28). However, a higher PEG-ratio inside the layers II and III would provide a higher ASE value. As there seems to have been practically no raise of the PEG-ratio-values in the planking during the 4th period of the conservation programme while the ceiling displayed increase from 9 to 1 percentage units PEG-ratio in the layers II and III (section 7.3., tables 7-XIII, 7-XIV).

The lack of diffusion of PEG molecules into the internal parts of the wood of the planking was accompanied by decrease of water-ratio of 17-22 percentage units while the decrease of water-ratio in the ceiling amounted to 12-17 percentage units (section 7.3., tables 7-IX, 7-X).

- The conclusion is that the drying of the planks of the planking was too fast and proceeded to too low water-ratios to allow for diffusion of PEG in the opposite direction.

In order to avoid stopping PEG molecules to diffuse into the interior parts of the wood while proceeding with the conservation programme the cutting down on the spraying rounds should have been postponed until the increment programme was terminated.

However, as a general observation, the rather low temperatures in the winter inside the pontoon super-structure may have affected the rate of diffusion both of the PEG molecules and of the water molecules inside the wood of the Vasa. The substantial differences in temperature between the summer and the winter periods, that produced condensation in the pontoon super-structure during a couple of months every year in the autumn, will obstruct a strict evaluation of the spray treatment of the Vasa hull.[191]

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[191] Håfors, 2001, pp 101-107, 76-77.

8. Immersion Treatment with PEG of Loose Wooden Objects and Construction Timbers from the Vasa

The immersion conservation treatment was started in 1962, i.e. at about the same time as the laboratory experimental work was started. Therefore no results of the experiments existed, that could be applied when designing the conservation programmes of the initial batches of immersion treatment.

Feed-back from the full-scale PEG immersion impregnations has been provided by monitoring of the conservation solutions by determination of the PEG concentration at regular time intervals during the conservation period, and by analysis of water and PEG of wood-cores. These were generally drilled before starting, and at the endpoint, of each conservation programme.

At each core sampling occasion wood-cores were drilled from c. 15 of the objects of a conservation batch. Each wood-core was drilled all through or to the middle point of the width of the wooden object. The wood-cores were cut into sections in accordance with a schedule that was settled down after some batches had been completed. The schedule stipulated that a 5 mm section was to be cut of the surface from which the wood-core had been drilled. This section was denominated layer I. The following sections, denominated layers II, III, IV, V, VI and VII, were cut to 5, 10, 10, 15, 15, and 20 mm respectively. Depending on the width of the object from which the wood-core was drilled an additional number of 20 mm sections were cut that ended the series if the wood-core had been drilled to the middle point of the width of the wooden item. If the wood-core was drilled all through the wood the series was terminated with sections of 15, 15, 10, 10, 5 and finally another 5mm.

Analysis of water and PEG in the wood-cores has been performed according to the "analytical programme for core samples 1962-1992" presented in "Conservation of the Swedish warship Vasa from 1628".[192]

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[192] Håfors, 2001, pp 113-114.

Treatment programmes

The disconnected wooden finds from the Vasa were immersion-treated with PEG in 20 batches during the period 1962 - 1977. The treatment programmes for 17 of the batches were designed to produce a fully preserved end-product while three of the batches were meant to catch up with the conservation situation of the Vasa hull so that the material could be refitted into the hull construction at an earlier stage than would otherwise have been advisable. A fourth group of material for refitting into the hull was treated together with the "sixth batch of material at a complete conservation programme" from the start of the conservation programme until it had proceeded to a PEG-concentration of 25%. The programme to put back constructional material was adopted because it was thought that keeping the hull in one piece during the conservation and drying periods was the best way to avoid too much deformation of the entire construction. This was also the reason why sometimes such material was removed from a batch before the programmed end concentration was reached. This created individual conservation programmes for those items.

The Vasa conservation workshop was equipped with two large tanks and one smaller tank for immersion treatment with PEG solution of the c. 15000 loose or disconnected wooden objects rescued from the Vasa underwater site or excavated from the Vasa hull during the summer of 1961. All three tanks were equipped with pipeline systems and pumps for continuous circulating of the conservation solution during the treatment procedure.

The first batch in each of the large tanks was monitored by core sampling during the conservation procedure to gain knowledge about the conservation process. These may be considered as preliminary batches. They were labelled "the first batch at a preliminary conservation programme" and "the second batch at a preliminary conservation programme", respectively.

The four parameters "water-ratio, PEG-ratio, ratio of an assumed PEG solution in the wood, and PEG-concentration of this assumed solution in the wood" calculated layer by layer on all the wood-core pieces belonging to a sample were intended to be calculated at each core-sampling occasion for evaluation of the conservation process. This has not always been possible e.g. for management reasons. If a figure has not been possible to establish this will be denoted with "-" in the tables. Otherwise all values have been abbreviated according to the following table:

- Values below 10 have been noted with one decimal;
- Values from 10 to 99 have been noted with two figures;
- Values between 100 and 150 have been noted with three figures; and
- Values above 150 have been noted with two figures.

8.1. Preliminary conservation programmes

As a basis for the immersion conservation programmes for the preliminary batches a test treatment had been performed in a 5 m^3 tank during a 7 month period.[193] The experiences from this test were mainly that the raising of the PEG concentration of the conservation solution should proceed at a slower pace than had been applied at the test programme and that a PEG-melt should never be used as conservation liquid. Moreover, it had revealed the fact that the Vasa oak wood and the Vasa pine wood reacted differently to the conservation procedure.

8.1.1. The first batch of Vasa wood at a preliminary conservation programme

In October 1962 the one of the large tanks that had a capacity of 34 m^3 for stowing material was charged with large objects like bases, sides, axles, and wheels of gun-carriages and other large timbers, in all 223 objects. Among these, 21 weighed between 100 and 300 kg, and 48 objects weighed less than 20 kg. The batch comprised 19 objects made of pine, 1 object was listed as made of lime wood while the majority of

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[193] Håfors, 1990, pp 202-203; Håfors, 1993, p 56.

the objects were made of oak. The total volume of wooden material in this batch was 15.63 m^3 that occupied c. 45% of the capacity of the tank.

The PEG 4000, that was the only PEG considered as suitable for tank treatment at the time when the first batch was started, was chosen as a conservation agent. In accordance with Morén & Centervall an initial period of 3 months duration with 10% PEG 4000 in the conservation solution followed by daily increments of 0.25% of the PEG-concentration was chosen as conservation programme. A temperature raising programme was chosen in accordance with a modification of the temperature programme recommended by Morén & Centervall.[194]

During most of the initial period the temperature of the conservation solution was kept at 30°C. At the end of that period the temperature was raised to 35°C and then it was raised in accordance with the following schedule:

- 40°C at 20% PEG-concentration
- 45°C at 30% PEG-concentration
- 50°C at 40% PEG-concentration
- 55°C at 50% PEG-concentration
- 60°C at 60% PEG-concentration

The PEG-concentration raising programme was stopped temporarily after c. 2 months, while the necessity of adding the PEG increments even on Sundays was investigated. As such a consideration implied hiring of extra staff, it would entail economic consequences. The outcome was that the PEG increment was recalculated to 1/3% that would be added 5 days a week. That would mean that a period of another 9 months would be required to run the programme.

The conservation programme was terminated at 80% PEG, when the actual end-concentration of PEG was 50-55%. This observation meant that the PEG-concentration development in the conservation solution had suddenly stopped at c. 50% for a period when it should have been raised by 12% by the PEG added to the solution (figure 8-1).

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[194] Moren & Centervall, 1960.

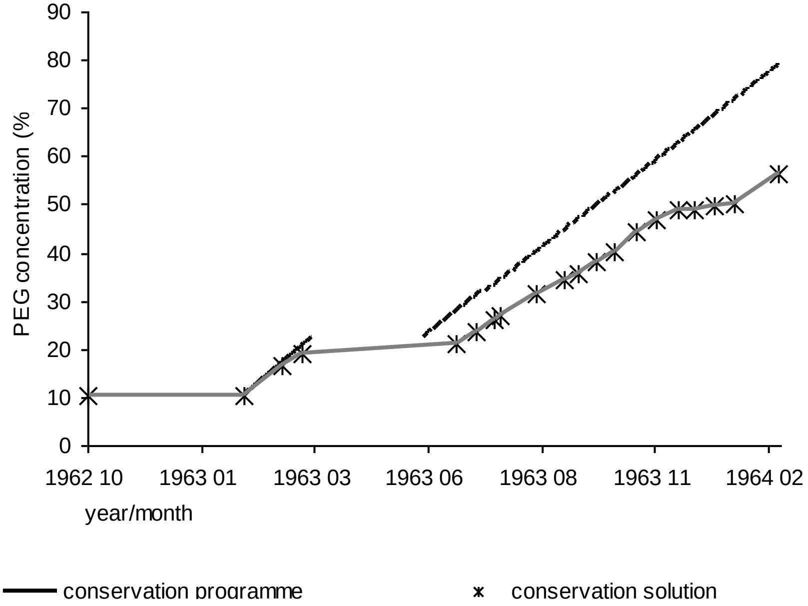

Figure 8-1. PEG-concentration of the conservation programme and of the conservation solution of the first batch of Vasa wood at a preliminary conservation programme.

As this was the first batch of immersion treatment of loose and disconnected wooden material, and there was some uncertainty about the choice of conservation programme, the conservation procedure was monitored by wood-core sampling at 6 occasions. These were performed at 15%, 20%, 35%, 50%, 60%, and 80% PEG, added according to the conservation programme. The actual PEG-concentrations in the conservation solution at the core-sampling occasions were 15%, 20%, 26%, 37%, 48% and 58% (tables 8-I – 8-VI).

The wood-core sampling was performed in a strictly controlled manner, in order not to disturb the conservation procedure unnecessarily. A volume of conservation solution was pumped out from the tank to make the upper layers of wooden material available. This made the temperature of the material still below the liquid surface decrease only by

c. 5 °C. Drilling of core-samples needed c. 2 hours. After the sampling had been performed the conservation solution was pumped back into the conservation tank, and the working temperature was reinstalled c. 12 hours later.

The wood-cores were drilled from the upwards-turned side of the object as placed in the conservation tank and as near to the middle of the object as possible. Cracks were avoided, and a certain distance was kept from previous drillings. Wood-cores were drilled from 8 oak objects and 3 pine objects at each sampling. The oak material consisted of a variety of constructional parts, like beams and knees of c. 200 mm width, but also some thin material like a step of a staircase of c. 40 mm width. The pine material consisted of three thin planks of c. 40 mm width. The amount of material in the monitoring procedure was c. 4% of the total volume of material in the batch.

The wood-cores were cut into c. 10 mm sections and the content of water and PEG have been analysed in each piece of a wood-core. From this the PEG-ratio, the water-ratio and the concentration of an assumed PEG solution inside the wood-core have been calculated. The grand means of these parameters have been calculated for the layers I, II, III, and IV of the oak and pine wood-cores, respectively. The concentrations of the assumed PEG solutions in the four layers investigated have been compared for the oak and pine material (figures 8-2, 8-3).

The assumed PEG solution inside the layer I of both the oak wood and the pine wood seem to show similar PEG concentration values during the conservation period. At the termination of the conservation period the PEG and water inside the layer I of both of the wood species corresponded to a PEG-concentration of 25%. The layers II and IV of the oak wood material showed a PEG concentration value of c. 7% at the end of the conservation period. The PEG-concentration inside the layer III of the oak wood was a little lower during the conservation period and terminated at c. 5% (figure 8-2).

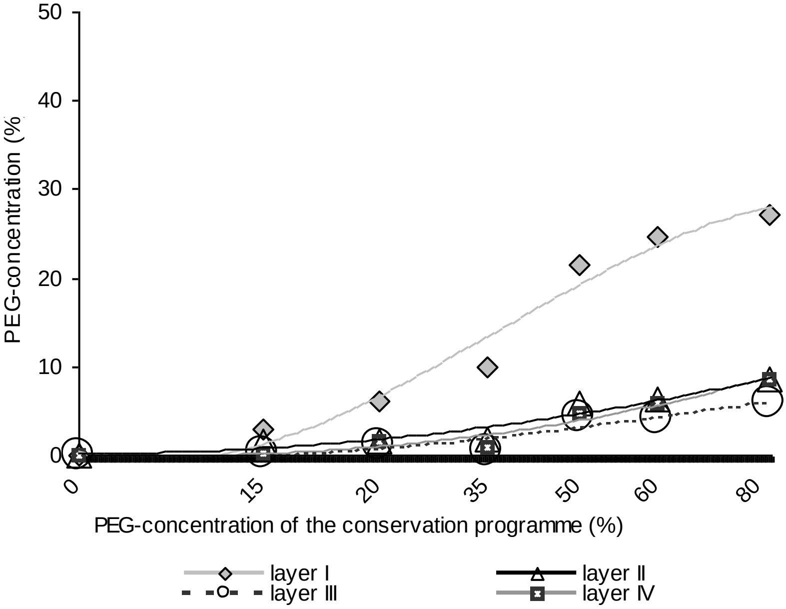

Figure 8-2. PEG-concentration of an assumed PEG solution inside the oak wood material of the first batch of Vasa wood at a preliminary conservation programme. Trend-lines; least square fittings.

The layers II, III, and IV of the pine wood material showed similar PEG-concentration levels as the layer I during the conservation period. However, in this case the internal layers II and IV terminated at PEG-concentrations of c. 30% while the layer III of the pine wood material terminated with c. 35% PEG-concentration (figure 8-3).

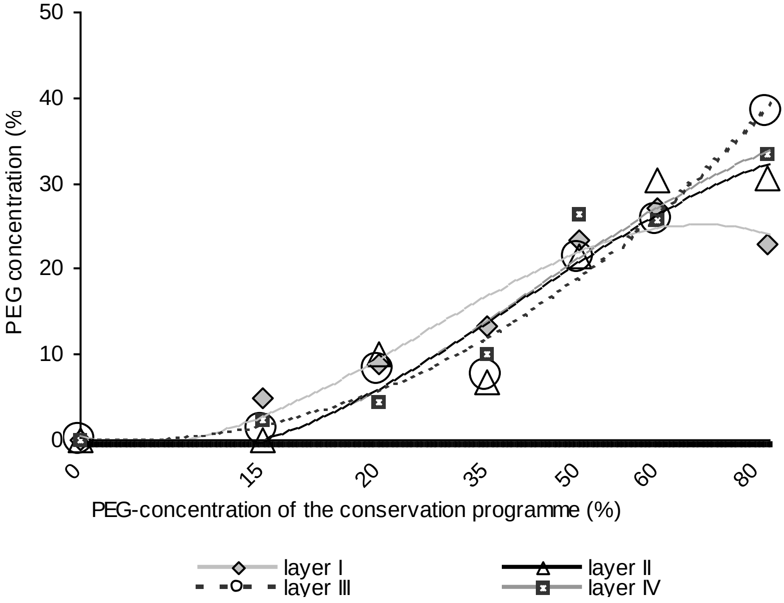

Figure 8-3. PEG-concentration of an assumed PEG solution inside the pine wood material of the first batch of Vasa wood at a preliminary conservation programme. Trend-lines; least square fittings.

The observation made that there was a close resemblance between the PEG-concentrations inside the layers II and IV while the PEG-concentration inside the layer III somewhat diverged and since the pine wood items were rather thin, which may have influenced the diffusion at both of the opposite surfaces of the objects, only three layers, comprising a depth of 30 mm from the upwards turned surface of the wood have been considered during the continued evaluation procedure.

The concentration of the assumed PEG solutions inside the oak wood seems to have developed at a slow pace, where practically nothing happened between the 15 and the 35% PEG-concentration levels of the conservation programme. Between the 35 and the 50% PEG-concentration levels a PEG-concentration raise of c. 4 percentage units occurred in each of the internal layers. There was practically a standstill until the 60 to 80% PEG-concentration raise of the conservation programme when there was a raise of c. 2% PEG-concentration at the 11-20 mm depth level and a raise of c. 1.5% at the 21-30 mm depth level of the oak wood (table 8-I).

The concentration of the assumed PEG solution at the 1-10 mm depth level of the oak wood, representing the upper surface layer shows a continuing development from 3 to c. 25% concentration of the assumed PEG solution inside the wood. The 1-10 mm depth level of the pine wood material shows practically the same situation (table 8-II).

The assumed PEG solution at the 11-20 mm and the 21-30 mm depth levels inside the pine wood material showed a similar concentration at the 35% PEG-concentration level of the conservation programme as at the corresponding depths of the oak wood at the 60% level of the conservation programme. The PEG-concentration raise between 35 and 50% of the conservation programme resulted in c. 20% PEG-concentration all through the 30 mm depth level investigated. The concentration of the assumed PEG solution inside the pine wood had risen to c. 25% and above 30% at the 60% and 80% PEG-concentration levels of the conservation programme respectively.

Depth	Number of cores	PEG-concentration of an assumed PEG solutions inside the wood (%): at					
		15%	20%	26%	37%	48%	58%
mm		PEG-concentration of the conservation solution					
1-10	5	3.0	6.2	10	22	25	27
11-20	5	1.5	1.5	1.9	5.9	6.3	8.5
21- 30	5	0.2	1.0	0.4	4.3	4.2	5.9
31- 45	5	0.3	1.6	0.8	4.8	5.9	8.7

Table 8-I. The PEG-concentration gradient of an assumed PEG solution inside the oak wood at the core sampling occasions.

Depth	Number of cores	PEG-concentration of an assumed PEG solutions inside the wood (%): at					
		15%	20%	26%	37%	48%	58%
mm		PEG-concentration of the conservation solution					
1-10	3	4.9	8.8	13	23	27	23
11-20	3	0.0	10	6.7	21	30	31
21- 30	3	1.1	8.2	7.5	21	26	38
31- 40	3	2.3	4.5	10	27	26	34

Table 8-II. The PEG-concentration gradient of an assumed PEG solution inside the pine wood at the core sampling occasions.

The PEG-ratio was an obvious parameter to examine since the purpose of the conservation treatment was to get PEG into the wood. The grand mean of the PEG-ratios in the layers I, II, III, and IV of the wood of the oak and pine material, respectively, have been calculated as representing the conservation result (figures 8-4 - 8-5).

The layers I of both the oak and the pine wood show similar curves of the PEG-ratios during the conservation period although at different levels. The PEG-ratio curves of the three layers towards the depth of the oak wood show PEG-ratios below 5% while the PEG-ratio values of the corresponding layers of the pine wood increase during the entire conservation period and terminate at c. 50% PEG-ratio inside the depth of the wood .

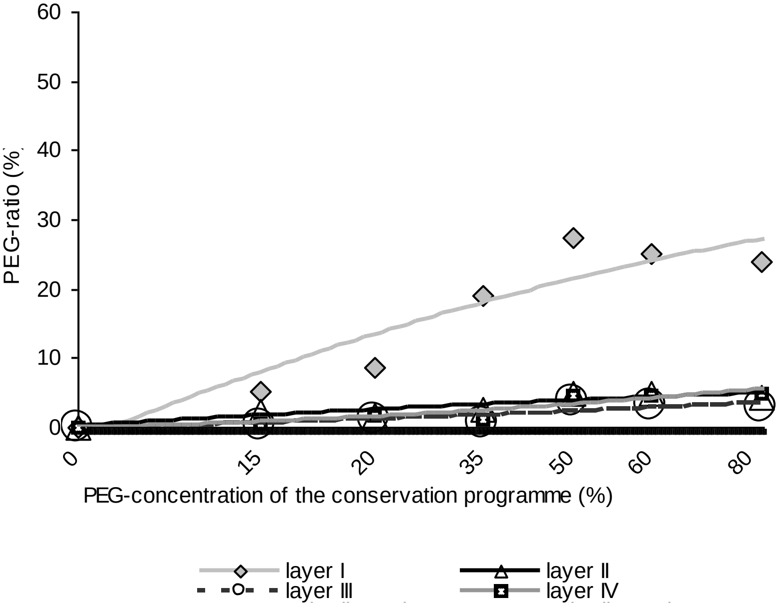

Figure 8-4. PEG-ratio inside the oak wood material of the first batch of Vasa wood at a preliminary conservation programme. Trend-lines; least square fittings.

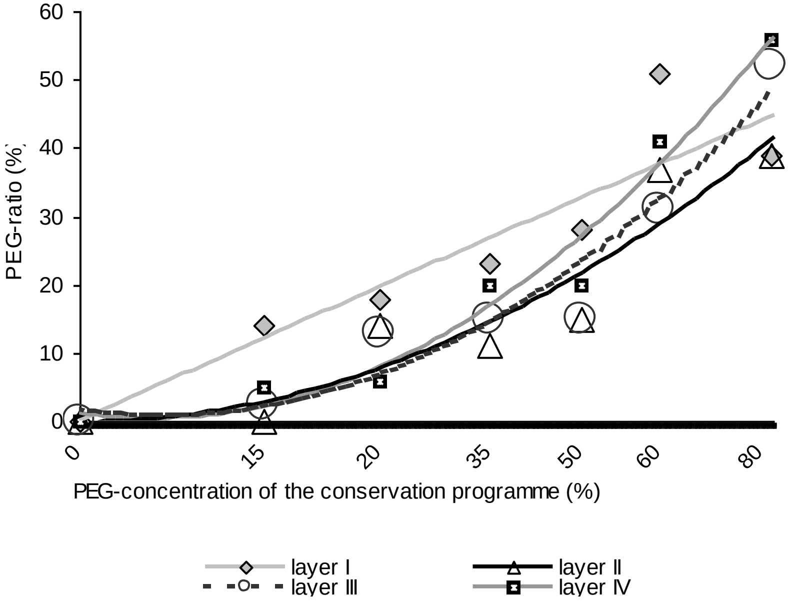

Figure 8-5. PEG-ratio inside the pine wood material of the first batch of Vasa wood at a preliminary conservation programme.
Trend-lines; least square fittings.

When the over-all picture of the PEG-ratio at the different sampling occasions was investigated it became evident that the PEG-gradients at the 50, 60 and 80% PEG-concentration levels of the conservation programme were quite similar where the oak wood was concerned. The diffusion of PEG molecules into the oak wood seems to have stopped at the 50% PEG-concentration level of the conservation programme which corresponded to 37% PEG in the conservation solution (table 8-III).

Depth mm	Number of cores	PEG-ratio (%): at					
		15%	20%	26%	37%	48%	58%
		PEG-concentration of the conservation solution					
1-10	5	5.3	8.7	19	28	25	24
11-20	5	2.3	1.7	2.5	4.8	4.8	4.4
21- 30	5	0.2	1.2	0.5	3.7	3.3	2.8
31- 45	5	0.5	1.7	1.1	4.5	4.7	4.9

Table 8-III. The PEG-ratio gradient inside the oak wood at the core sampling occasions.

Where the pine wood was concerned, however, there seemed to have been one substantial raise of PEG-ratio between the 50 and the 60% levels and another one between the 60 and the 80% levels of the conservation programme (table 8-IV). The first one of these was preceded, between the 35 and 50% PEG-concentration levels of the conservation programme, by a loss of water corresponding to c. 100 percentage units water-ratio from the levels 11 - 20 and 21 – 30 mm depth in the pine wood. The raise of the PEG-ratios that followed was accompanied by c. 30 percentage units raise of water-ratio of the same levels in the wood. These circumstances pointed to the possibility that a liquid transportation of PEG solution had occurred from the surrounding conservation solution into the wood (tables 8-IV, 8-VI).

Depth mm	Number of cores	PEG-ratio (%): at					
		15%	20%	26%	37%	48%	58%
		PEG-concentration of the conservation solution					
1-10	3	14	18	23	28	51	39
11-20	3	0.0	14	11	15	37	39
21- 30	3	2.3	13	15	15	31	52
31- 40	3	5.0	6.0	20	20	41	56

Table 8-IV. The PEG-ratio gradient inside the pine wood at the core sampling occasions.

As a complementary to the PEG-ratio the grand mean of the water-ratios in the layers I, II, III, and IV of the wood of the oak and pine material, respectively, have been calculated as representing the conservation result. The fact should be noted (figures 8-6 - 8-7), that the loss of water seems to stop in the pine wood at the end of the conservation period while the oak wood was loosing water during the entire treatment period.

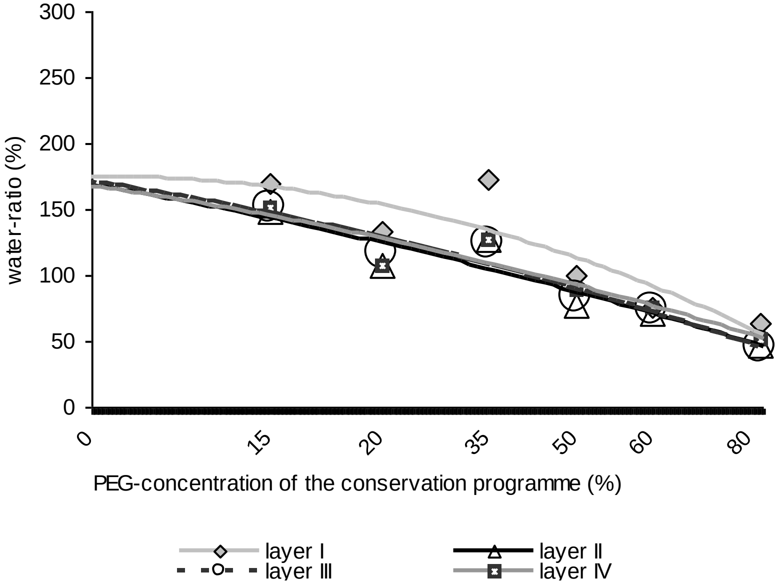

Figure 8-6. Water-ratio inside the oak wood material of the first batch of Vasa wood at a preliminary conservation programme.
Trend-lines; least square fittings.

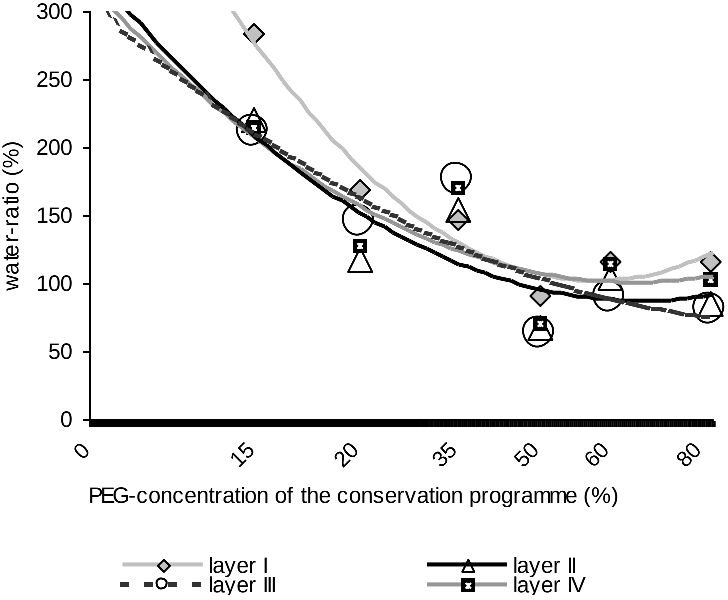

Figure 8-7. Water-ratio inside the pine wood material of the first batch of Vasa wood at a preliminary conservation programme.
Trend-lines; least square fittings.

During the continuing raise of the PEG-concentration, water molecules seem to have diffused out of the oak wood, that had lost c. 70 % of the water, leaving only c. 50% water-ratio inside the wood when the conservation programme was terminated (table 8-V). This may be due to too fast raising of the PEG-concentration of the conservation solution. The temperature raising programme too might have had some influence on the diffusion processes as was established by the experiment described in section 4.2.

Depth mm	Number of cores	water-ratio (%): at					
		15%	20%	26%	37%	48%	58%
		PEG-concentration of the conservation solution					
1-10	5	170	133	170	100	76	64
11-20	5	148	107	127	77	71	47
21- 30	5	150	116	124	83	75	45
31- 45	5	150	107	128	89	76	52

Table 8-V. The water-ratio gradient inside the oak wood at the core sampling occasions.

The pine wood material showed water-ratios of c. 100% in the surface layer and a little lower, c. 80% in the internal layers when the conservation process was completed. This implied a loss of c. 60% of the water during the conservation procedure (table 8-VI).

Depth mm	Number of cores	water-ratio (%): at					
		15%	20%	26%	37%	48%	58%
		PEG-concentration of the conservation solution					
1-10	3	284	169	147	91	116	116
11-20	3	220	118	154	67	105	85
21- 30	3	212	146	177	63	90	81
31- 40	3	215	128	170	70	115	103

Table 8-VI. The water-ratio gradient inside the pine wood at the core sampling ccasions.

Conclusions

A severe problem was the fact, that the interior layers of the oak wood material had obtained PEG-ratios below 5%. Contrary to the oak wood material, the pine wood material had reached PEG-ratios of 40-55% in all layers involved.

Depending on the difference between the oak wood and the pine wood in degree of PEG impregnation, the decision was taken, that only pine wood material would be conserved until the experimental work had produced a suitable conservation programme for the oak wood material.

8.1.2. The second batch of Vasa wood at a preliminary conservation programme

In May 1963 the one of the large tanks that had a capacity of 42 m^3 effective volume for stowing material was charged with 469 objects, only 12 of these weighing more than 100 kg each, while 126 weighed less than 10 kg. As this conservation procedure was started before the information from the experimental work was available the second batch comprised objects made of oak as well as objects made of pine.

The PEG 4000 was chosen as preservative. As with the first batch an initial period of 3 months duration with 10% PEG 4000 in the conservation solution was performed. This was followed by increments of 1/3%, added 5 days a week.

A temperature raising programme was chosen with a modification compared to the temperature programme applied with the first batch. During the initial period until the PEG concentration of the conservation programme had reached 15% the temperature was kept at 40 °C. After that period the temperature was raised in accordance with the following schedule:

- 45°C at 15% PEG-concentration
- 55°C at 40% PEG-concentration
- 60°C at 45% PEG-concentration

The analysis of the conservation solution demonstrates a PEG concentration that followed the conservation programme closely up to c. 50%. The continuing addition of PEG-increments to the 60% level of the conservation programme did not appear in the analyses of the conservation solution above the 50% level.

The conservation programme was terminated when the PEG-concentration of the conservation programme was 60%. This level was reached after 9 months of treatment. The conservation procedure was continued for 6 months at the stable PEG-concentration level of c. 50% that was the actual end-concentration of PEG in the conservation bath (figure 8-8).

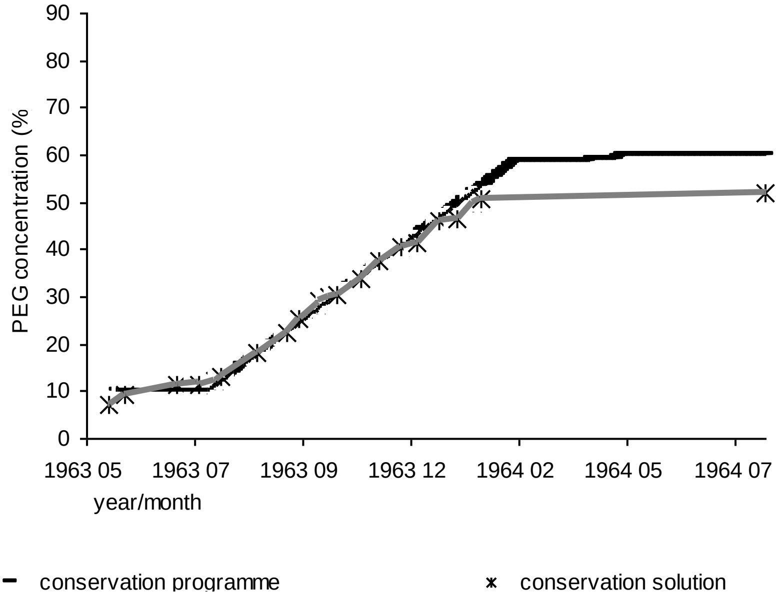

Figure 8-8. PEG-concentration of the conservation programme and the conservation solution of the second batch of Vasa wood at a preliminary conservation programme.

Since there was still uncertainty about the conservation programme, the conservation procedure was monitored by wood-core sampling at 4 occasions. These were performed at 10%, 30%, 50% PEG, added according to the conservation programme, and 60%, at the end of the prolonged period at this PEG-concentration. The actual PEG-concentrations in the conservation solution at the core-sampling occasions were 11.5%, 30%, 50% and 52% (tables 8-VII – 8-XII).

At each sampling 8 wood-cores were drilled from oak wood objects, 6 rather thin and two thick timbers, and 4 wood-cores were drilled from pine wood objects, of which 2 were thin and two were from thick timbers.

The wood-cores were cut into sections of c. 10 and 15 mm. The content of water and PEG have been analysed in each section of a wood-core. From this the water-ratio, the PEG-ratio, and the concentration of an assumed PEG solution inside the wood-core sections have been calculated.

The layers I of both wood species seem to show similar PEG concentration values during the conservation period which finished with c. 35% PEG-concentration at the end of the conservation period for both of the wood species (figures 8-9, 8-10).

The PEG concentration inside the oak wood was increasing during the entire conservation period reaching a value between 15 and 20% at the end of the treatment. This means c. twice as high a concentration value as in the batch described in section 8.1.1. (figures 8-9, 8-2).

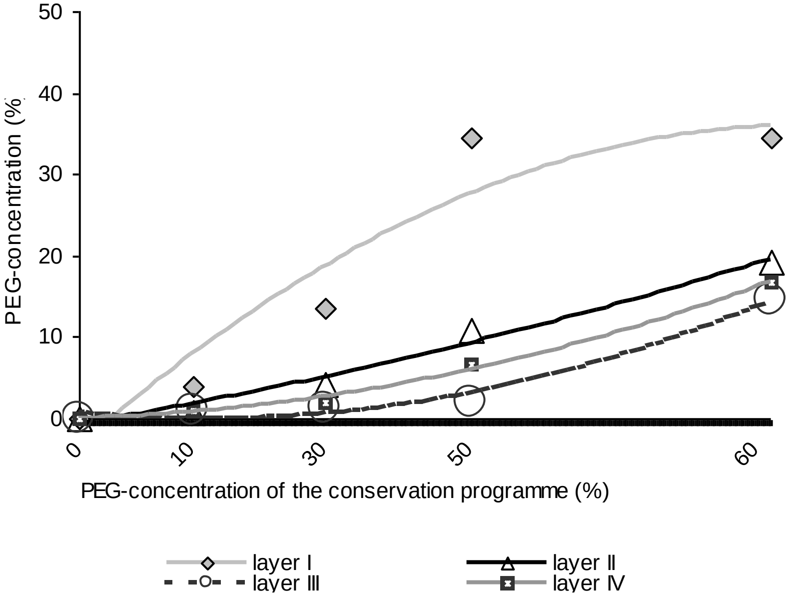

Figure 8-9. The concentration of an assumed PEG solution inside the oak wood at the core sampling occasions. Trend-lines; least square fittings.

The PEG concentration inside the pine wood was increasing during the entire conservation period reaching a value between 29 and 36% at the end of the treatment. This was about the same concentration value as in the batch described in section 8.1.1. (figures 8-10, 8-3).

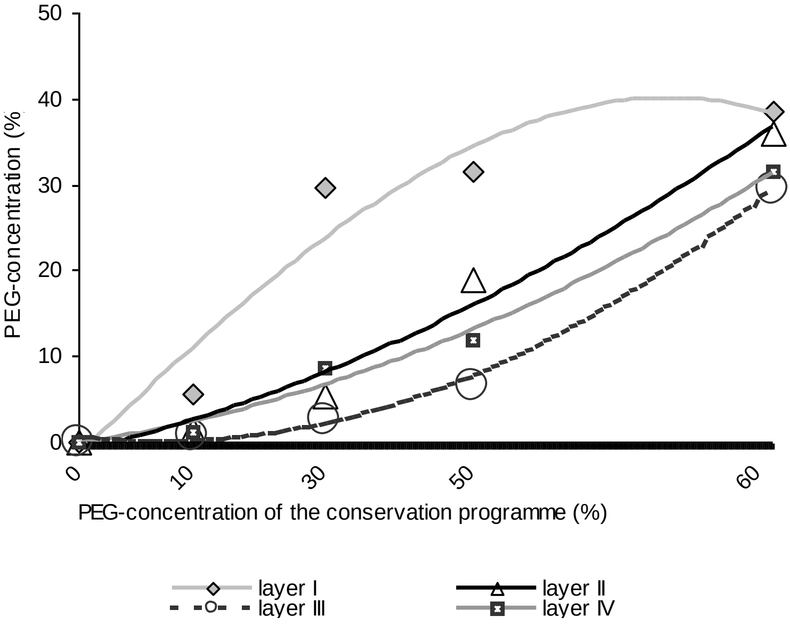

Figure 8-10. The concentration of an assumed PEG solution inside the pine wood at the core sampling occasions. Trend-lines; least square fittings.

In this conservation batch the PEG-concentration gradient showed increasing values in all sections of the oak wood material all through the conservation process (table 8-VII). This was the case also with the pine wood material until the end of the conservation procedure, when the pine wood showed very near to even PEG-concentration all through the investigated layers of the wood. The oak wood, however, showed a PEG-concentration gradient still at the end of the conservation programme. (tables 8-VII, 8-VIII).

Depth	Number of cores	PEG-concentration of an assumed PEG solution inside the wood (%): at			
		11.5%	30%	50%	52%
mm		PEG-concentration of the conservation solution (%)			
1-10	8	4.0	14	35	35
11-20	8	0.8	4.1	11	20
21- 30	8	0.9	1.2	2.0	15
31- 45	8	1.1	1.9	6.7	16

Table 8-VII. The PEG-concentration gradient of an assumed PEG solution inside the oak wood at the core sampling occasions.

Depth	Number of cores	PEG-concentration of an assumed PEG solution inside the wood (%): at			
		11.5%	30%	50%	52%
mm		PEG-concentration of the conservation solution (%)			
1-10	4	6.7	30	32	39
11-20	4	1.4	5.4	19	36
21- 30	4	0.7	2.7	6.5	29
31- 40	4	0.9	8.4	12	32

Table 8-VIII. The PEG-concentration gradient of an assumed PEG solution inside the pine wood at the core sampling occasions.

The PEG-ratio has developed all through the conservation procedure for both of the wood species (figures 8-11, 8-12). This is different from the situation in the batch described in section 8.1.1. where the PEG absorption into the oak wood ceased at the 50% level of the conservation programme (figure 8-11, 8-4). This may be due to the change both of the temperature programme and the extended period in a conservation solution of 50% PEG-concentration (figure 8-8).

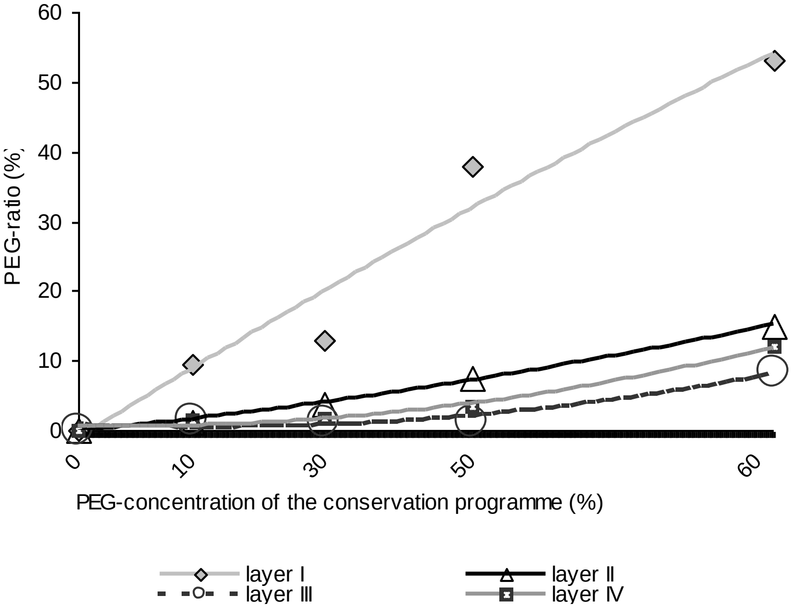

Figure 8-11. The PEG-ratio inside the oak wood at the core sampling occasions. Trend-lines; least square fittings.

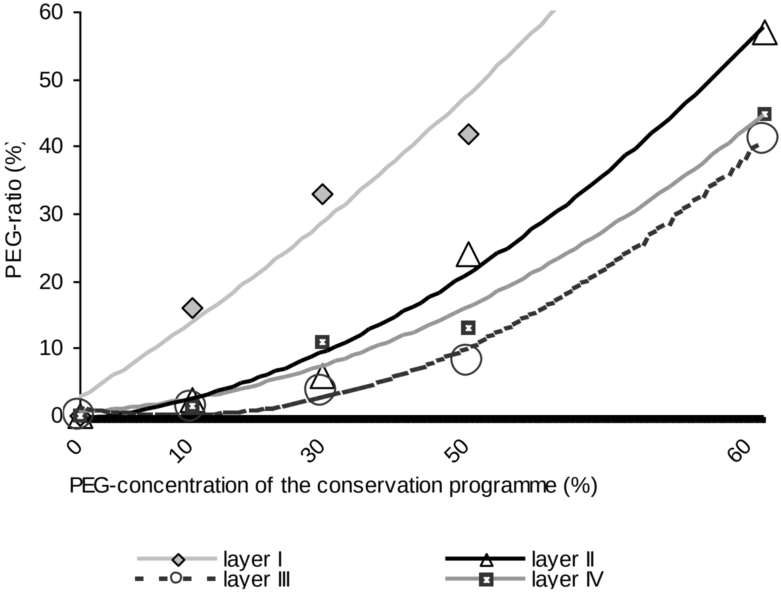

Figure 8-12. The PEG-ratio inside the pine wood at the core sampling occasions. Trend-lines; least square fittings.

The PEG-ratio gradient of the oak wood material developed rather slowly. However, the PEG-ratio was increasing all through the conservation programme and reached 15 and 8% at the 11-20 and 21-30 mm levels, respectively, at the end of the conservation process. The interior levels of the pine material finished at PEG-ratios of 40 - c. 60% at the end of the conservation programme (tables 8-IX, 8-X).

Depth	Number of cores	PEG-ratio (%): at			
		11.5%	30%	50%	52%
mm		PEG-concentration of the conservation solution (%)			
1-10	8	9.5	13	38	53
11-20	8	1.2	3.8	7.6	15
21- 30	8	1.4	1.2	1.1	8.2
31- 45	8	1.5	1.6	3.4	12

Table 8-IX. The PEG-ratio gradient inside the oak wood at the core sampling occasions.

Depth	Number of cores	PEG-ratio (%): at			
		11.5%	30%	50%	52%
mm		PEG-concentration of the conservation solution (%)			
1-10	4	16	33	42	95
11-20	4	2.3	6.0	24	57
21- 30	4	1.1	3.5	8.1	41
31- 40	4	1.5	11	13	45

Table 8-X. The PEG-ratio gradient inside the pine wood at the core sampling occasions.

The water-ratio values of the oak wood material as well as of the pine wood material were declining until the conservation programme had reached the 50% PEG-concentration level. Between the 50 and the 60% PEG-concentration level of the conservation programme, however, nothing seemed to have happened with the water-ratio values of the interior of the wood, both where the oak wood material and the pine wood material were concerned (figures 8-13, 8-14).

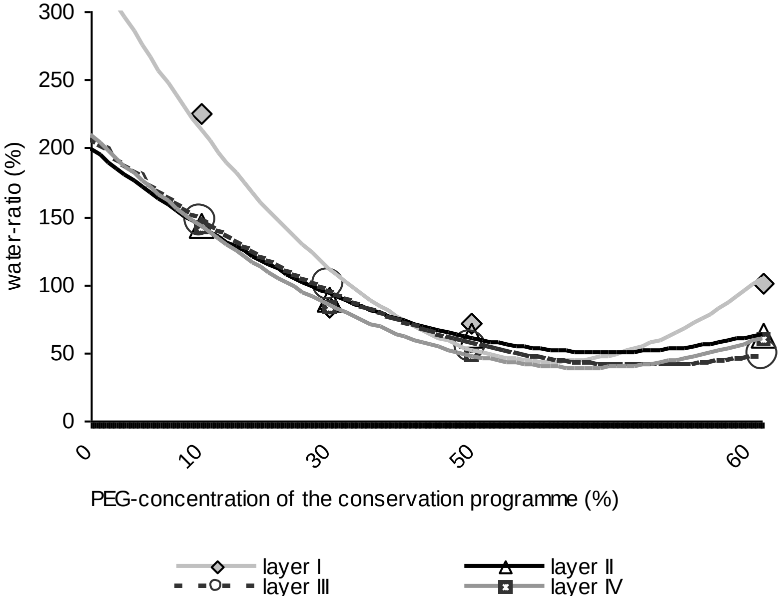

Figure 8-13. The water-ratio gradient inside the oak wood at the core sampling occasions. Trend-lines; least square fittings.

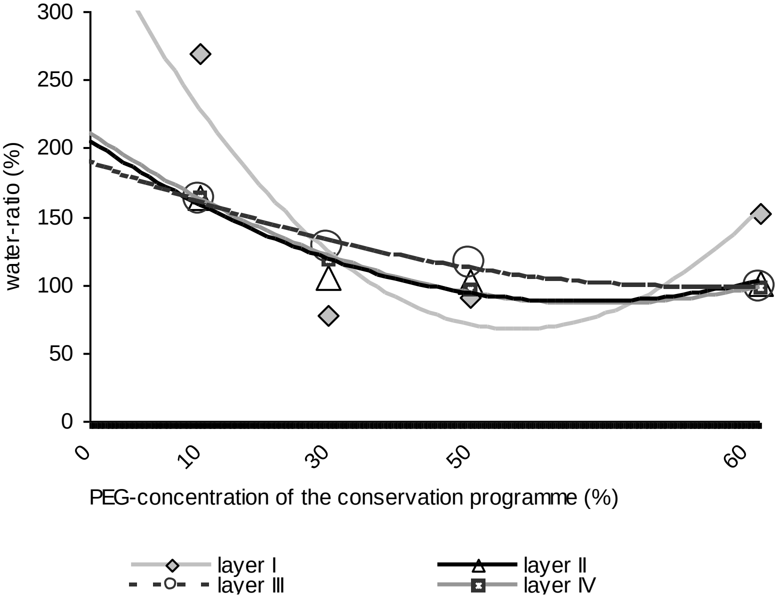

Figure 8-14. The water-ratio gradient inside the pine wood at the core sampling occasions. Trend-lines; least square fittings.

The surface layer of the oak material showed 30 percentage units higher grand mean water-ratio value and the pine wood material 60 percentage units higher grand mean water-ratio value at the 60% than at the 50% PEG concentration level of the conservation programme. The fact that there had been a substantial increase of the PEG-ratio of the surface layer of the oak wood material and that the surface layer of the pine wood material had more than doubled its PEG-ratio value between the 50 and the 60% PEG-concentration levels of the conservation programme indicates that a liquid transportation of conservation solution into both of the oak and the pine woods may have occurred during the period mentioned (tables 8-XI, 8-XII).

Depth mm	Number of cores	water-ratio (%): at			
		11.5%	30%	50%	52%
		PEG-concentration of the conservation solution (%)			
1-10	8	230	83	72	101
11-20	8	144	89	63	63
21- 30	8	146	99	54	48
31- 45	8	142	84	48	60

Table 8-XI. The water-ratio gradient inside the oak wood at the core sampling occasions.

Depth mm	Number of cores	water-ratio (%): at			
		11.5%	30%	50%	52%
		PEG-concentration of the conservation solution (%)			
1-10	4	270	78	91	150
11-20	4	160	105	103	101
21- 30	4	160	128	116	98
31- 40	4	160	118	96	98

Table 8-XII. The water-ratio gradient inside the pine wood at the core sampling occasions.

Conclusions and decisions about further immersion treatment of the Vasa wooden material

The wooden material of both the preliminary batches had been stored in water tanks and the wood was waterlogged when the conservation treatment started. In both of the test batches the pine material had obtained a higher degree of PEG in the wood compared to the oak material. It was observed that the diffusion of PEG-molecules into the pine wood was continuing during the entire conservation period. This phenomenon was not observed in the oak wood of the first test batch but there was a tendency that the diffusion of PEG-molecules into the oak wood of the second test batch was continuing during the 6 months long concluding phase of 60% stable PEG-concentration of the conservation programme. This might be attributed to the fact that the temperature programme of the second test batch had reached 60°C at as low PEG-concentration of the conservation programme as 45%, while in the first test batch, this temperature was not initiated until the PEG-concentration of the conservation programme had reached 60%. The conclusion drawn from this was that the diffusion of PEG-molecules into the wood might be hampered or even reversed by the difference of temperature between the conservation solution and the interior of the wood that might temporarily arise at the temperature raising occasions, and that this phenomenon might be more pronounced at higher PEG-concentrations.

The decision made was to use a stable and rather high temperature level during the entire conservation programme for the remaining immersion conservation batches.

8.2. Conservation of batches exclusively with pine wood material

The better response of the pine material to both conservation programmes tested became the basis for the decision to start the immersion treatment with the pine material. Parallel to this the laboratory work with the experiments would proceed to develop a more suitable conservation programme for the oak material.

8.2.1. The first batch exclusively with pine wood material

The first batch of pine wood material was started in a rather small tank of c. 2.5m^3. For this batch, forty-one mostly small pine wood objects were selected. The main part of the objects weighed between 10 and 15 kg. However, one large object, a sculpture that weighed a little more than 100 kg was included in the batch.

The tank was filled with objects and supporting material to a fraction of c. 20%. The remaining 80% was filled with water. 10% PEG 4000 and 1% of the selected biocide, a mixture of boric acid and sodium borate, were dissolved in the water. The temperature of the conservation solution was raised to 60 °C. The PEG-concentration raising programme selected was a 1/6% increment, 5 days a week, during a period of c. 8 months followed by a 1/3% increment, 5 days a week, during a period of c. 8 months.

The analysis of the conservation solution demonstrates a PEG concentration that followed the conservation programme closely up to c. 20%. The continuing addition of PEG-increments to the 25% level of the conservation programme did produce a slight declination in the PEG-concentration of the conservation solution compared to the conservation programme. The addition of PEG increments was stopped for c. 2 months at the 25% level. During this period the PEG-concentration of the conservation solution decreased by c. 10 percentage units to 15%. The PEG-concentration raising programme was started again at the same pace as before the intermission and proceeded to 35%. During this period the 10 percentage unit gap of PEG-concentration between the conservation programme and the conservation solution remained. At that point of the conservation programme the increments were changed to 1/3% per day. This made the PEG-concentration development slow down a little more compared to the conservation programme. At the 60% level the gap between the PEG-concentration of the programme and the conservation solution had widened to 15 percentage units and at the 65% level to 20 percentage units where it remained to the 75% level of the conservation programme. The PEG-concentration development of the conservation solution stopped at 55% while the conservation programme was continued to 80% PEG-concentration (figure 8-15).

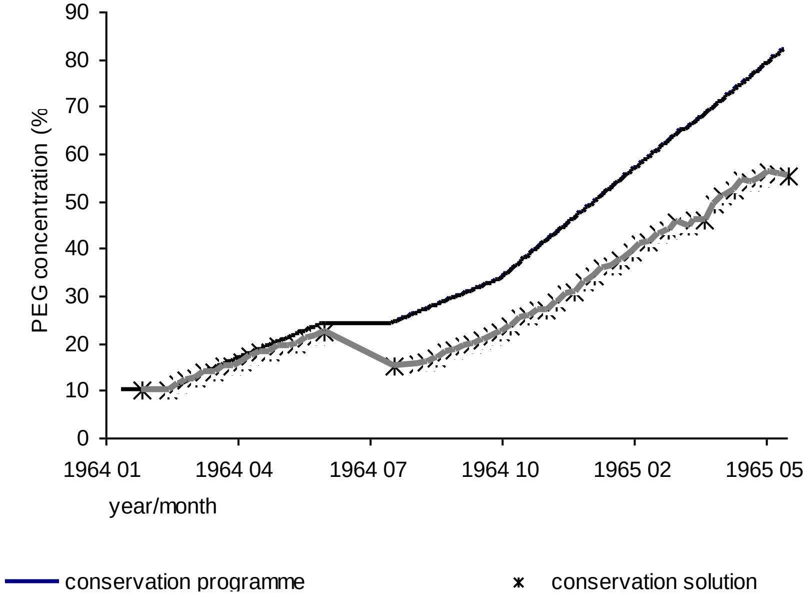

Figure 8-15. PEG-concentration of the conservation programme and the conservation solution of the first batch exclusively with pine wood material.

Wood-cores were drilled from 15 objects to determine the water-ratio of the material before the conservation was started. These objects were c. 150 mm wide. The wood-cores were drilled to the mid point of the width of each object. Each core was cut into three sections. The section labelled "I" represented the surface layer to a depth of 20 mm, the section labelled "II" represented a layer between 21 and 50 mm depth, and the section labelled "III" represented a layer between 51 and 75 mm depth in the wood.

The grand mean PEG-concentration of the assumed PEG-solution in the 20 mm thick, layer I equals 50% which is just a little below the PEG concentration of the conservation solution. This indicates that the diffusion of PEG molecules into the layer I has been almost complete. The layer II that is c. 30 mm thick displays a grand mean PEG-concentration of 37% and the c. 25mm thick layer III that represents the mid part of the interior of the wood displays a grand mean PEG-concentration of 26%. Thus, the diffusion of PEG molecules has proceeded beyond a depth of 50mm, and may have penetrated all through the wood (table 8-XIII).

The PEG-ratio gradient at the conclusion of the conservation programme showed declining values towards the deeper levels in the wood. However, the grand mean PEG-ratio of 31% in the layer III indicates that the PEG molecules may have penetrated all through the pine wood objects. (table 8-XIII).

At the conclusion of the conservation programme the water-ratio values at the different levels in the wood were rather similar to each other. There was a slight tendency towards a reversed gradient compared to the PEG-ratio gradient (table 8-XIII).

The grand mean of the water-ratio before the conservation was started was c. 140% with a gradient of 160, 131 and 129% related to the layers I, II and III, respectively. If the initial water-ratios are compared with the sum of the PEG- and the water-ratios, which may be considered as PEG-solution ratios inside the wood at the termination of the immersion conservation treatment, these values are 149, 131 and 119% in the layers I, II and III respectively. Thus, the loss of water has been fully compensated by absorption of PEG (tables 8-IV, 8-XIII).

Depth mm	Number of cores	water-ratio (%)		PEG-ratio (%)		concentration of an assumed PEG solution inside the wood (%)	
		before conser-vation	after conser-vation	before conser-vation	after conser-vation	before conser-vation	after conser-vation
1-20	15	160	78	0.0	71	0.0	50
21-50	15	131	83	0.0	48	0.0	37
51-75	15	129	88	0.0	31	0.0	26

Table 8-XIII. The water ratio gradient, the PEG-ratio gradient and the PEG-concentration gradient of an assumed PEG solution inside the pine wood before and after the conservation procedure.

8.2.2. The second batch exclusively with pine wood material

The second batch, containing exclusively pine wood material, was started in the 42 m^3 conservation tank in October 1964. The 1739 items arranged in the tank were mainly construction material. Among these were five heavy timbers that were parts of the inner core of the main mast, which is a built mast with oak timbers surrounding a core made of pine wood. The pine wood parts weighed 1350, 1250, 900, 830 and 49 kg respectively. Apart from these very large timbers, there were only three timbers weighing more than 90 kg. The main part of the items of the batch was filling material that weighed less than 10 kg apiece.

The tank was filled with objects and supporting material to a fraction of c. 35%. The remaining space was filled with 26 000 l of water. Since a previously used conservation solution that apart from PEG also contained borates from previous conservation processes was going to be used for raising the PEG concentration, no biocides were dissolved in the water. The temperature of the water in the conservation tank was raised from 16 to 60°C during a period of c. 10 days. No PEG was added to the water in the conservation tank until the temperature of the water had reached 60°C. The PEG raising programme selected was, with 0.4% PEG concentration increments, added 5 days a week, during a period of one year.

The development of the PEG-concentration of the conservation solution took a slightly diverging path to the conservation programme, and landed at c. 40% when the programme had reached 50%. During the PEG-concentration raising period between 50 and 65% the actual PEG-concentration of the conservation solution increased as little as from 40 to 45%. When the conservation programme was continued from 65 to 85% another 10 percentage units were added to the actual PEG-concentration of the conservation solution which reached 56% at the end of the conservation procedure.

The conservation programme was concluded when 85% PEG had been added to the conservation solution. Some heavy items were then removed from the conservation bath. This resulted in a substantial lowering of the liquid surface in the conservation tank. The height of the liquid surface came by mistake to be re-established by adding water to the conservation tank which lowered the PEG concentration of the conservation solution. The PEG concentration was reinstalled by c. 3 months continuation of the conservation programme. The actual PEG-concentration of the conservation bath was 56% at both of the concluding occasions (figure 8-16).

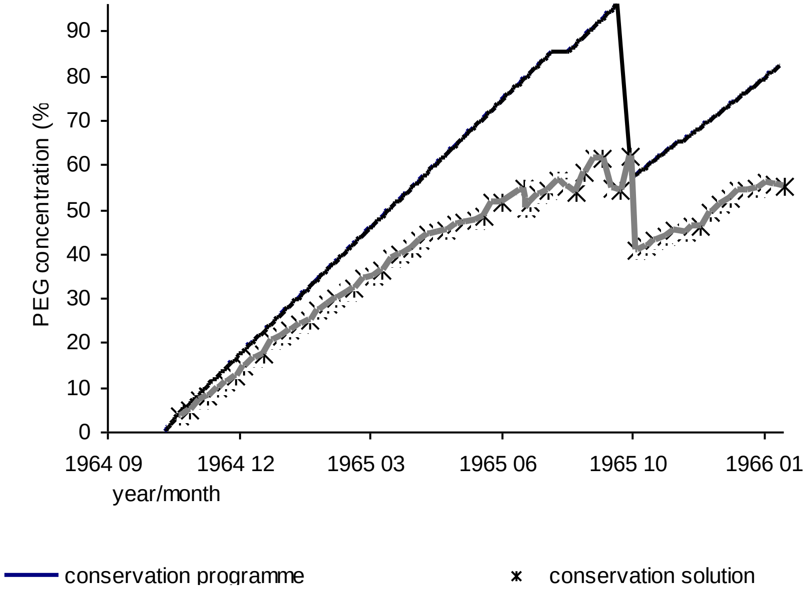

Figure 8-16. PEG-concentration of the conservation programme and the conservation solution of the second batch exclusively with pine wood material.

In order to determine the water-ratio of the material before the conservation was started wood-cores were drilled from 27 objects. All of these were rather large items. Ten represented rather thick material while the remaining 17 objects represented rather thin material. Some of the objects could not be re-found after the conservation procedure, which reduced the number of objects representing thick material to 7 and the number that represented thin material was reduced to 13. The wood-cores of the thick material were drilled to the mid-point of each object while the wood-cores of the thin material were drilled all through the objects.

Each core was cut into a number of sections in accordance with the schedule mentioned at the beginning of this chapter. Of these wood-cores the outer four sections have been used for investigating the movements of the PEG and water molecules. The section labelled "I" represented the surface layer to a depth of 5 mm, the section labelled "II" represented a layer between 6 and 10 mm depth, the section labelled "III" represented a layer between 11 and 20 mm depth in the wood, and the section labelled "IV" represented a layer between 21 and 30 mm depth in the wood. To investigate whether the width of the object would be an important parameter of the conservation process the analytical values of the parameters "water-ratio" and "PEG-ratio" of the wood-cores of the thick and the thin material have been evaluated separately.

The width of each of the originally ten objects of thick pine wood material selected for core-sampling was found to be between 80 and 180 mm with a mean value of c. 100 mm. The widths of the 17 objects which were going to represent the thin material were between 30 and 70 mm with a mean value of c. 50 mm. The objects of the two groups displayed the same mean weight, namely 27 kg. The weight of the objects representing the thick material ranged from 10 to 75kg while the objects representing the thin material weighed between 9 and 47 kg.

At the termination of the conservation procedure the grand mean PEG-concentration of an assumed PEG solution inside the 1-5 mm layer of the wood of the group of thick pine wood material was 55%, and the same parameter of the 1-5 mm layer of the thin material was 53%. The layers between 6 and 30 mm of the thick material showed a descending PEG-concentration gradient from 46 to 31% from the outside and inwards while the PEG-concentration remained at the 50% level at each of the investigated layers in the group of thin materials (tables 8-XIV, 8-XV).

The grand mean PEG-ratio of the of the thick timbers was c. 50% and the gradient of the PEG-ratios of the layers from the surface towards the 30 mm depth was descending from the surface inwards from 95 to c. 35%. The group of thin material displayed a grand mean PEG-ratio of c. 60% and a descending gradient from 78 to 55% from the surface of the wood and inwards to the 21 to 30 mm level (tables 8-XIV, 8-XV).

8. IMMERSION TREATMENT WITH PEG OF LOOSE WOODEN OBJECTS AND CONSTRUCTION TIMBERS FROM THE VASA

Before the conservation started the wood-cores of the thick material had a grand mean water-ratio of c. 200% while the thin material had a grand mean water-ratio of 220%. The thick material displayed a water-ratio gradient of 290, 260, 190 and 170% in the outer 30 mm of the wood while the thin objects showed a successively descending water-ratio gradient of 420, 300, 230 and 230% from the surface of the wood and inwards (tables 8-XIV, 8-XV).

Apart from the difference of width between the thick pine wood material and the thin pine wood material the water-ratio gradients before the conservation treatment indicated a more poorly wood quality of the group of thin items than the wood quality of the thick material.

After the conservation the grand mean water-ratio of the thin pine wood material was c. 60% and the layers beneath the 5 mm thick surface layer displayed a stable water-ratio value of c. 55%.

After the conservation procedure had been stopped the grand mean water-ratio of the thick objects was c. 85%. At this occasion the thin material displayed a grand mean water-ratio value of c. 60%.

No water-ratio gradient was observed in either the thick or the thin items after the conservation procedure. The water-ratio values amounted to between c. 70% and c. 90% inside the thick pine wood material and the thin items displayed water-ratio values close to 55% at all levels inside the wood (table 8-XIV, 8-XV).

Depth mm	Number of cores	water-ratio (%)		PEG-ratio (%)		concentration of an assumed PEG solution inside the wood (%)	
		before conservation	after conservation	before conservation	after conservation	before conservation	after conservation
1-5	10	290	81	0.0	95	0.0	55
6-10	10	260	71	0.0	65	0.0	46
11- 20	10	190	87	0.0	57	0.0	37
21-30	10	170	71	0.0	36	0.0	31
31-45	10	170	83	0.0	30	0.0	27

Table 8-XIV. The water-ratio gradient, the PEG-ratio gradient and the PEG-concentration gradient of an assumed PEG solution inside the thick pine wood before and after the conservation procedure.

Depth mm	Number of cores	water-ratio (%)		PEG-ratio (%)		concentration of an assumed PEG solution inside the wood (%)	
		before conservation	after conservation	before conservation	after conservation	before conservation	after conservation
1-5	17	420	72	0.0	78	0.0	53
6-10	17	300	54	0.0	70	0.0	56
11- 20	17	230	59	0.0	55	0.0	48
21-30	17	230	56	0.0	55	0.0	52

Table 8-XV. The water-ratio gradient, the PEG-ratio gradient and the PEG-concentration gradient of an assumed PEG solution inside the thin pine wood before and after the conservation procedure.

Conclusions

The fact that the thick material showed a PEG-concentration gradient while the PEG-concentration inside the thin items had obtained the same value as the surrounding conservation solution indicates that the thick material would need a longer conservation period either to get diffusion of more PEG molecules into the wood or to get diffusion of more water molecules out of the wood eventually to obtain the same PEG-concentration inside the wood as in the surrounding conservation solution.

The fact that the 21-30 mm layer of the wood of the thick material displayed a PEG-ratio value, 20 percentage units lower than the corresponding layer of the wood of the thin material, may have been caused both by the difference in width and by the difference in wood quality (tables 8-XIV, 8-XV).

As conclusion may be put forward that the differences in size and the difference of wood quality may be the reasons for the higher PEG-ratio and the lower water-ratio of the pine material of a width of c. 50 mm compared to the pine material of a width of c. 100 mm at the termination of the conservation procedure.

8.3. Conservation programmes for construction material to be refitted into the Vasa hull

Doubts had arisen about the possibility to reshape heavy construction material that had gone through a complete conservation procedure if the material had shrunk or got distorted. Therefore the museum management took the decision that such material should be treated by immersion for a rather short period of time in order to reach the same level of conservation as the wood of the Vasa hull that had been spray-treated for a couple of years. Three such immersion conservation procedures were performed from 1964 to the end of 1966.

8.3.1. The first conservation programme for construction material for refitting into the Vasa hull

The first conservation procedure of construction material for refitting into the Vasa hull was started in October 1964 and was terminated in April 1965. The batch consisted of 1287 objects, mostly of small sizes. 20% of the items weighed less than 1 kg and 60% weighed between 1 and 10 kg. Most of these belonged to constructions like staircases, doors and panels onboard the Vasa. Both oak and pine wood were represented. Only 389 of the items of the batch were taken to be refitted into the

Vasa hull when the conservation programme was finished, among these were 7 timbers weighing more than 100 kg and 69 items weighing between 20 and 100 kg. The remainder of the batch was joined with other batches to receive a complete conservation treatment.

The first conservation procedure of construction material for refitting into the Vasa hull was performed in the 34 m^3 tank. The wooden material occupied 37% of the volume of the tank. PEG 4000 was used for the conservation treatment. The conservation programme applied was a raise of the PEG concentration by 0.2 % increments every work day. The end concentration of the conservation programme was 17% while analysis of the PEG concentration of the conservation solution showed a value of 15% (figure 8-17).

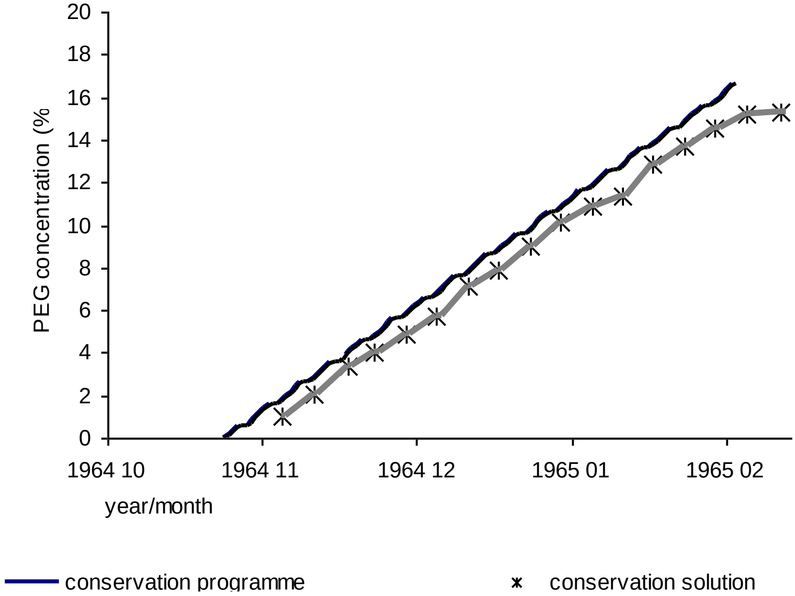

Figure 8-17. PEG-concentration of the first conservation programme designed for material for refitting into the Vasa hull and the resulting PEG-concentration of the conservation solution.

8. IMMERSION TREATMENT WITH PEG OF LOOSE WOODEN OBJECTS AND CONSTRUCTION TIMBERS FROM THE VASA

Core-sampling was performed when the conservation programme was finished. Wood-cores were drilled from 15 timbers of the heavy oak wood material, from 5 objects of the medium size oak wood material, from 2 objects of the heavy pine wood material, and from 2 objects of the medium size pine wood material.

Heavy oak wood material

Six of the standard layers cut from the wood-cores have been presented for the heavy oak, to represent half the width of the material, since the grand mean of the width of the 15 timbers that were selected for core sampling was 108 mm. The PEG-concentration of the assumed PEG solution in the surface layer was 12% that barely corresponded to the PEG-concentration of the conservation solution. The layer beneath the surface layer displayed c. half this concentration, and the layers inside continued the descending series down to 1.3% PEG-concentration at the middle of the width of the group of heavy oak objects (table 8-XVI).

Concordant with the PEG-concentration values, the 1-5 mm layer of 7.6%, the 6-10 mm layer c. half that figure and the successive layers towards the middle of the width of the group of heavy oak material displayed an even distribution around 2% PEG-ratio (table 8-XVI).

Depth mm	Number of cores	water-ratio (%) before the conservation procedure	water-ratio (%) after the conservation procedure	PEG-ratio (%) after the conservation procedure	PEG-concentration (%) after the conservation procedure
1-5	15	-	64	7.6	12.0
6-10	15	-	71	3.5	5.4
11- 20	15	-	115	1.9	1.9
21-30	15	-	102	2.1	1.9
31-45	15	-	111	2.0	1.7
46-60	15	-	100	1.4	1.3

Table 8-XVI. The water-ratio gradients, before and after the conservation procedure, the PEG-ratio gradient and the PEG-concentration gradient of an assumed PEG-solution inside the heavy oak wood material after the conservation procedure.

The water ratios of the surface layers were quite low, which may indicate that drying before the conservation was started. The water-ratios inside the wood were rather high and displayed no gradient but seemed rather untouched by the conservation procedure (table 8-XVI).

Medium sized oak wood material

The mean width of the group of medium-sized oak material was c. half that of the heavy oak timbers. It was covered by 4 of the standard layers (table 8-XVII).

The assumed PEG solution inside the wood shows a PEG concentration gradient similar to the heavy timbers with 12% in the surface layer and c. half that value in the layer beneath the surface layer (tables 8-XVII, 8-XVI).

Depth mm	Number of cores	water-ratio (%) before the conservation procedure	water-ratio (%) after the conservation procedure	PEG-ratio (%) after the conservation procedure	PEG-concentration (%) after the conservation procedure
1-5	5	-	43	6.8	12.2
6-10	5	-	58	4.7	7.7
11- 20	5	-	80	1.3	1.5
21-30	5	-	78	1.7	2.0

Table 8-XVII. The water-ratio gradients, before and after the conservation procedure, the PEG-ratio gradient and the PEG-concentration gradient of an assumed PEG solution inside the medium size oak wood after the conservation procedure.

The PEG-ratio values of the medium size oak wood resembled those of the heavy oak wood material (tables 8-XVII, 8-XVI).

The water-ratio values of the layers were lower by c. 20 percentage units compared to those of the heavy material. The fact that the water-ratios were quite low all through the wood, and that the gradient had low values in the surface layers may indicate drying before the conservation was started (tables 8-XVII, 8-XVI).

The water-ratio of the oak wood of the layer II of the planking of the Vasa hull decreased from c. 125 to 100% and the water-ratio of the layer II of the ceiling decreased from c. 140 to 120% during the period of “catch up” conservations. There was practically no PEG in the layer II, neither of the planking nor the ceiling of the Vasa during the period.

The PEG-ratios of the oak wood material, especially of the medium sized material, like the PEG-ratios of the planking and the ceiling of the Vasa hull during the corresponding time interval, were low at the termination of the conservation process. Even the water-ratios were low and since there were signs that the oak material had dried before the conservation was started, the “catch up” conservation treatment may have been without effect on the oak material.

Heavy pine wood material

The mean length of the two wood-cores that represented the heavy pine wood was 83 mm. This makes five standard layers a proper presentation of the material (table 8-XVIII).

The PEG-concentration of an assumed PEG solution inside the wood of the 1-5 mm, and the 6-10 mm layers was 19 and 27%, respectively. This unexpected situation conveys the idea there had been an amount of PEG in these two surface layers before the immersion conservation took place. An amount of PEG may then have dissolved into the conservation solution. This is supported by the fact that some of the heavy material was noted to have been stored on the pontoon where it may have acquired some PEG from conservation solution dripping from the hull.

In the present case, where the two objects can be identified as beams the explanation might be that these belong to the group of beams of poor quality that were removed from the hull to be reinforced by being mounted on beams made of steel. The combined steel-wood beams were then refitted into their former positions. As being a part of the hull, the beams had been treated by hand-spraying with PEG solution up to the occasion when they were removed to be reinforced. The PEG found in the wood would then be the result of this hand-spraying treatment and the reaction to the immersion treatment would be that PEG dissolved from the wood, which may account for the unexpected PEG-concentration gradient of an assumed PEG solution inside the wood (table 8-XVIII).

Depth mm	Number of cores	water-ratio (%) before the conservation procedure	water-ratio (%) after the conservation procedure	PEG-ratio (%) after the conservation procedure	PEG-concentration (%) after the conservation procedure
1-5	2	-	750	140	19
6-10	2	-	100	35	27
11- 20	2	-	170	17	9.6
21-30	2	-	205	9.5	4.4
31-45	2	-	165	12	6.7

Table 8-XVIII. The water-ratio gradients, before and after the conservation procedure, the PEG-ratio gradient and the PEG-concentration gradient of an assumed PEG solution inside the heavy pine wood material after the conservation procedure.

The heavy pine wood material displayed very high PEG-ratio values after the conservation treatment. These were probably the result of the hand-spraying treatment before the immersion conservation (table 8-XVIII).

The heavy pine wood material displayed high water-ratio values after the conservation procedure (table 8-XVIII).

These two beams may not have had any benefit from the immersion treatment considering their conservation history.

Medium sized pine wood material

The mean width of the medium sized pine wood material was 28 mm. This means that the three standard layers presented covers nearly the whole of the wood cores (table 8-XIX).

The concentration of an assumed PEG solution inside the 1-5 mm and the 6-10 mm surface layers was very high compared to the PEG-concentration of the conservation solution. However, there was no sign of reversed concentrations in the gradient as with the heavy pine material (tables 8-XIX, 8-XVIII).

Depth mm	Number of cores	water-ratio (%) before the conservation procedure	water-ratio (%) after the conservation procedure	PEG-ratio (%) after the conservation procedure	PEG-concentration (%) after the conservation procedure
1-5	2	-	20	13	36
6-10	2	-	30	7.0	19
11- 20	1	-	51	5.0	8.9

Table 8-XIX. The water-ratio gradients, before and after the conservation procedure, the PEG-ratio gradient and the PEG-concentration gradient of an assumed PEG solution inside the medium size pine wood material after the conservation procedure.

The PEG-ratio values obtained in the medium-sized pine wood were low compared to the those of the corresponding parameter of heavy pine wood (tables 8-XIX, 8-XVIII).

The low water-ratio after the conservation procedure of the thin pine wood material compared to the heavy pine wood material indicates that the thin material had dried during the storage period before the conservation treatment (tables 8-XIX, 8-XVIII).

8.3.2. The second conservation programme for construction material for refitting into the Vasa hull

The 276 timbers selected for this "catch up" conservation procedure was mainly oak wood material. It was placed in the conservation tank of 42 m^3. The tank was filled with 27 300 litres of water which means that 35% of the volume was occupied by wooden material. The conservation procedure was started at the end of November 1965 and was concluded at the middle of March 1966. The PEG-concentration was raised by 1/3% each work day. The end concentration of the conservation programme was 19% while the PEG concentration of the solution that was analysed only at the termination of the conservation programme was 16% at that occasion (figure 8-18).

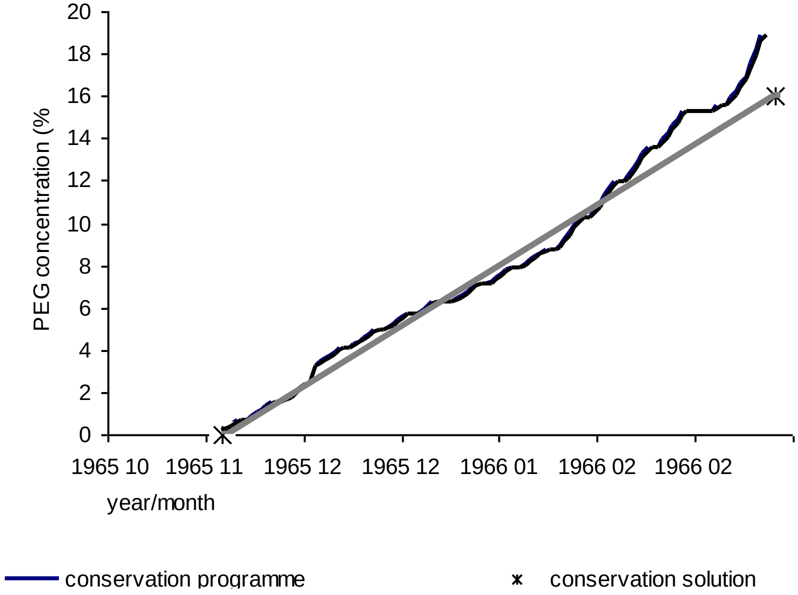

Figure 8-18. PEG-concentration of the second conservation programme designed for material for refitting into the Vasa hull and the resulting PEG-concentration of the conservation solution.

The main part of the timbers selected for this “catch up” conservation programme were rather heavy construction timbers, but a small portion consisted of medium sized material. The width chosen as demarcation between these groups was 80 mm.

Wood cores were drilled from 18 timbers of the batch before and after the conservation procedure. Twelve of the wood cores representing heavy timbers had a mean length of 235 mm, while 6 of the wood cores representing medium sized material, showed a mean length of 65 mm. These values divided by 2 have been considered as representing the wood of the two groups of wooden material, respectively. The figures of those “half values” have been used as a guide when choosing what number of layers should be included in the tables of PEG-concentration of an assumed PEG solution inside the wood, PEG-ratio and water-ratio.

Heavy oak wood material

It should be noted that the heavy construction timbers were stored underneath the Vasa hull which means that they had been subjected to PEG solution dripping from the hull and thus may have absorbed PEG before the immersion conservation procedure. As no analysis has been made of PEG before the conservation procedure there will be no notation in the tables of PEG before treatment for the heavy timbers (table 8-XX).

The concentration of an assumed PEG solution inside the wood of the heavy timbers at the termination of the conservation period displayed as high a value as 25% in the 1-5 mm surface layer. The fact that the PEG-concentration of the conservation solution was 16% at that occasion indicated that the PEG of the surface layer had not been obtained by diffusion from the immersion conservation solution. The PEG-concentration of 18% in the 6-10 mm layer also indicates such an interpretation. The remaining 6 layers contained low PEG-concentration values of between 0.8 and 2.7% (table 8-XX).

Depth mm	Number of cores	water-ratio (%) before the conservation procedure	water-ratio (%) after the conservation procedure	PEG-ratio (%) after the conservation procedure	PEG-concentration (%) after the conservation procedure
1-5	12	126	21	7.4	25
6-10	12	95	22	10	18
11- 20	12	87	35	0.9	2.7
21-30	12	94	41	0.5	1.4
31-45	12	88	56	0.5	0.8
46-60	12	87	59	0.6	1.0
61-80	12	88	56	1.3	2.2
81-100	12	88	58	0.8	1.3

Table 8-XX. The water-ratio gradients, before and after the conservation procedure, the PEG-ratio gradient and the PEG-concentration gradient of an assumed PEG-solution inside the heavy oak wood after the conservation procedure.

In correspondence with this, the PEG-ratio values of the 1-5 mm and the 6-10 mm surface layers amounted to c. 10% while the inside layers displayed PEG-ratios of between 0.5 and 1.3% (table 8-XX).

The water-ratio values of the heavy oak timbers were c. 90% in the layers inside the wood, and a little higher in the surface layers before the conservation procedure. These are much lower water-ratio values than the c. 120% of the medium-sized oak wood material that had been stored submerged in water in tanks before the conservation treatment (tables 8-XX, 8-XXI).

The water-ratio values after the conservation procedure have declined by 30 to 40 percentage units in the inside layers of the timbers and even more in the surface layers. This indicates that the process going on during the conservation period had mainly been a diffusion of water molecules from the wood of the timbers (table 8-XX).

It may be assumed that the heavy oak timbers in addition to some PEG diffusing into the wood also have been drying during the storage period.

Medium sized oak wood material

The medium sized timbers generally have been stored in tanks with water why these should not have been contaminated with PEG before the immersion conservation procedure. This means also that the wooden material was in its waterlogged state when the "catch up" conservation started.

The width of medium sized material should not exceed the chosen demarcation width of 80 mm. The mean width of the medium sized oak material of this batch was 65 mm. Since the individual width of the wood cores range between 30 and 78mm it seems suitable to present 45 mm of the these as a mean value for the medium sized material.

Since the medium sized material was collected from water tanks where it had been stored submerged in water for a period of time it was supposed that this material was water-logged and devoid of PEG before the immersion conservation treatment.

The concentration values of an assumed PEG solution in the 1-5 mm and the 6-10 mm layers were of the same magnitude as these values of the heavy oak material. Like in the heavy material the PEG-concentration values of the layers underneath those surface layers were as low as between 0.6 and 1.5% (tables 8-XXI, 8-XX).

Depth mm	Number of cores	water-ratio (%) before the conservation procedure	water-ratio (%) after the conservation procedure	PEG-ratio (%) after the conservation procedure	PEG-concentration (%) after the conservation procedure
1-5	6	192	46	65	27
6-10	6	134	25	3.4	11
11- 20	3	117	54	0.4	0.7
21-30	3	107	48	0.6	1.5
31-45	6	112	60	0.3	0.6

Table 8-XXI. The water-ratio gradients, before and after the conservation procedure, the PEG-ratio gradient and the PEG-concentration gradient of an assumed PEG-solution inside the medium size oak wood after the conservation procedure.

Especially the fact that the PEG-concentration in the 1-5 mm surface layer was as high as 27% when the PEG concentration of the conservation solution was only 16% at the termination of the treatment indicated a contact with PEG-solution during the storage period. The material probably has been stored in the same area as the heavy oak material before being transferred to water tanks.

The PEG-ratio values of the medium size oak wood material showed as high a PEG-ratio value as 65% in the 1-5 mm surface layer. The layers deeper in the wood showed PEG-ratio values between 3.4 and 0.3%.

The water-ratio values had decreased by c. 60 percentage units inside the wood and by as much as c. 150 and 110 percentage units in the 1-5 mm and the 6-10 mm layers, respectively, from the beginning to the termination of the conservation period. The assumption made of these facts might be that the high PEG-concentration of the PEG solution inside the surface layers rather attracts water-molecules from inside the wood than from the conservation solution (table 8-XXI).

The main conclusion of this “catch up” conservation might be that the timbers that went through the immersion conservation procedure would have been better taken care of by being refitted into the Vasa hull without this treatment.

8.3.3. The third conservation programme for construction material for refitting into the Vasa hull

For the third batch of construction material, 1314 objects of importance to the refitting work were selected. These were placed in the 34 m^3 tank where they occupied 25% of the working volume.

The PEG conservation programme chosen started with pure water and ended at 15% PEG concentration. The raise of PEG concentration was made by adding 1/6% increments, 7 days a week during a period of four and a half months. When the programme was terminated the PEG concentration reached was 14% by analysis of the conservation solution (figure 8-19).

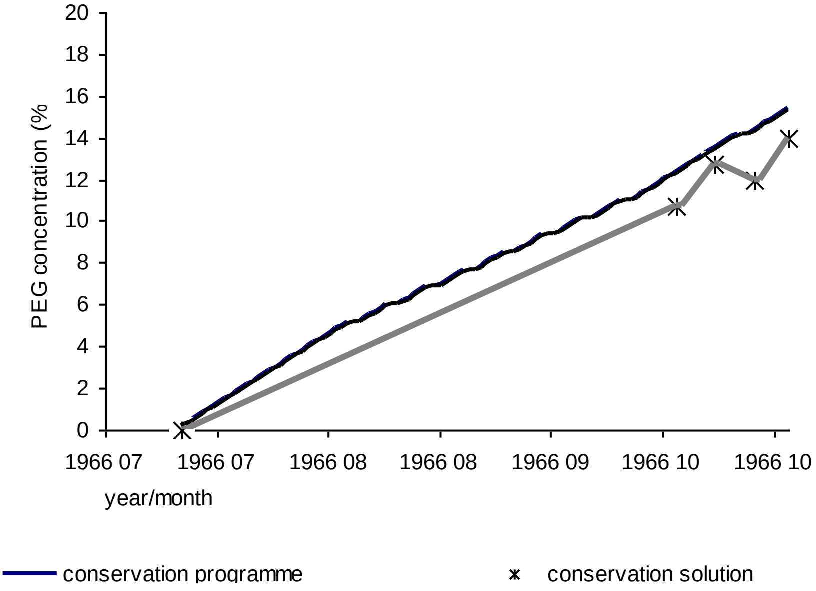

Figure 8-19. PEG-concentration of the third conservation programme designed for material for refitting into the Vasa hull and the resulting PEG-concentration of the conservation solution.

At this occasion 176 objects of immediate importance to the refitting work were selected to be removed from the batch at this occasion. The remaining material was subjected to a continuing conservation programme that is presented in this dissertation as the "fourth batch" under the heading "Complete immersion conservation programmes for all kinds of woods in the Vasa conservation project".

Core-sampling of 8 rather large oak objects had been performed before the conservation started and when the material for refitting was removed from the tank. The degree of conservation showed to be very modest with only 6% PEG-ratio in the surface layer and practically no PEG deeper into the wood (table 8-XXII).

Depth mm	Number of cores	water-ratio (%) before the conservation procedure	water-ratio (%) after the conservation procedure	PEG-ratio (%) before the conservation procedure	PEG-ratio (%) after the conservation procedure
1-5	8	73	-	0.0	6.2
6-10	8	65	-	0.0	0.5
11- 20	8	82	-	0.0	0.2
21-30	8	81	-	0.0	0.3
31-45	8	86	-	0.0	0.1

Table 8-XXII. The water-ratio gradient before and the PEG-ratio gradient inside the medium size oak wood before and after the conservation procedure.

As the degree of PEG conservation was the main concern there were no analyses made of water after the conservation procedure. The figures of water-ratio of the timbers before conservation indicate that a drying process has been going on during the storage period (table 8-XXII).

8.3.4. Conclusions drawn from the three conservation programmes for construction material to be refitted into the Vasa hull

The material selected for the “catch-up” treatment by re-examination divides into two groups, one group of material that could have needed this treatment according to the criteria set up for it and one group of material that was mistakenly given this treatment.

The heavy pine wood and also the medium-sized pine wood items of the first conservation programme for refitting that had been mounted on the Vasa hull and sprayed with conservation solution were not in a stage of conservation to be able to benefit from the treatment.

Both of the heavy and the medium sized oak material of the second conservation programme showed, after the conservation treatment, much higher concentrations of the assumed PEG solutions in the 1-5 mm surface layer than the PEG-concentration of the surrounding conservation solution. This indicates that the material had been removed from a position where it had been subjected to conservation treatment. The treatment might have dissolved some PEG from the surface of the wood but there is no proof of this assumption as there is no reversion of the PEG-concentration gradient.

The oak material of the first and the third conservation programmes may have had a starting point with no PEG, but with some drying of the wood. This material may be the proper target group for the “catch-up” treatment. The concentration of an assumed PEG solution inside the 1-5 mm surface layer showed values just a little below the PEG-concentration of the surrounding conservation solution. The PEG-ratios were low which was in concordance with the situation in the planking and ceiling of the Vasa hull. The water-ratios before the treatment, where these have been analysed in some cases show values of c. 80% inside the wood. After the treatment water-ratio values of above 100% have been recorded in the wood of the proper target group.

The items of the group that had been removed from some kind of contact with PEG had lost between 30 and 60 percentage units water-ratio during the treatment period. The water-ratio values after treatment were below 25% in the surface layers and c. 60% in the middle of the wood (tables 8-XX, 8-XXI).

Some complaint was made from the refitting group, indicating that the treated material did not fit properly where it belonged. This may have been due to the rather low water-ratio of the treated material. However, no item was discarded as result of the treatment.

The main conclusion of this "catch up" conservation might be, that the timbers that went through the immersion conservation procedure would have been better taken care of by being refitted into the Vasa hull without this treatment.

8.4. Complete PEG immersion conservation programmes

Oak material was the main part of the loose timbers and other wooden objects, and when the batches exclusively composed of pine wood material, and all construction material — that was going to be refitted into the Vasa hull had been treated — there was no excuse not to start a complete conservation programme that would suit also oak material. There was also a time table for the conservation work, depending on the contractual disposal of the conservation facilities, to keep in mind.

8.4.1. The first batch of material at a complete immersion conservation programme

The first batch of material that would receive a complete conservation treatment was started in June 1965. The 34 m^3 tank was used for the batch that consisted of 134 objects. Most of these were rather small, weighing c. 2000 g. About 50 objects, however, weighed between 15 and 100 kg. Mixed among the oak wood material there were also objects made of pine wood and objects that were made of lime wood. As the oak wood had been observed to be more difficult to preserve the conservation programme that was created to suite the oak wood, would also be suitable for the objects made of the other species of wood that belonged to the Vasa wooden material. The wooden material, supporting material included, occupied 34% of the volume of the tank.

In 1965, when the present batch was started the PEG 4000 had not been questioned in its capacity as the only molecular weight PEG suitable for immersion conservation treatment, although the PEG 1500 had recently been selected for the spray treatment of the hull. The PEG 4000 held its position at the Vasa conservation laboratory at most of the immersion conservation programmes, partly due to conventional thinking and partly due to difficulties of handling large amounts of solutions of different molecular weight PEG's at the Vasa conservation laboratory. There were, of course, economic reason too.

The conservation programme started with a conservation solution of 4.5% PEG-concentration as a modification of the recommendations of the Morén & Centervall programme. The conservation solution was heated stepwise during a period of 10 days to 60°C. After the 60°C temperature level was reached the increase of the PEG-concentration was started. The chosen increment programme was 0.4% raise of the PEG-concentration, 6 days a week. The fact that the increment programme was applied 6 days a week instead of 5 days a week made the PEG-concentration increase 20% faster than the PEG-concentration of the conservation programme applied at the "second batch exclusively with pine wood material" (section 8.2.2.).

The conservation programme had been set to be concluded when 85% PEG had been added to the conservation solution. This occurred in May 1966 after a conservation period of 11 months. In December 1965 the filling of water for compensation of evaporation was left running. This caused overflow of conservation solution and a loss of c. 5 percentage units PEG-concentration from the solution. This incident has been marked in the graph of the conservation programme.

The conservation programme was monitored by analyses of the PEG-concentration of the conservation solution. The PEG-concentration in the conservation solution kept practically an even pace with the conservation programme until reaching 35%, when the analysis of the conservation solution gave a PEG-concentration value of c. 30%. When continuing the conservation programme there was a sharp divergence from the programme of the PEG-concentration of the conservation solution that eventually at 75% PEG added to the solution reached a analytically determined value of 60%. During the last two months of the conservation treatment there was no increase in PEG-concentration of the conservation solution although the conservation programme was continued from 75 to 85% at the same pace as before (figure 8-20).

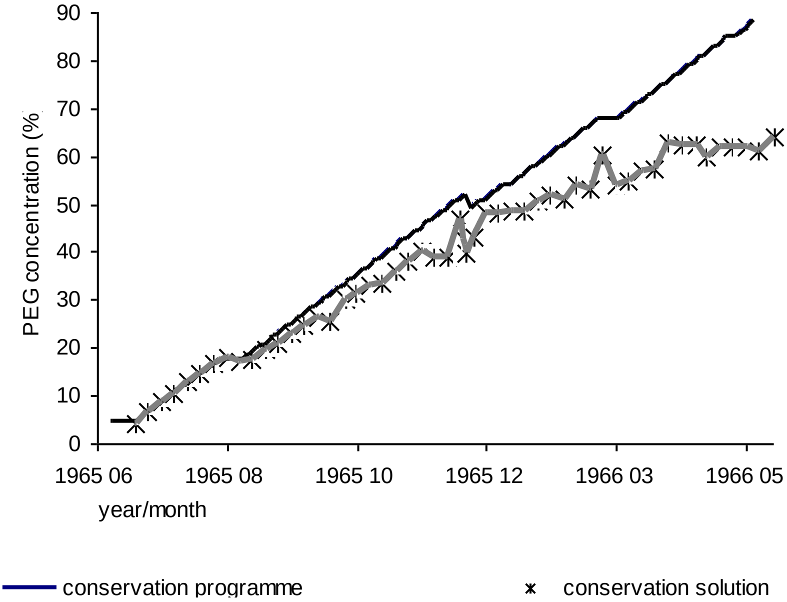

Figure 8-20. PEG-concentration of the conservation programme and the conservation solution of the first batch at a complete immersion conservation programme.

Core-sampling was performed on: 5 heavy oak objects (mean width = 156 mm), 6 medium sized oak objects (mean width = 70 mm), 14 heavy pine objects (mean width = 175 mm), 2 thin objects made of pine (mean width = 28 mm), and 5 heavy objects made of lime wood (mean width = 218 mm).

Heavy objects made of oak, pine and lime wood.

Some objects from all three species of wood had been stored beneath the Vasa hull on the pontoon, where these may have been subjected to dripping of conservation solution from the spraying of the hull. This may have produced a PEG-ratio in the wood before the immersion conservation procedure. As the laboratory was not aware of this situation when starting the analysis work, PEG was not analysed in the wood-cores drilled in the heavy objects before the immersion conservation procedure.

However, the water-ratio gradient before conservation of each of the five groups of objects mentioned above are presented starting with the surface layer and ending with a layer which represents the halfway through the width of the material of the group in question. This provided an opportunity to compare the water-ratios of core samples of heavy objects made of oak wood, pine wood and lime wood, respectively, from the Vasa before the conservation procedure (figure 8-21; table 8-XXIII).

The water-ratio gradient of the oak wood started at the surface of the wood with two rather low values. The gradient then showed increasing water-ratio values all the way to the middle of the width of the wood. This gradient indicates that the oak wood objects from which the cores were drilled had dried before the immersion conservation procedure was started.

The pine wood and the lime wood, respectively showed high water-ratios in the superficial 1-5 mm layer but much lower water-ratios in the 6-10 mm layer beneath this layer. This indicated that both of these groups of wooden items had first dried and then been put into water. The water-ratio gradient of the deeper layers of the pine wood showed increasing water-ratio values towards the middle of the wood.

Neither the oak wood nor the pine wood seemed to show as high water-ratios as was expected from the earlier core-samplings of loose material made of these wood species. The water-ratios of the layers beneath the two surface layers of the lime wood were high and equal all through to the middle of the width of the wood.

The conclusion drawn from this was that the loose wooden material had dried during the storage period beneath the hull of the Vasa despite the high RH of the storage space. The pine wood and the lime wood may then have been placed in the conservation tank where the material was covered in water at periods when no work was going on, during the period of preparing the batch for start of the conservation procedure. As this took several weeks there was enough time for the surface of the wood to absorb water. This may then have happened after the objects were taken to the conservation tank but before the core-sampling was performed.

Depth	Water-ratio gradient (%)		
mm	oak wood	pine wood	lime wood
1-5	48	160	240
6-10	43	80	54
11- 20	68	96	127
21-30	70	88	128
31-45	84	86	136
46-60	99	100	118
61-80	104	102	131
81-100	-	-	92

Table 8-XXIII. The water-ratio gradients inside the heavy oak wood, the heavy pine wood, and the lime wood, respectively, before the immersion conservation procedure.

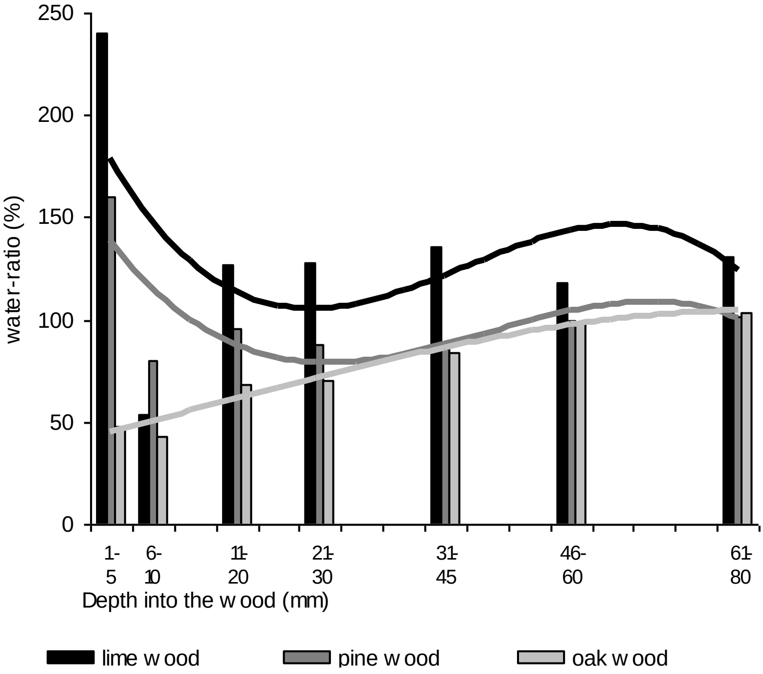

Figure 8-21. The water-ratio gradients inside the heavy oak wood, the heavy pine wood, and the lime wood, respectively, before the immersion conservation procedure. Trend-lines, least square fittings.

Since a high PEG-ratio in the preserved wood by definition was considered as a good result of the conservation treatment, there was no interest in the water-ratios at the end of the conservation period. At the beginning of the conservation period analysis of water in the core-samples was a means of deciding about the degree of deterioration of the wood, which was of importance for the design of the conservation programme.[195]

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[195] Morén & Centervall, 1960.

The present conservation batch presented, however, an opportunity to compare the PEG-ratios after the conservation procedure of core samples of heavy oak wood, pine wood and lime wood from the same objects as had provided the water-ratios before the conservation treatment.

The PEG-ratio gradient of each of the above mentioned five groups of objects are presented starting with the surface layer and ending with a layer which represents the halfway through the width of the material of the group in question (figure 8-22; table 8-XXIV).

The question was raised whether the water-ratio gradient before the conservation procedure might influence the ability of diffusion into the wood of PEG molecules during the immersion conservation procedure.

Studying the PEG-ratio and the water-ratio gradients of each of the groups of objects in the core-sample the three wood species show increasing both of water-ratio and PEG-ratio values in the order oak, pine, and lime wood.

Since Vasa pine wood material contrary to Vasa oak wood material, had been successfully preserved at conservation treatments combining a temperature raising programme and a PEG increment programme involving rather large PEG increments (section 8.1.1., 8.1.2.), it might be of interest to compare the reaction to the present conservation programme of oak wood and pine wood, respectively.

The PEG-ratio gradient in the oak wood after the immersion conservation procedure showed a PEG-ratio of c. 90% in the 1-5 mm surface layer, c. 40% in the 6-10 mm layer, 23% in the 11-20 mm layer and still lower PEG-ratio values deeper into the wood. The conservation result of the oak wood of this first complete conservation programme seems to be about the same as in the second preliminary batch (tables 8-XXIV, 8-IX).

The PEG-ratio gradient in the pine wood started with 150% in the 1-5 mm surface layer and proceeded to a stable level of c. 50% inside the wood. The PEG-ratio of the pine wood of this first complete conservation programme seems to be higher by c. 10 units than in the second preliminary batch (tables 8-XXIV, 8-X).

The lime wood displayed a PEG-ratio of 240% in the 1-5 mm layer and c. 150% in the 6-10 mm layer. Deeper into the lime wood there was practically no PEG-ratio gradient and the PEG-ratios remained mostly well above 100% .

Depth mm	PEG-ratio gradients (%)		
	oak wood	pine wood	lime wood
1-5	91	150	240
6-10	39	111	149
11- 20	23	87	135
21-30	6.9	69	110
31-45	6.5	57	122
46-60	13	48	120
61-80	14	51	100
81-100	-	-	80

Table 8-XXIV. The PEG-ratio gradients inside the heavy oak wood, the heavy pine wood, and the lime wood, respectively, after the immersion conservation procedure.

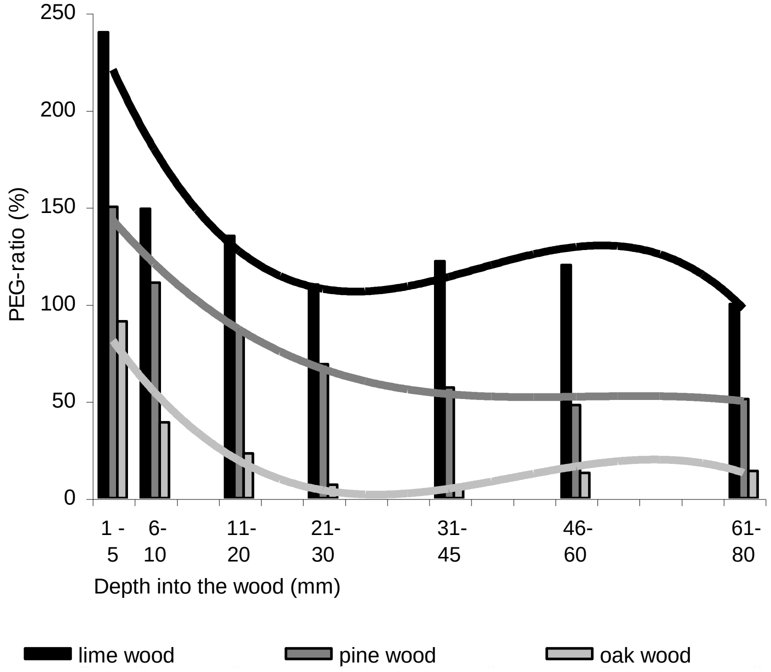

Figure 8-22. The PEG-ratio gradients inside the heavy oak wood, the heavy pine wood, and the lime wood, respectively, after the immersion conservation procedure. Trend-lines, least square fittings.

Medium sized oak timbers

The water-ratio gradients before the conservation treatment of both of the heavy and the medium sized oak timbers show similar water-ratio values, c. 45%, at the surface of the wood and 104% water-ratio at the middle of the thickness of the timbers, before the conservation procedure. This indicates that both of the groups of oak timbers have dried during the storage period before conservation (figure 8-21; tables 8-XXIII, 8-XXV).

Depth mm	Number of cores	water-ratio (%) before the conservation procedure	water-ratio (%) after the conservation procedure	PEG-ratio (%) before the conservation procedure	PEG-ratio (%) after the conservation procedure
1-5	6	47	-	3.8	75
6-10	6	46	-	1.2	32
11- 20	6	73	-	0.6	19
21-30	6	79	-	2.8	11
31-45	6	104	-	3.2	14

Table 8-XXV. The water-ratio gradient before the conservation procedure and the PEG-ratio gradient before and after the conservation procedure inside the medium size oak wood.

The PEG-ratios before and after the conservation treatment have been determined in the core-samples from the medium sized oak material. As a result of this processing, small amounts of PEG have been detected in the wood-cores before the immersion conservation procedure. Both of the groups of oak timbers show PEG-ratio gradients from c. 35% just beneath the surface to 14% at the middle point of the timbers after the immersion conservation treatment (figure 8-22; tables 8-XXIV, 8-XXV).

The thin pine material

The water-ratio gradient before the conservation treatment of the group of thin pine timbers show as low a water-ratio value as 30% at the surface and c. 60% at the middle of the width of the timbers while the heavy pine timbers show water-ratios of c. 80% at the surface of the wood and c. 100% at the middle of the width of the timbers before the conservation procedure (tables 8-XXIII, 8-XXVI).

Depth mm	Number of cores	water-ratio (%) before the conservation procedure	water-ratio (%) after the conservation procedure	PEG-ratio (%) before the conservation procedure	PEG-ratio (%) after the conservation procedure
1-5	2	20	-	13	137
6-10	2	30	-	7	87
11- 20	2	61	-	13	55

Table 8-XXVI. The water-ratio gradient before and the PEG-ratio gradient before and after the conservation procedure inside the thin pine wood.

The group of thin pine material items shows rather high PEG-ratio values before the immersion conservation treatment that provides proof of contact with PEG during the storage period. Both of the groups of pine timbers show PEG-ratio gradients from c. 100% at the surface to c. 50% at the middle point of the timbers after the immersion treatment (tables 8-XXIV, 8-XXVI).

Conclusions

The present conservation programme produced rather low PEG-ratios inside the oak wood. The low PEG-ratio values may be due to the fact that the low water-ratio values before the immersion treatment procedure — especially in the surface region of the oak wood material — may have provided poor diffusion possibilities for the PEG molecules.

The pine wood material seemed well preserved despite the fact that both groups of pine wood timbers had dried during the storage period before conservation.

The lime wood material consisted of large sculptures. These showed very high PEG-ratios in all the layers analysed despite the fact that some drying of the wood before the conservation treatment was observed.

8.4.2. The second batch of material at a complete immersion conservation programme

The second batch of material to receive a complete immersion conservation treatment was started in October 1965 in the 2.5 m^3 tank. A small number of oak sculptures, weighing between 21 and 27 kg were placed in the tank together with c. 120 rather small objects.

Since the result of the previous conservation treatment had not improved in comparison to the preliminary batches (sections 8.1.1, 8.1.2.), some parameters of the conservation treatment had to be changed. The general idea was that one batch might not take longer than c. 12 months to finish if the time schedule for the project would be kept. The laboratory experiments had indicated that adding the PEG at a slow pace would be beneficial to the conservation result. In order to be able to feed the conservation solution with smaller increments the possibility to conclude the conservation programme at a lower PEG-concentration was chosen to be tested.

The conservation programme chosen was 1/6% increments, 7 days a week. The conservation programme was completed at the beginning of December 1966 when 65% PEG 4000 had been added to the conservation solution. Thus, the total length of the period of the conservation procedure was 13 months. The PEG-concentration of the conservation solution started to diverge from the PEG-concentration programme at c. 25%. However, there was a uniform PEG-concentration development in the conservation solution through the entire conservation period. At the endpoint of the conservation programme the PEG-concentration of the conservation solution as established by analysis was 58% (figure 8-23).

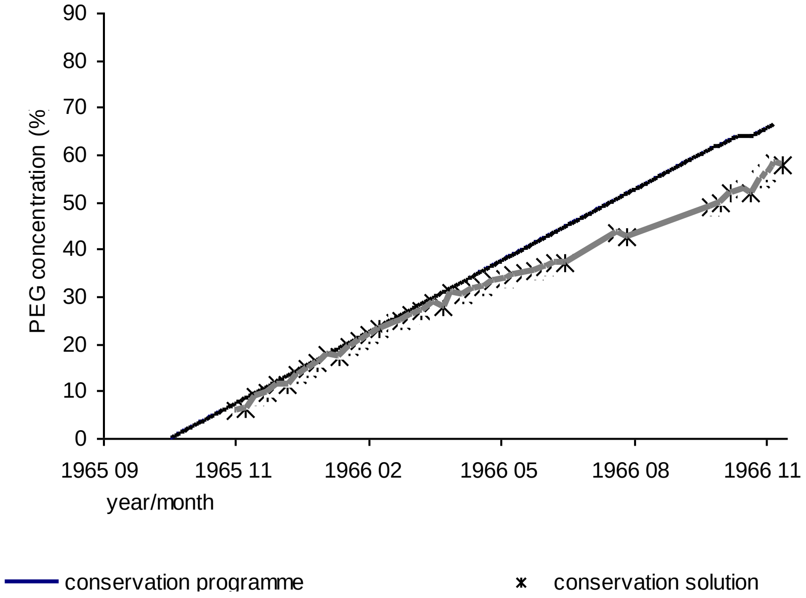

Figure 8-23. PEG-concentration of the conservation programme and the conservation solution of the second batch at a complete immersion conservation programme.

Core-samples were drilled from 9 of the large oak sculptures before and after the conservation procedure. The mean width of these oak sculptures was 130 mm.

The PEG-ratio values obtained after the conservation describes a gradient rather similar to the one obtained by the oak in the previous conservation procedure. It started at 56% just beneath the outer surface and finished at c. 10% PEG-ratio at the middle of the thickness of the wood (table 8-XXVII).

Depth mm	Number of cores	water-ratio (%) before the conservation procedure	water-ratio (%) after the conservation procedure	PEG-ratio (%) before the conservation procedure	PEG-ratio (%) after the conservation procedure
1-5	9	370	-	0.0	174
6-10	9	160	-	0.0	56
11- 20	9	130	-	0.0	18
21-30	8	125	-	0.0	11
31-45	8	121	-	0.0	13
46-60	8	126	-	0.0	6.3

Table 8-XXVII. The water-ratio gradient before and the PEG-ratio gradient before and after the conservation procedure inside the oak wood.

Apart from the outer surface layer the water-ratios of the inner layers of the wood were rather homogenous before conservation. The water-ratio value was c. 125% which indicated that no drying had taken place before the immersion conservation procedure (table 8-XXVII). However, the PEG-ratios inside the oak wood material after the conservation procedure (table 8-XXVII) corresponds to the PEG-ratio values of the oak material of the previous batch (tables 8-XXIV), This indicated that, neither the fact that the oak material had been waterlogged at the start of the conservation procedure nor the changes made in the conservation programme had been sufficient for improving the conservation result. No analysis of water-ratio was made after the conservation procedure.

8.4.3. The third batch of material at a complete immersion conservation programme

To maintain an interest for the Vasa and to attract visitors was important for the financing of the project, and to attain this an exhibition with the sculptures of the stern of the Vasa had been planned to open in the spring of 1968. This led to a start early in 1966 of the planning of the conservation of the sculptural decoration of the stern. As these were the most important sculptures of the Vasa it was essential to choose a proper PEG conservation programme. The laboratory experiments had given some notion that the PEG-concentration of the conservation solution should be raised slowly but there was no knowledge available of how the difference in size between the laboratory test specimens and the sculptures would influence the conservation process. With no other information at hand the same PEG increment programme was selected as the slowest of the programmes of the laboratory experiments, i.e. 1/12% raise of the PEG concentration, for 7 days a week.

The PEG 4000 was chosen as conservation substance. The 1/12% increment programme was run from April 1966 to March 1967 when the PEG-concentration of the conservation programme reached 30%. The actual PEG-concentration in the conservation solution at that occasion was 28%. However, to enable the exhibition to be opened as planned, the rate of raising the PEG-concentration was increased after the 12 months period. The new programme was continued for another six months with 1/5% increments, 7 days a week. The PEG-conservation programme was terminated in October 1967. At this point of time, 67% PEG 4000 had been added to the conservation solution. Analysis of the conservation solution displayed a PEG-concentration of 56% (figure 8-24).

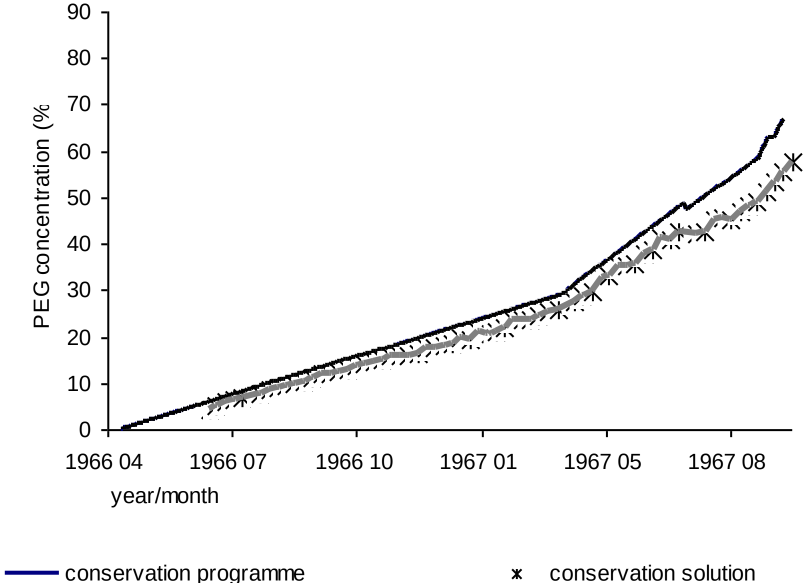

Figure 8-24. PEG-concentration of the conservation programme and the conservation solution of the third batch of material at a complete immersion conservation programme.

There were 294 sculptures belonging to this group of decorationst on the Vasa. Many of these sculptures had been exhibited in the pontoon super structure where a high RH was maintained. Spraying of the wooden sculptures during the exhibition was performed in order to protect the wood from drying. This resulted in the existence of a PEG-ratio in the wood before the immersion conservation treatment started.[196]

The sculptures were placed in the 42 m^3 tank. The volume of the wooden material, the sculptures and the supporting material together was 8.7 m^3. Thus, the wood occupied a fraction of 21% of the usable volume of the tank.

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[196] Håfors, note, 1966 03 21.

8. IMMERSION TREATMENT WITH PEG OF LOOSE WOODEN OBJECTS AND CONSTRUCTION TIMBERS FROM THE VASA

Wood-core samples were drilled before the sculptures were placed in the conservation tank, and when the conservation programme was finished and the material was removed from the conservation tank. Since the sculptures had been treated with PEG solution before the immersion treatment the PEG-ratios of the wood-cores drilled before the conservation procedure were determined for each of the groups of oak, pine and lime wood (table 8-XXIX).

Due to lack of laboratory staff, analyses were not performed until after a storage period of more than 6 months after the occasion when the wood-cores were drilled. At that time the wood-cores had already dried in the test-tubes, and the water-ratios could not be determined.

As there were no water-ratio values analysed before the immersion treatment had been performed, there were no values of PEG-concentration of an assumed PEG solution inside the wood before the immersion conservation treatment either.

The PEG-ratio gradient obtained by the protective spraying with conservation solution during the exhibition period in the pontoon super structure, before the material was taken to the immersion conservation procedure, had produced a grand mean of the PEG-ratio of c. 1% inside the oak wood and a little more in the surface layers.

The PEG solution treatment of the pine wood sculptures during the exhibition period before the immersion conservation period seems to have produced rather high grand mean PEG-ratio values at all levels in the wood. The surface layer, the layers at between 20 and 45 mm depth, and the layer at between 61 and 80 mm depth displayed PEG-ratios of c. 25%. These layers with high PEG-ratios alternated with layers with between 5 and 12 % PEG-ratios.

The PEG-ratios of the lime wood before the immersion conservation treatment resembled those of the oak wood in that these were evenly distributed, and rather low. The grand mean of the PEG-ratio value of the lime wood was c. 2% (table 8-XXVIII).

Depth mm	PEG-ratio gradients before the immersion conservation procedure (%)		
	oak wood sculptures	pine wood sculptures	lime wood sculptures
1-5	8.6	28	3.7
6-10	2.2	12	4.7
11- 20	1.3	6.7	2.2
21-30	1.1	24	2.0
31-45	1.0	26	2.3
46-60	1.3	9	2.2
61-80	0.7	27	1.8
81-100	1.6	5.5	2.0

Table 8-XXVIII. PEG-ratio gradients inside the oak, pine, and lime wood, respectively, before the immersion conservation procedure.

The sculptures in the conservation batch were made of oak wood, pine wood, and lime wood. When the conservation procedure was finished wood-core samples were drilled from each of those three categories of wooden sculptures. The largest wood-core sample, 31 cores, was taken from the oak wood sculptures since these were in majority. The next largest group of sculptures was the lime wood sculptures, where wood-cores were taken from 13 objects. The smallest group, the pine wood sculptures, were represented by 4 wood-cores.

The three parameters, the PEG-concentration of an assumed PEG solution inside the wood, the PEG-ratio and the water-ratio, which have been considered to be of significance to the evaluation of the conservation result are listed in tables for the wooden species, oak, pine and lime wood (tables 8-XXIX - 8-XXXI).

The PEG-concentration after the immersion conservation procedure, of an assumed PEG solution inside the surface layers of the wood of the three different wood species of the batch were just a little lower than the PEG-concentration value of the surrounding PEG solution. This also applied to the layer beneath the surface layer where pine wood and lime wood were concerned while the corresponding layer by the oak wood showed a PEG-concentration of 38%, i.e. 12 percentage units lower value than that of the surface layer. In the pine and the lime wood the PEG concentration had decreased to c. 40% in the fourth layer, i.e. at a depth of 21-30 mm into the wood.

Through the consecutive three layers beneath the surface layer of the oak wood the PEG-concentration values decreased steeply to 15%. This PEG-concentration level was maintained through to the middle of the width of the wood. The pine wood and the lime wood displayed a uniform stepwise decrease of the PEG-concentration towards the middle of the width of the wood, the pine wood finishing with a value somewhat above 25%, and the lime wood finishing with a value somewhat below 25% (table 8-XXIX, figure 8-25).

Depth	PEG-concentration gradients after the termination of the conservation procedure (%)		
mm	oak wood	pine wood	lime wood
1-5	50	55	53
6-10	38	51	50
11- 20	21	47	44
21-30	15	40	39
31-45	11	34	33
46-60	12	29	31
61-80	16	26	27
81-100	15	28	23

Table 8-XXIX. The gradients of the concentration of an assumed PEG solution inside the wood of the sculptures made of oak, pine, and lime wood, respectively, after the conservation procedure.

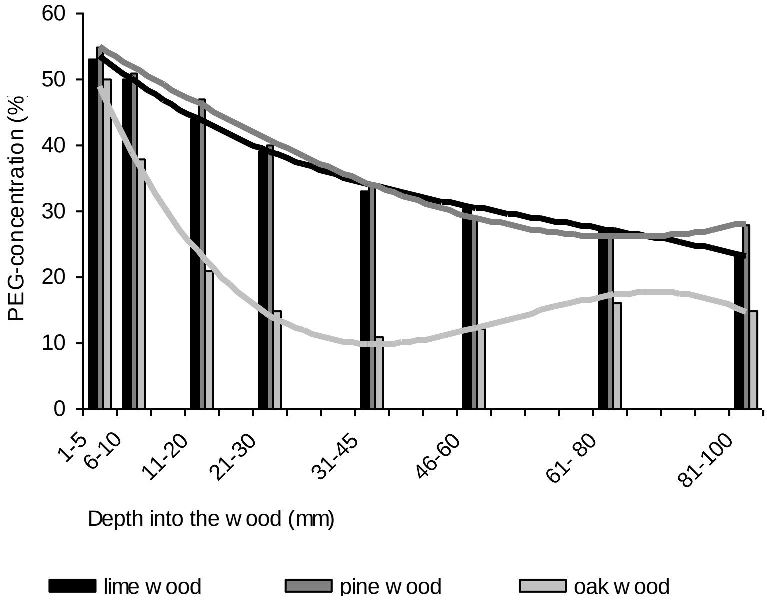

Figure 8-25. The gradients of the concentration of an assumed PEG solution inside the wood of the sculptures made of oak, pine, and lime wood, respectively, after the immersion conservation procedure. Trend-lines; least square fittings.

8. IMMERSION TREATMENT WITH PEG OF LOOSE WOODEN OBJECTS AND CONSTRUCTION TIMBERS FROM THE VASA

After the immersion conservation procedure the grand mean of the PEG-ratio of the outer surface layer of 5 mm width of the oak wood material was 110%. There was then a steep dip to the next 5 mm layer that displayed a grand mean PEG-ratio value of 37%. The lowest PEG-ratio values, 10 – 15% existed from 20 mm depth and inwards into the wood of the oak sculptures (table 8-XXX).

The three layers, from the surface and inwards to a depth of c. 20 mm, of the pine wood showed a PEG-ratio gradient from 150 to c. 90 %. Deeper into the wood, at the 21 – 45 mm level, the next step downwards took the PEG-ratio down to 65 %. The lowest PEG-ratios, at the interior of the pine wood, were c. 40% (table 8-XXX).

The PEG-ratios of the lime wood after the immersion conservation showed a resemblance to the pine wood in that the level of the PEG-ratios proceeded from very high to c. 100 % from the surface of the wood through to c. 30 mm depth into the wood. The lowest grand mean PEG-ratio level obtained inside the lime wood was 45% (table 8-XXX).

Depth	PEG-ratio gradients after the conclusion of the immersion conservation procedure (%)		
mm	oak wood sculptures	pine wood sculptures	lime wood sculptures
1-5	110	150	260
6-10	37	130	180
11- 20	19	92	130
21-30	13	65	99
31-45	10	68	78
46-60	11	42	66
61-80	18	46	59
81-100	15	61	45

Table 8-XXX. PEG-ratio gradients inside the oak, pine, and lime wood, respectively, after the termination of the immersion conservation procedure.

The water-ratios after the immersion conservation treatment of the oak wood material made a sharp dip of c. 50 percentage units water-ratio from the first 5 mm surface layer to the second 5 mm layer. From the second layer and deeper inwards into the wood there was practically no gradient but the water-ratio value remained at c. 50% (table 8-XXXI).

The water-ratios after the immersion conservation of the pine wood material showed a similar lack of a gradient. Each of the two 5 mm layers displayed a water-ratio value of 120%, while the layers inside the wood showed water-ratio values of c. 100% (table 8-XXXI).

The lime wood displayed an even more uniform water-ratio inside the wood, with a value of 140% nearly through the whole depth from beneath the surface layer to the middle of the wood (table 8-XXXI).

Depth	Water-ratio gradients after the termination of the immersion conservation procedure (%)		
mm	oak wood	pine wood	lime wood
1-5	110	120	230
6-10	52	120	190
11- 20	48	100	150
21-30	49	87	140
31-45	55	100	140
46-60	62	93	140
61-80	68	110	140
81-100	74	120	140

Table 8-XXXI. The water-ratio gradients inside the oak wood, the pine wood, and the lime wood, respectively, after the immersion conservation procedure.

Since no core-sampling was performed when the sculptures were removed from the water tank storage, no maximum water-ratio values had been determined for the three different species of wooden material that belonged to the batch of material. To get an idea of the capacity of the wood and possible level of maximum water-ratio values of these oak, pine and lime woods, the ratios of assumed PEG solution inside each of the layers of the wooden cores drilled after the conservation procedure were calculated (table 8-XXXII, figure 8-26).

In the oak wood the solution ratio level dropped sharply just below the 5 mm outer surface layer to a value that remained practically stable at c. 70% to the middle of the width of the wood. Where the pine wood was concerned there was a gradually declining value of solution ratio through the three outer layers to a depth into the wood of c. 20 mm. The PEG solution ratios of the internal layers of the pine wood amounted to values around 150%. The lime wood showed a somewhat similar situation as the pine wood with a gradually declining PEG solution ratio through the four outer layers down to a depth into the wood of 30 mm where a stable solution ratio value of c. 200% remained (table 8-XXXII).

Depth	PEG solution ratio gradients after the conclusion of the conservation (%)		
mm	oak wood sculptures	pine wood sculptures	lime wood sculptures
1-5	220	270	490
6-10	89	250	380
11- 20	67	192	280
21-30	62	152	239
31-45	65	168	218
46-60	73	135	206
61-80	86	156	199
81-100	89	181	185

Table 8-XXXII. The gradients of the ratios of an assumed PEG solution after the conservation procedure inside the sculptures made of wood, pine wood, and the lime wood, respectively.

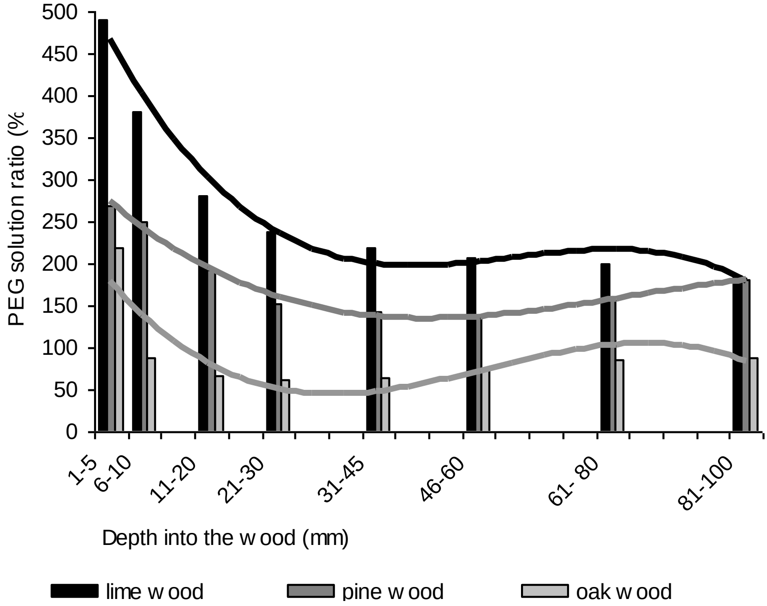

Figure 8-26. The gradients of the ratios of an assumed PEG solution inside the wood of the sculptures made of oak, pine, and lime wood, respectively, after the immersion conservation procedure. Trend-lines; least square fittings.

Conclusion

The changes made in the PEG increment programme did not produce significantly higher PEG-ratios in the oak wood material of the batch (table 8-XXX) than in the oak material of the two previous batches (tables 8-XXIV, 8-XXV, 8-XXVI).

8.4.4. The fourth batch of material at a complete immersion conservation programme

This conservation programme was performed in the 34 m^3 tank as a direct continuation of the third conservation procedure of construction material for refitting into the Vasa hull (section 8.3.3.). This implied that the programme started at 15% PEG 4000. From this PEG-concentration level the conservation programme continued at a pace of 1/6% increments, 7 days a week. This was performed from November 1966 to March 1967 at which occasion the conservation programme had reached 35% PEG-concentration. At the same time the actual PEG-concentration of the conservation solution was c. 28%. At that occasion 495 objects were removed for refitting into the Vasa hull.

The preserved objects were weighed in connection to their removal from the conservation bath. By comparing these weights to the weights of the same objects before the conservation procedure, loss of weight was noted to have occurred during the part of the conservation period ending with 28% PEG-concentration in the conservation solution. This made the conservation programme to be stopped at the obtained level for a 5 months period. To analyse the situation, four wood-cores were drilled, two of these from heavy oak objects and the two others from rather medium sized oak material. It was, however, not possible to judge from these, whether or not drying of the wood in the conservation bath had actually taken place. The items from which the core-samples were drilled before the conservation treatment, which had shown rather low water-ratios at that occasion, had been removed from the conservation tank when the third batch of material for refitting into the Vasa hull was terminated (table 8-XXII).

The adding of increments started again in August 1967 and continued during September the same year when the conservation programme reached the 40% level. Then there was a another period of intermission at the 40% level, which lasted until February 1968. During this period the actual PEG concentration of the conservation solution decreased gradually from 35 to 30 %. At the end of this period of intermission a second wood-core sampling was performed to monitor the conservation process.

The terminating period of raising the PEG-concentration from 40 to 75% according to the conservation programme, which gave a corresponding raise of the PEG-concentration of 30 percentage units to 58%, according to analysis, was performed from February to September 1968. The third wood-core sampling took place after the conservation programme was terminated (figure 8-27).

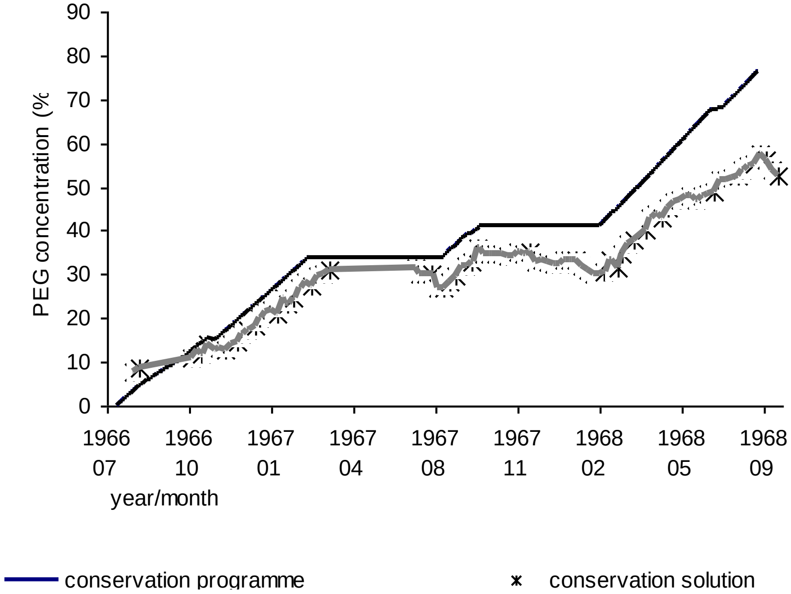

Figure 8-27. PEG-concentration of the conservation programme and the conservation solution of the fourth batch of material at a complete immersion conservation programme.

The core-samplings of material from the fourth batch were performed at three occasions during the fourth batch. The PEG concentrations according to the conservation programme were 35%, 40% and 75% that matched 28%, 33% and 58% of actual PEG-concentrations in the conservation solution, respectively.

The core-sampling of the heavy oak material from the third conservation programme of construction material for refitting into the Vasa hull, that was part of the conservation programme of the fourth batch of material at a complete immersion conservation programme, has been added to the tables and graphs of the assumed PEG-concentrations, PEG-ratios and water-ratios, respectively of the present batch.

Since the objects selected for core-sampling at the third conservation procedure of construction material for refitting into the Vasa hull obviously had dried during the storage period there is no reliable water-ratio gradient available before the present conservation procedure. Since there was trouble financing laboratory staff for the task, only the PEG was analysed in the core sample drilled after the termination of the third conservation of material for refitting into the Vasa hull (table 8-XXII).

The PEG-concentration of the assumed PEG solution in the wood was very low in the oak wood material for refitting into the Vasa hull at the removal in February 1967 from the conservation solution with a PEG-concentration of 28%. Not even the outer 5 mm surface layer with its 6% PEG-concentration showed anything near to the PEG concentration of the surrounding PEG solution and most of the layers showed PEG-concentrations of less than 1%. In December 1967, at 33% PEG-concentration in the conservation solution there was a marked difference both of the surface layer, that showed a PEG-concentration of 21% and deeper into the wood where the gradient started at 10% and proceeded with decreasing values to 2.3%. Nearly a year later, at the termination of the conservation procedure, the PEG-concentration in the surface layer was 51% while the PEG-concentration of the surrounding conservation solution was 58%. The PEG-concentration gradient showed decreasing values but this time from 42 to 21% (table 8-XXXIII).

Depth	Number of cores	PEG-concentration of an assumed PEG solution inside the wood (%): at			
		14%	28%	33%	58%
mm		PEG-concentration of the conservation solution (%)			
1-5	9	-	6.0	21	51
6-10	9	-	1.5	10	42
11- 20	9	-	0.0	8.7	31
21-30	9	-	0.5	8.0	27
31-45	9	-	1.0	7.3	27
46-60	9	-	0.5	4.3	23
61-80	9	-	0.0	2.3	21

Table 8-XXXIII. The PEG-concentration gradient of an assumed PEG solution inside the heavy oak wood at 14, 28, 33, and 58% PEG-concentration in the conservation solution.

The PEG-ratios of the materials removed at 14 and 28% PEG-concentration of the conservation solution show seemingly equal gradients and rather low values in both cases but a little higher at 28% PEG-concentration. The reason for this insignificant increase in PEG-concentration might be a slow diffusion of PEG molecules into the wood, or some diffusion of water molecules out of the wood.

The latter presumption seems more likely because the loss in weight of some wooden objects noted at the removal of material at 28% PEG-concentration in the conservation solution indicates that water molecules must have been diffusing out of the wood without being compensated by a diffusion of PEG molecules in the opposite direction.[197]

The wood-core sampling performed 5 months later, when the PEG increment programme had been stopped at 40% during c. 2.5 months, showed PEG-ratio values inside the wood that were 10 times higher than at the previous occasion. The final wood-core sampling drilled c. 10 months later, when the conservation programme had been completed at 75%, PEG added to the conservation solution showed PEG-ratio values inside the wood of 45 to 19% in a decreasing gradient inwards to the middle of the wooden objects (table 8-XXXIV; figure 8-28).

Depth mm	Number of cores	PEG-ratio (%): at			
		14%	28%	33%	58%
		PEG-concentration of the conservation solution (%)			
1-5	9	6.2	7.3	24	71
6-10	9	0.5	1.6	9.3	45
11- 20	9	0.2	0.1	9.0	28
21-30	9	0.3	0.7	10	27
31-45	9	0.1	1.4	8.1	25
46-60	9	-	0.6	4.7	22
61-80	9	-	0.5	2.4	19

Table 8-XXXIV. The PEG-ratio gradient inside the heavy oak wood at 14, 28, 33, and 58% PEG-concentration in the conservation solution.

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[197] Håfors, personal note, 1968 03 07.

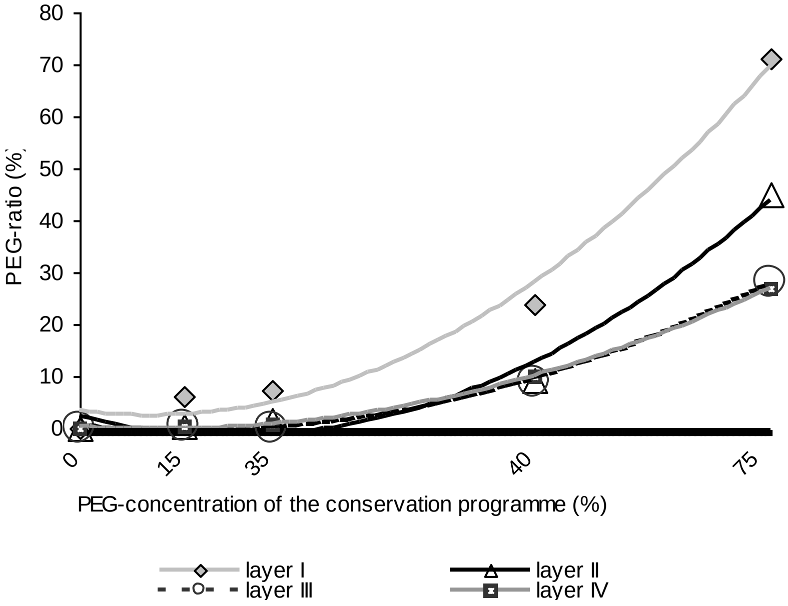

Figure 8-28. The development of the PEG-ratios inside the heavy oak wood at 15, 35, 40, and 75% PEG-concentration according to the conservation programme. Trend-lines; least square fittings.

The water-ratio values seem nearly unchanged between the two wood-core samplings at the 35 and the 40% levels of the conservation programme and were still rather high when the conservation procedure was finished in September 1968 (table 8-XXXV; figure 8-29).

Depth mm	Number of cores	water-ratio (%): at			
		14%	28%	33%	58%
		PEG-concentration of the conservation solution (%)			
1-5	9	-	110	88	66
6-10	9	-	105	92	58
11- 20	9	-	105	97	51
21-30	9	-	120	102	55
31-45	9	-	120	103	58
46-60	9	-	120	103	63
61-80	9	-	115	103	65

Table 8-XXXV. The water-ratio gradient inside the heavy oak wood at 14, 28, 33, and 58% PEG-concentration in the conservation solution.

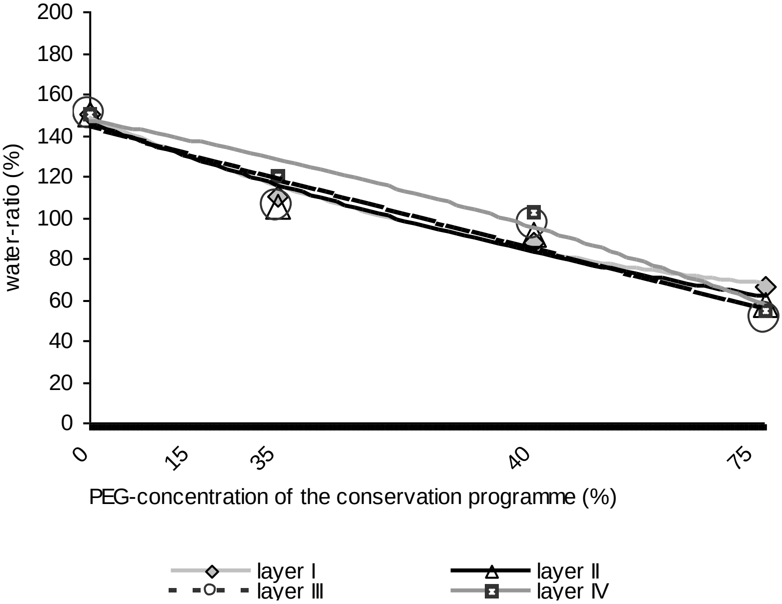

Figure 8-29. The drying curves inside the heavy oak wood at 15, 35, 40, and 75% PEG-concentration according to the conservation programme. Trend-lines; least square fittings.

8. IMMERSION TREATMENT WITH PEG OF LOOSE WOODEN OBJECTS AND CONSTRUCTION TIMBERS FROM THE VASA

Since wood-cores were drilled before the immersion conservation treatment only from the objects that were selected for the initial conservation of material for refitting into the Vasa hull, there was no initial water-ratios of the fourth batch of material at a complete immersion conservation programme. To get an idea of the initial water-ratios of the material that has been dealt with in the present section, the sum of PEG- and water-ratios, that represent the PEG solution-ratios has been calculated layer by layer at the three wood-core sampling occasions where both these ratios have been presented (table 8-XXXVI).

Depth	Number of cores	PEG solution ratio (%) at			
		14%	28%	33%	58%
mm		PEG-concentration of the conservation solution (%)			
1-5	9	-	117	112	137
6-10	9	-	107	101	103
11- 20	9	-	105	106	79
21-30	9	-	121	112	82
31-45	9	-	121	111	83
46-60	9	-	121	108	85
61-80	9	-	116	105	84

Table 8-XXXVI. The PEG solution ratio gradient inside the heavy oak wood at 14, 28, 33, and 58% PEG-concentration in the conservation solution.

The previously mentioned notation of weight loss of some of the material removed from the conservation bath in February 1967 makes the core-sample drilled at that occasion especially important to examine. Since the gradient of assumed PEG-solution inside the wood at the occasions of 28% PEG-concentration show PEG-solution-ratios in the wood from 105 to 121% the initial water-ratio of the material dealt with in the present section may well have been 150%, which value has been chosen for the presentation of the development of the water-ratio during the immersion conservation procedure (figure 8-29).

It may be noted that there is a loss of PEG solution from the wood-cores at each of the two later samplings compared to the previous sampling. The conclusion drawn is that there is a loss of water from the oak wood during the entire conservation procedure. This loss of water was not fully compensated by the addition of PEG in the Vasa oak wood.

Conclusion

The PEG-ratios at a depth from 10 mm below the surface inwards of the oak material at the termination of the conservation procedure amounted from 28 to 19% (table 8-XXXVIII, figure 8-28), while the oak material of the third batch (8.4.3.) displayed a series of PEG-ratios at corresponding depth of from 19 to 10% (table 8-XXX). The difference in lengths of the conservation periods with 2 years for the present batch and 1½ years for the third batch may be a possible reason.

8.4.5. The fifth batch of material at a complete immersion conservation programme

The conservation procedure was performed with PEG 4000 and the PEG-conservation programme was divided into two parts with different sizes of the daily PEG-increments. Like in the section 8.4.3., the first part of the programme was carried through during 12 months with 1/12% daily increments to a total of 30% PEG-concentration added to the solution. This part finished at 22% PEG-concentration in the conservation solution. The second part of the programme was proceeding during the succeeding 10 months with 1/6% daily increments to a total of 74%, that produced an actual PEG-concentration of 52% in the conservation solution (figure 8-30).

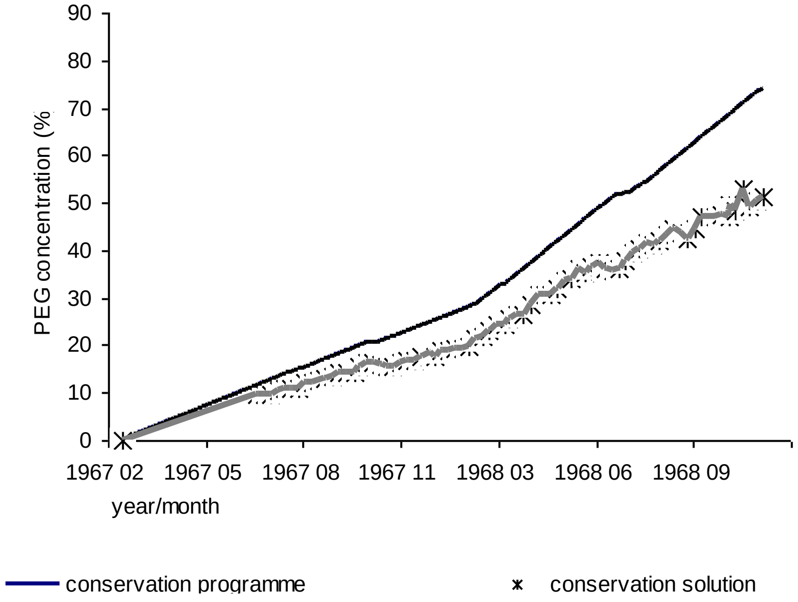

Figure 8-30. PEG-concentration of the conservation programme and the conservation solution of the fifth batch of material at a complete immersion conservation programme.

The 206 objects selected for this batch were placed in the 2.5m^3 tank. One of the objects was a sculpture of 50 kg that was made of pine wood, one sculpture, made of oak wood and weighing 36 kg belonged to the Wasa court of arms and another sculptural decoration, made of oak wood, weighed 19 kg. The remainder of the material were small objects and parts of sculptures. Most of these weighed only 300 to 500 g. The three wood species, oak, pine and lime wood were represented among the material.

Wood cores were drilled from 6 of the oak wood objects, one of the pine wood objects and 3 of the lime wood objects. The drilling was always made from the back-side of a sculptured object.

All of the wooden material had been stored in water tanks before the immersion conservation treatment was started. Some of the water-ratios found indicated, however, that some of the objects had not been continuously immersed in water since the excavation. This was the situation with 2 of the oak wood objects, possibly also with the pine wood object, and seemingly with 2 of the lime wood objects. Considering the character of the objects these probably had been on exhibition in the pontoon super-structure.[198]

There was thus, unexpectedly a possibility that the objects had dried as well as that an amount of PEG existed in the wood before the immersion conservation procedure. Since PEG had not been analysed in the wood cores drilled before the conservation treatment, neither the PEG-ratios nor the PEG-concentrations of assumed PEG solutions in the layers inside the wood could be registered for that occasion.

The circumstances that some of the objects selected for analysis may have dried before the conservation started was made a basis for grouping the core-sample material from oak and from lime wood each into 2 groups, namely: *Oak wood without obvious drying damage, Oak wood with obvious drying damage, Lime wood seemingly without drying damage*, and *Lime wood seemingly with drying damage, while the pine wood object constituted a group of its own.*

Oak wood

Four of the oak wood items were labelled "oak without obvious drying damage". The width of each of 2 of the items of this group of oak objects was 60 mm while the width of each of the other 2 items was 100 mm. Thus, the mean width of the tested objects was 80 mm which makes the 31-45 mm layer of the wood-core reach past the middle point of the width of the thin objects and, thus, representing only the large objects.

Before the conservation treatment started two of the oak wood items displayed the very low water-ratio of 12% in the 6-10 mm layer. This fact was the reason that made these two oak wood items, No 23108 and No

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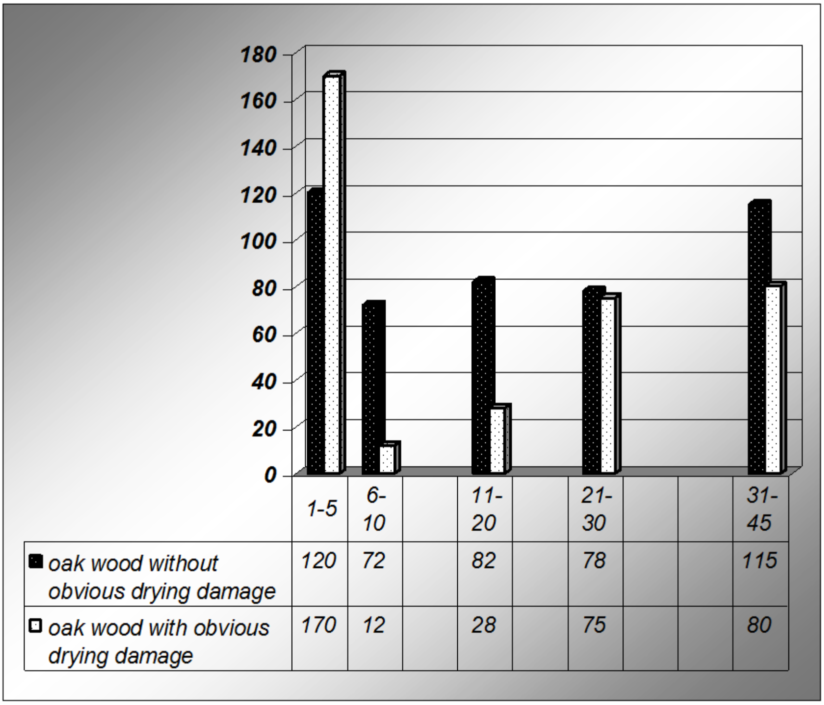
[198] Håfors, personal note, 1966 03 21.

23112, being labelled "oak with obvious drying damage". Both of the items were rather large specimens, No 23108 was 140 mm in width and No 23112 was 100 mm in width, and weighed 36 kg. This made the 31-45 mm layer represent both of the items.

The water-ratios found in the two surface layers of the oak wood "without obvious drying damage" before the immersion conservation treatment was started were 120 and 72% and deeper into the wood in the region of 80%. The water-ratio values of the corresponding layers of oak wood "with obvious drying damage" were 170 and 12% followed by 28% in the succeeding 10 mm layer, which then was followed by water-ratio values of c. 80% deeper into the wood (table 8-XXXVII – 8-XXXVIII).

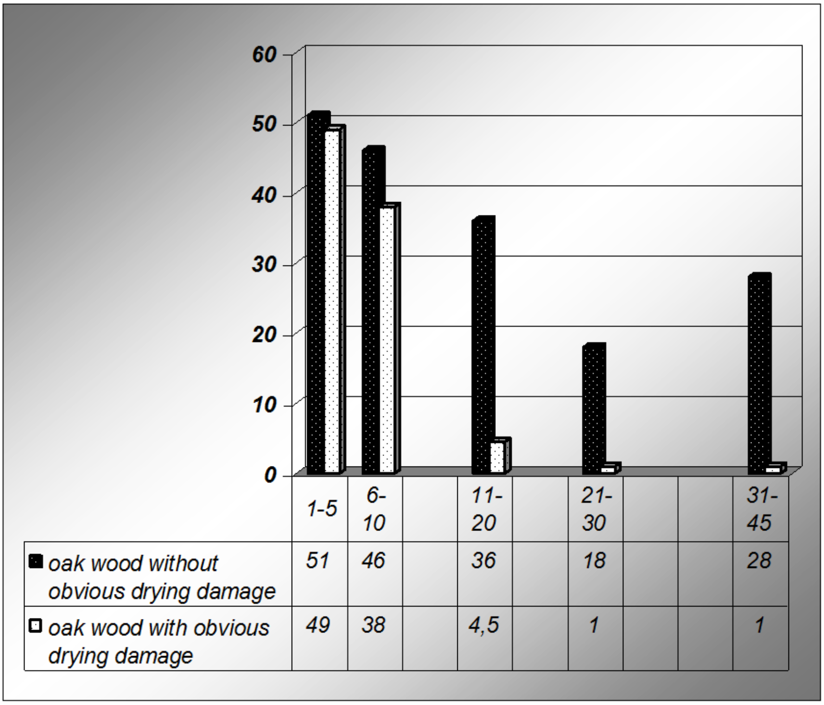


	1-5	6-10		11-20		21-30			31-45
■ oak wood without obvious drying damage	120	72		82		78			115
□ oak wood with obvious drying damage	170	12		28		75			80

Table 8-XXXVII. The water-ratio gradients inside the oak wood before the conservation procedure.

If the layers down into the wood to a depth of 30 mm of the "oak without obvious drying damage" are considered, there was a decreasing gradient of PEG-concentration of the assumed PEG solution inside the wood from 51%, which corresponds with the PEG-concentration of the surrounding conservation solution, down to 18% in the middle of the wood. This is in accordance with the corresponding values in the section 8.4.4. (table 8-XXXIII).

The gradient of the PEG-concentration of the assumed PEG solution inside the wood of the 2 items labelled "oak with obvious drying damage" started in the 1-5 mm layer with a PEG-concentration value that was close to the concentration of the surrounding conservation solution, the PEG-concentration of the 6-10 mm layer was rather high but there seems to be a discontinuity of the diffusion of PEG molecules further into the depth of the wood where the PEG-concentration decreased to 1% (table 8-XXXVIII).

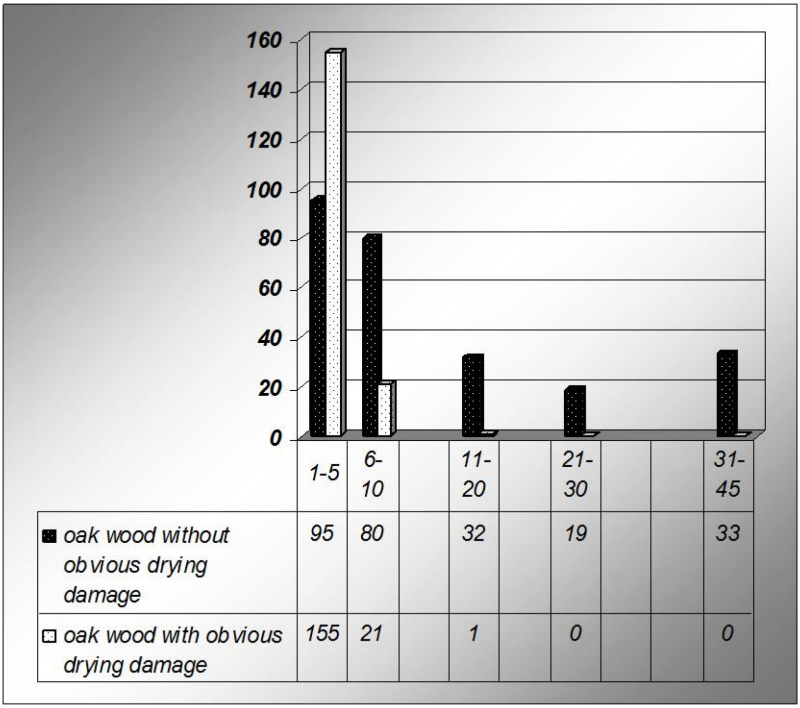


	1-5	6-10		11-20		21-30			31-45
■ oak wood without obvious drying damage	51	46		36		18			28
□ oak wood with obvious drying damage	49	38		4,5		1			1

Table 8-XXXVIII. The PEG-concentration gradients of an assumed PEG solution inside the oak wood after the conservation procedure.

The PEG-ratio gradient of the “oak without obvious drying damage” displayed rather high values in both of the 5-mm layers. Deeper into the wood the PEG-ratio gradient of the oak material at hand resembled those of the previously presented conservation procedures with sculptured material (table 8-XXXIX, 8-XXX).

The PEG-ratio gradient of the “oak with obvious drying damage” showed very high values in the 1-5 mm layer, still c. 20% in the 6-10 mm layer but practically no PEG deeper into the wood (table 8-XXXIX).



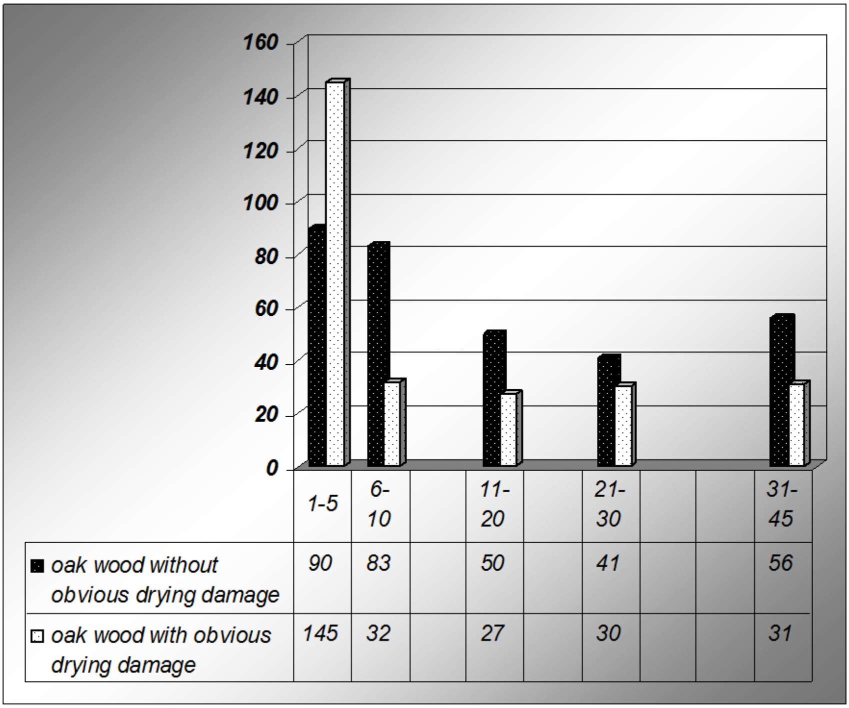
	1-5	6-10		11-20		21-30			31-45
■ oak wood without obvious drying damage	95	80		32		19			33
☐ oak wood with obvious drying damage	155	21		1		0			0

Table 8-XXXIX. The PEG-ratio gradients inside the oak wood after the conservation procedure.

The water-ratio gradient after the conservation procedure of the "oak without obvious drying damage" did not diverge from the previous situation of water-ratio gradients in oak wood at the end of the conservation treatment. However, the water-ratio gradient before the conservation procedure in the oak wood showed much lower values, c. 80% inside the wood instead of the expected 120 – 130% (table 8-XL).

This indicates that although the four oak objects did not show any difference from what had been considered normal of the gradients of PEG-concentrations or PEG-ratios, these also seem to have dried before the conservation treatment. This may have been caused by keeping them on exhibition for a period of time before returning them to storage in the water tank from where they were collected for conservation.

The two oak items called “oak with obvious drying damage” that before the immersion treatment had shown the very low water-ratio value of 12% in the 6-10 mm layer after the immersion treatment showed water-ratio values of c. 30% all through from the 6-10 mm layer to the middle of the objects (table 8-XL).



	1-5	6-10		11-20		21-30			31-45
■ oak wood without obvious drying damage	90	83		50		41			56
□ oak wood with obvious drying damage	145	32		27		30			31

Table 8-XL. The water-ratio gradients inside the oak wood after the conservation procedure.

Summary

The immersion treatment of the oak wood “with obvious drying damage” had produced an increase of the water-ratio value in the 6-10 mm layer, a stand-still of the water-ratio value of the 11-20 mm layer and

c. 50 percentage units decrease of the water-ratios deeper into the wood, while practically no PEG had entered the wood.

In the same conservation batch the oak wood "without obvious drying damage" had retained high water-ratios in the surface layers and had lost c. 30 percentage units water-ratio inside the wood. After the conservation this group displayed rather high PEG-ratio values all through the wood.

Depending on the differences between their respective water-ratio gradients before the conservation treatment, the two items No 23108 and No 23112 have been discussed separately.

Oak wood with obvious drying damage (Object No 23108)

From the water-ratio values before the conservation procedure (table XXXVII), the information is derived, that this sculpture had dried extensively from the surface to a depth of 20 mm into the wood. The water-ratios before the immersion conservation in the middle of the wood also were rather low.

After the conservation procedure the water-ratio of the 1-5 mm layer was c. 60% while the corresponding value of oak wood without obvious drying damage was c. 90%. The remainder of the water-ratio gradient had equalised towards c. 30%, that is c. 2/3 of the corresponding values of oak wood without obvious drying damage.

The PEG-ratio gradient only existed to a depth of 20 mm. The PEG-ratios displayed were much lower than the corresponding values for oak wood without obvious drying damage of the same batch.

After the conservation procedure the PEG-concentration of an assumed PEG solution inside the wood was much lower than the corresponding values in oak wood without obvious drying damage from the same batch (table 8-XLI).

Depth mm	Number of cores	water-ratio (%) before the conservation procedure	water-ratio (%) after the conservation procedure	PEG-ratio (%) after the conservation procedure	PEG-concentration (%) after the conservation procedure
1-5	1	22	58	48	45
6-10	1	12	30	12	28
11- 20	1	15	29	1	5
21-30	1	64	32	0	1
31-45	1	65	32	0	1

Table 8-XLI. The water-ratio gradient, before and after the conservation procedure, the PEG-ratio gradient and the PEG-concentration gradient inside the oak wood of sculpture No 23108.

Oak wood with obvious drying damage (Object No 23112)

The other item of the category “oak wood with obvious drying damage” was a sculpture that weighed 36 kg and belonged to the Vasa court of arms. Despite the very high water-ratio of 310% of the outside surface layer before the conservation treatment, the low water-ratio of 12% of the second layer indicates that the sculpture had dried on some occasion. This may have happened on exhibition during a period of time. As this sculpture is a very valuable item it would have been treated very carefully with PEG 4000 solution during such an exhibition period. This treatment may have left a high PEG-ratio in the 1-5 mm surface layer, which may have caused the very high water-ratio of the outside surface layer when the sculpture was returned to storage in water.

Apart from the extremely high water-ratio of 310% in the 1-5 mm layer, the extremely low water-ratio of 12% in the 6-10 mm layer, and the rather low water-ratio of 40% in the 11-20 mm layer, the water-ratio gradient before the conservation procedure, of the item No 23112, showed about the same water-ratios, c. 80%, as the corresponding values of the “oak wood without obvious drying damage” (tables 8-XLII, 8-XXXVII).

After the conservation procedure the water-ratio of the 1-5 mm layer was still extremely high while an equalising towards c. 30% of the water-ratios of the internal layers, the 6-10 mm layer included, had occurred during the conservation procedure.

The PEG-ratio gradient started with 260% PEG in the 1-5 mm surface layer, while the PEG-ratio of the 6-10 mm layer was 30%. The corresponding PEG ratio values of the oak wood without obvious drying damage amounted to 95 and 80%. Deeper into the wood of item No 23112 the PEG-ratios went down to zero, while the corresponding PEG-ratios of the oak wood without obvious drying damage never went below 19%.

The PEG-concentration gradient of an assumed PEG solution inside the wood down to a depth of 10 mm into the wood resembles the corresponding PEG-concentration gradient of oak wood with no obvious drying damage, taken from the same batch. However, deeper into the wood practically no PEG can be identified in the object No 23112 (table 8-XLII).

Depth mm	Number of cores	water-ratio (%) before the conservation procedure	water-ratio (%) after the conservation procedure	PEG-ratio (%) after the conservation procedure	PEG-concentration (%) after the conservation procedure
1-5	1	310	230	260	53
6-10	1	12	33	30	48
11- 20	1	40	24	1	4
21-30	1	85	27	0	1
31-45	1	94	30	0	1

Table 8-XLII. The water-ratio gradient, before and after the conservation procedure, the PEG-ratio gradient and the PEG-concentration gradient after the conservation procedure inside the oak wood of sculpture No 23112.

Conclusions

An explanation to the fact that these oak objects with obvious drying damage dried further during the immersion treatment may be that the very dry 6-10 mm layer had extracted water from the internal layers. This movement of water molecules from the inside towards the surface of the wood may have discontinued the movement of PEG molecules towards the interior of the wood. The very dry 6-10 mm layer, thus, seems to have prevented PEG molecules to proceed into the wood.

The possibly existing PEG in the surface layers of the wood before the immersion conservation treatment may have enhanced the ability of the outer layers to attract water molecules from the deeper layers of the wood.

Pine wood

The pine wood object was a large sculpture that weighed 49.7 kg at the start of the immersion conservation procedure. After the conservation procedure it weighed 52.4 kg. Thus, it had gained weight during the conservation period which indicated that it had not been waterlogged when placed in the conservation tank.

The water-ratio before the conservation procedure of 26% in the 1-5 mm surface layer and the water-ratio gradient 10%, 16% and 13% in the three layers between 11 and 45 mm depth in the wood, places this object in the same category as the oak objects labelled "oak with obvious drying damage".

The PEG-concentration gradient of an assumed PEG solution inside the pine wood after the immersion conservation procedure shows values from 47% in the 1-5 mm surface layer in a descending gradient to 31% in the middle of the wood.

Like in the case with the "oak material with obvious drying damage" there may exist a possibility that the low water-ratio values of the 1-5 mm surface layer and three layers between 11 and 45 mm depth before the immersion conservation treatment may have caused some damage to the diffusion of PEG and water molecules into the pine material. This, however, was contradicted by the gradients of PEG- and water-ratios in the pine object which both show high ratio values. The PEG-ratios ranged from a very high value in the 1-5 mm layer to c. 80% in the two layers between 6 and 20 mm and with no PEG-ratio value below 35% inside the pine wood.

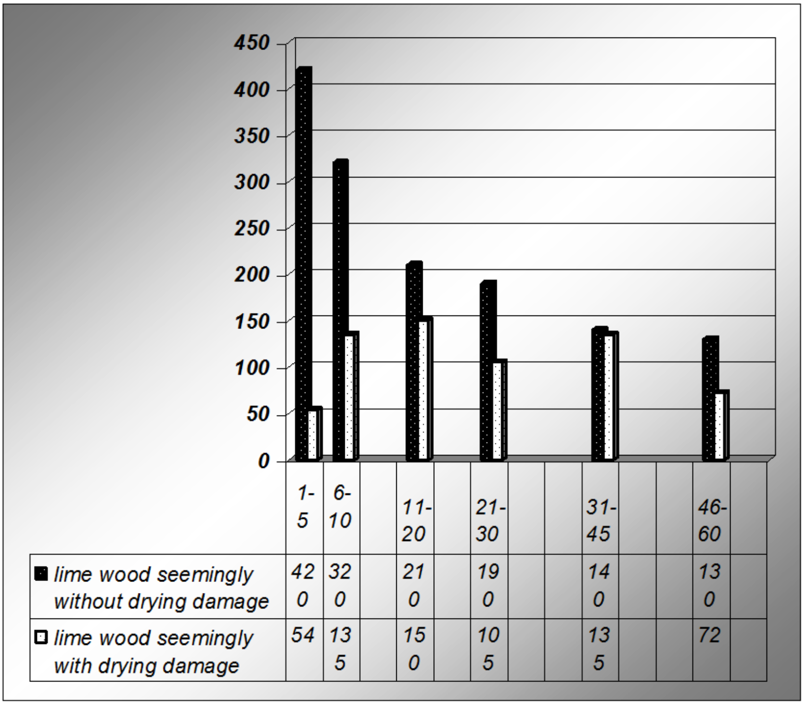
Despite the fact that the water-ratio gradient before the immersion conservation treatment contained a surface layer with 26% and 3 layers with values below 16% inside the wood no water-ratio values below 72% were found after the conservation procedure (table 8-XLIII).

Depth mm	Number of cores	water-ratio (%) before the conservation procedure	water-ratio (%) after the conservation procedure	PEG-ratio (%) after the conservation procedure	PEG-concentration (%) after the conservation procedure
1-5	1	26	140	125	47
6-10	1	61	95	80	46
11- 20	1	10	100	77	44
21-30	1	16	90	64	41
31-45	1	13	72	45	39
46-60	1	92	79	35	31
61-80	1	91	110	50	31

Table 8-XLIII. The water-ratio gradients, before and after the conservation procedure, the PEG-ratio gradient and the PEG-concentration gradient after the conservation procedure inside the pine wood.

Lime wood

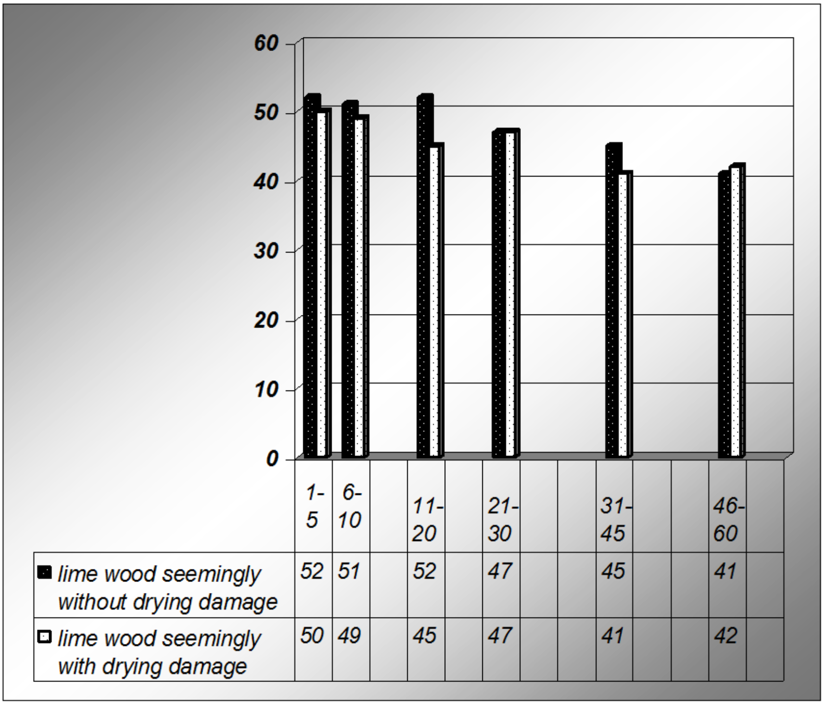
Even the 2 of the 3 wood-cores from the lime wood seemed to have dried before the immersion conservation treatment, showing water-ratios as low as c. 50% in the 1-5 mm surface layer, while the third wood-core showed a water-ratio of 420% in its corresponding layer. Since most of the interior layers show water-ratio values well above 100% it is possible that the drying may have affected only the 1-5 mm surface layer (table 8-XLIV).



	1-5	6-10		11-20		21-30			31-45			46-60	
■ lime wood seemingly without drying damage	420	320		210		190			140			130	
□ lime wood seemingly with drying damage	54	135		150		105			135			72	

Table 8-XLIV. The water-ratio gradients inside the lime wood before the conservation procedure.

The PEG-concentration of the assumed PEG-solution inside the wood of the "lime wood, seemingly with drying damage" from the surface down to 20 mm depth in the wood shows the series of PEG concentrations 50, 49 and 45%, while the corresponding PEG-concentration of the "lime wood seemingly without drying damage" was 52, 51 and 52% i.e. the same PEG-concentration as the surrounding conservation solution (table 8-XLV).



	1-5	6-10		11-20		21-30			31-45			46-60	
■ lime wood seemingly without drying damage	52	51		52		47			45			41	
□ lime wood seemingly with drying damage	50	49		45		47			41			42	

Table 8-XLV. The PEG-concentration gradients of an assumed PEG solution inside the lime wood after the conservation procedure.

The values of the PEG-ratio gradients of both of the “lime wood seemingly without drying damage” and the “lime wood seemingly with drying damage” were rather high and possibly sufficient as to dimension stabilising effect. The difference in PEG-ratio between the two groups may be due to the fact that the two items of the group “seemingly with drying damage” were thinner by c. 80 mm than the item labelled “seemingly without drying damage”. No further conclusions about diffusion of PEG- and water molecules have been drawn from the lime wood in this batch of material (table 8-XLVI).

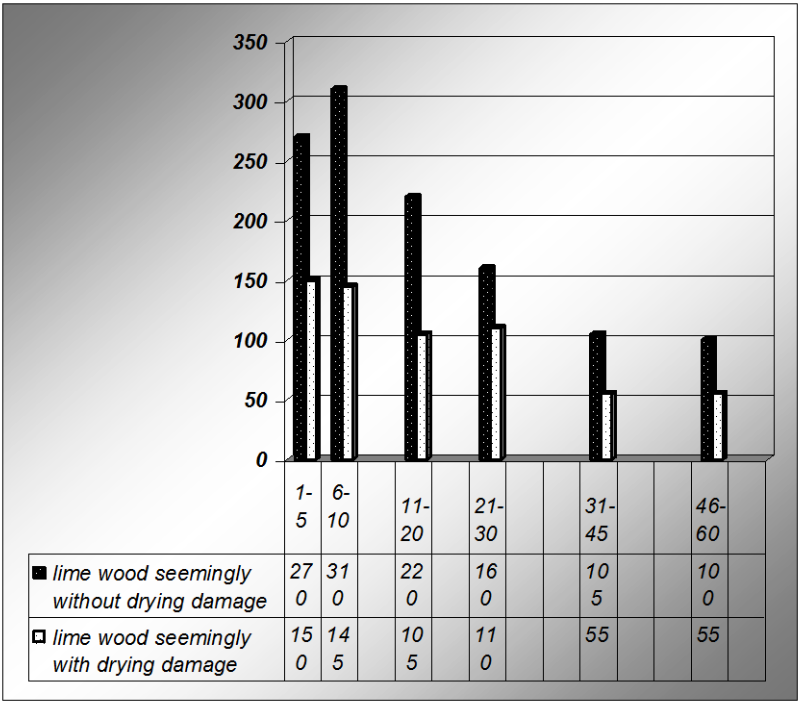
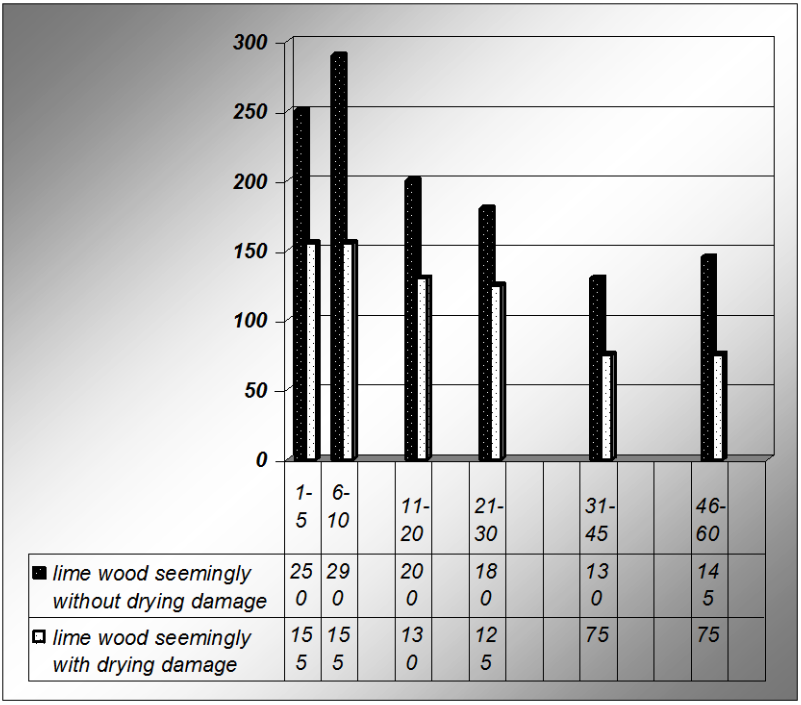


Table 8-XLVI. The PEG-ratio gradients inside the lime wood after the conservation procedure.

Like the PEG-ratios, the water-ratio values of the material labelled "seemingly with drying damage" were lower than the water-ratio values of the material labelled "seemingly without drying damage" after the immersion conservation treatment (table 8-XLVII).



	1-5	6-10		11-20		21-30			31-45			46-60	
■ lime wood seemingly without drying damage	250	290		200		180			130			145	
☐ lime wood seemingly with drying damage	155	155		130		125			75			75	

Table 8-XLVII. The water-ratio gradients inside the lime wood after the conservation procedure.

Conclusions

Since the water-ratio values in the surface of the lime wood “seemingly with drying damage” was higher after, than before the conservation treatment in most of the layers, the assumption that the material had dried before the immersion conservation procedure seemed to be justified (tables 8-XLVII, 8-XLIV).

8.4.6. The sixth batch of material at a complete immersion conservation programme

The 931 items selected for this batch were large construction materials, components of gun-carriages, sculptures and fractions of sculptures and small objects. The items weighed between c. 150 kg and c. 150 g. The items were placed in the 42m^3 tank. The three wood species, oak, pine and lime wood were represented among the material.

The conservation procedure was performed with PEG 4000 and the PEG-conservation programme was divided into two parts of different sizes of the daily PEG-increments. The first part of the programme was proceeding during 16.5 month with 1/12% daily increments to a total of 35% PEG-concentration added to the solution. This part finished at 30% PEG-concentration in the conservation solution. The second part of the programme was proceeding during the succeeding 6 months with 1/6% daily increments to a total of 74%, that produced an actual PEG-concentration of 51% in the conservation solution (figure 8-31).

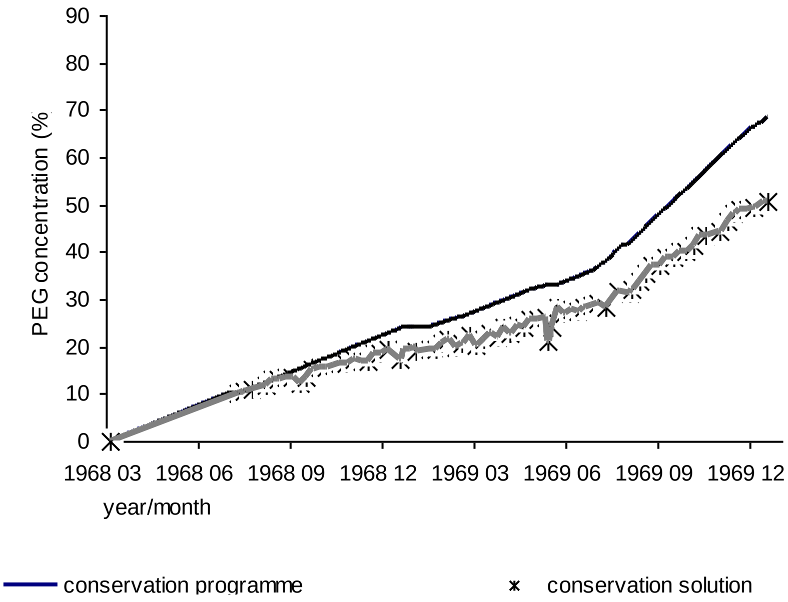


Figure 8-31. PEG-concentration of the conservation programme and the conservation solution of the sixth batch of material at a complete conservation programme.

The total duration of the conservation procedure was 22.5 months. However, the conservation programme was stopped for a couple of weeks after 10 months to get the construction components of the bow of the Vasa removed from the conservation tank.

Wood-cores were drilled from 41 objects before the conservation programme was started. Eleven of these belonged to the construction components of the bow, 12 wood-cores were taken from construction timbers that were going to be treated at the complete conservation programme, 18 wood-cores were taken from sculptures, where oak, pine and lime wood were represented. This made comparisons possible between sculptured and not sculptured oak wood and between carved wood of the three species oak, pine and lime wood.

8. IMMERSION TREATMENT WITH PEG OF LOOSE WOODEN OBJECTS AND CONSTRUCTION TIMBERS FROM THE VASA

Oak wood construction components

The construction material that had been treated at the complete conservation programme was waterlogged when it was brought to the tank for immersion conservation. The water-ratio gradient at that time showed the very high value of 270% in the surface layer and a gradient from 150 to 115 % inwards from the layer beneath the surface layer (table 8-L). This provided optimal conditions for diffusion of PEG-molecules. The PEG-concentration gradient produced started at 48% in the 1-5 mm surface layer that was in close contact with the surrounding conservation solution which arrived at 51% PEG as end concentration. The PEG-concentration gradient of assumed PEG solutions inside the interior layers of the wood made a dip of c. 10 percentage units at each layer going further inwards, ending with a 3% PEG solution at the middle of the width of the material (table 8-XLVIII).

The PEG-ratio gradient started with a value of 88% in the 1-5 mm surface layer, while the 6-10 mm layer showed as low a value as 35%. The remaining part of the gradient proceeded from a PEG-ratio of 23% in the 11-20 mm layer to values at, and below 10% PEG-ratio, deeper into the wood (table 8-XLVIII). This level is not as much as in the oak material "without obvious drying damage" (section 8.4.5., table 8-XXXIX).

The water-ratios of the oak material of the present batch after the immersion conservation treatment were, however, of comparable level to those of the "oak without obvious drying damage" of the fifth batch (section 8.4.5., table 8-XXXIX).

Depth mm	Number of cores	water-ratio (%)		PEG-ratio (%)		concentration of an assumed PEG solution inside the wood (%)	
		before conser-vation	after conser-vation	before conser-vation	after conser-vation	before conser-vation	after conser-vation
1-5	12	270	87	0.0	88	0.0	48
6-10	12	150	51	0.0	35	0.0	38
11- 20	12	125	47	0.0	23	0.0	26
21-30	12	125	42	0.0	10	0.0	13
31-45	12	120	45	0.0	5	0.0	6
46-60	12	115	48	0.0	3	0.0	3

Table 8-XLVIII. The water-ratio gradient, The PEG-ratio gradient and the PEG-concentration gradient of an assumed PEG solution inside the oak wood construction material before and after the immersion treatment.

To be noted is that both of the conservation programmes and the conservation procedures of the present batch and of the fifth batch were identical. This enables comparison between the oak wood construction material of the present batch and the oak wood material "without obvious drying damage" of the fifth batch. The differences to be noted may be the larger dimensions of the material in the present batch, compared to the dimensions of the oak material of the fifth batch. This may explain why the oak wood of the present batch showed lower PEG-ratios than the oak wood of the fifth batch. However, the oak wood material "without obvious drying damage" of the fifth batch was not in a waterlogged state before treatment, that according to the assumptions made, ought to be a draw-back for the diffusion process of the PEG molecules.[199]

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[199] The term "waterlogged wood" denotes wood, that has been dried and used for manufacturing an object or a construction , and thereafter has been submerged into water and swelled to or near to its highest possible degree of water content (see Section "Terminology" of this dissertation).

8. IMMERSION TREATMENT WITH PEG OF LOOSE WOODEN OBJECTS AND CONSTRUCTION TIMBERS FROM THE VASA

Oak wood sculptures

In order to test the assumption that the PEG molecules would diffuse more easily into the wood of sculptured oak material containing a larger fraction of transverse surfaces, than into the wood of construction components made of oak timbers which have a rather low fraction of transverse surfaces, the two categories have been investigated separately.

Both of the construction material and the sculptured material, were waterlogged when brought to the tank for immersion conservation. Like the construction timbers the oak wood of the sculptures showed a very high water-ratio value, 260%, in the 1-5 mm surface layer and a gradient from 125 to 115 % inwards from the layer beneath the surface layer (table 8-XLIX).

Like the situation by the construction material the conditions for diffusion of PEG-molecules should have been excellent. The PEG-concentration gradient started at 50% in the 1-5 mm surface layer that was in close contact with the surrounding conservation solution with 51% PEG as end concentration. The PEG-concentration gradient of assumed PEG solutions inside the interior layers of the wood made a dive corresponding to 17 percentage units to the 6-10 mm layer. The gradient proceeded by downward steps of 10 percentage units to 13% in the 21-30 mm layer that was exactly the same value as in the corresponding layer of the construction timbers. The PEG-concentration of the two layers representing c. 30 mm at the middle of the width of the timber were c. 5% respectively in the construction material and in the sculptures (tables 8-XLVIII, 8-XLIX).

The PEG-ratio gradient started with a value of 105% in the 1-5 mm surface layer, while the 6-10 mm layer showed as low a value as 29%. The rest of the gradient proceeded from 17% to 3% PEG-ratio at the middle of the width of the material. The PEG-ratio values of the sculptures were lower than those of the construction material, a circumstance that had not been anticipated (tables 8-XLIX, 8-XLVIII).

The water-ratio gradient values after the immersion conservation treatment were of a magnitude of c. 40% of the water-ratio values before the conservation treatment. The water-ratio gradients of the sculptured oak material and the construction material made of oak in the batch after the immersion conservation treatment were, however, of comparable level to each other (tables 8-XLIX, 8-XLVIII).

The fact that the wood-cores were drilled from the back-side of the sculptures, however, may be considered as a circumstance in favour of the assumption that a greater fraction of transverse surfaces promotes the diffusion of PEG-molecules into the wood.

Depth mm	Number of cores	water-ratio (%)		PEG-ratio (%)		concentration of an assumed PEG solution inside the wood (%)	
		before conser-vation	after conser-vation	before conser-vation	after conser-vation	before conserva-tion	after conser-vation
1-5	10	260	100	0.0	105	0.0	50
6-10	10	125	47	0.0	29	0.0	33
11- 20	10	120	44	0.0	17	0.0	23
21-30	10	115	44	0.0	10	0.0	13
31-45	10	120	45	0.0	6	0.0	8
46-60	10	115	49	0.0	3	0.0	4

Table 8-XLIX. The water-ratio gradient, The PEG-ratio gradient and the PEG-concentration gradient of an assumed PEG solution inside the oak wood sculptures before and after the conservation procedure.

Pine wood sculptures

The PEG-concentration of the 1-5 mm and the 6-10 mm layers of the pine wood sculptures were nearly identical and nearly as high as in the surrounding conservation solution. The PEG-concentration gradient of the assumed PEG solutions inside the interior layers of the wood made a dive of c. 10 percentage units to the 11-20 mm layer. This was followed by a downward step of 13 percentage units to c. 25% in the 21-30 mm and the 31-45 mm layers. The PEG-concentration of the layer representing c. 15 mm at the middle of the width of the timber was 16% (table 8-L).

The PEG-ratio gradient of the pine wood started at 100% in the 1-5 mm layer and twice made substantial dives of c. 30 percentage units PEG-ratio to the 6-10 mm and to the 11-20 mm layer. The PEG-gradient proceeded inwards into the wood by a c. 10% step to 25-30% PEG-ratio that prevailed in the two layers from 21 to 45 mm depth in the wood. The lowest PEG-ratio value, 16%, prevailed in the area around the midpoint of the width of the wood (table 8-L).

The water-ratio gradient after the immersion conservation procedure showed values of c. half the magnitude of the values before the conservation treatment in the 3-4 layers inwards from the surface of the wood. The water-ratios of the consecutive interior layers had retained as much as 70% of the water-ratios before the conservation treatment, and did in fact not form a descending but rather an ascending gradient towards the middle of the width of the wood (table 8-L).

Depth	Number of cores	water-ratio (%)		PEG-ratio (%)		concentration of an assumed PEG solution inside the wood (%)	
mm		before conservation	after conservation	before conservation	after conservation	before conservation	after conservation
1-5	5	200	120	0.0	100	0.0	48
6-10	5	160	76	0.0	68	0.0	47
11- 20	5	130	66	0.0	40	0.0	38
21-30	5	135	73	0.0	29	0.0	25
31-45	5	135	81	0.0	26	0.0	24
46-60	5	135	94	0.0	16	0.0	16

Table 8-L. The water-ratio gradient, the PEG-ratio gradient and the PEG-concentration gradient of an assumed PEG solution inside the pine wood before and after the immersion treatment.

Lime wood sculptures

The PEG-concentration in the 1-5 mm and the 6-10 mm layers, respectively, of the lime wood sculptures were as high as the PEG-concentration in the surrounding conservation solution. Even the PEG-concentration of the 11-20 mm layer might be added to this group. The PEG-concentration in the remaining four layers showed a steady value a little above 40% (table 8-LI).

The PEG-ratios of the lime wood sculptures show a gradient that in three steps, each of c. 30 percentage units, proceeded from a value of 180% in the 1-5 mm layer to a value of 97% in the 21-30 mm layer. The PEG-gradient proceeded inwards into the wood by a c. 20% step to 70-75% PEG-ratio that prevailed in the three layers from 31 to 80 mm depth in the wood (table 8-LI).

The water-ratio gradient after the immersion conservation procedure showed values of c. half the magnitude of the values before the conservation treatment in the three layers from 5 to 20 mm depth into the wood. The water-ratios of the succeeding interior layers inwards to the middle of the width of the sculpture had retained c. 60% of the water content before the conservation treatment (table 8-LI).

Depth	Number of cores	water-ratio (%)		PEG-ratio (%)		concentration of an assumed PEG solution inside the wood (%)	
mm		before conser-vation	after conser-vation	before conser-vation	after conser-vation	before conser-vation	after conser-vation
1-5	3	310	180	0.0	180	0.0	51
6-10	3	330	160	0.0	150	0.0	50
11- 20	3	310	140	0.0	125	0.0	46
21-30	3	220	125	0.0	97	0.0	43
31-45	3	180	110	0.0	77	0.0	41
46-60	3	170	105	0.0	71	0.0	40
61-80	3	170	105	0.0	74	0.0	41

Table 8-LI. The water-ratio gradient, the PEG-ratio gradient and the PEG-concentration gradient of an assumed PEG solution inside the lime wood before and after the immersion treatment.

Evaluation of the diffusion of PEG and H_2O in sculptures of oak, pine and lime wood, respectively

The situation that wood-cores have been drilled from a number of sculptures of each of the three wood species, oak, pine and lime wood, before as well as after the immersion conservation procedure and the fact that the wood of all of these sculptures was waterlogged when brought to the conservation tank made possible an evaluation of the diffusion of PEG and H_2O-molecules into or out of the wood during the immersion conservation procedure.

Depth	Oak wood before the conservation	Oak wood after the conservation	Pine wood before the conservation	Pine wood after the conservation	Lime wood before the conservation	Lime wood after the conservation
mm	Water-ratio (%)	Solution-ratio (%)	Water-ratio (%)	Solution-ratio (%)	Water-ratio (%)	Solution-ratio (%)
1-5	260	205	200	220	310	360
6-10	125	76	160	144	330	310
11-20	120	61	130	106	310	265
21-30	115	54	135	102	220	222
31-45	120	51	135	107	180	187
46-60	115	52	135	110	170	176

Table 8-LII. The gradient of water-ratio before the conservation procedure and the ratio of an assumed PEG solution after the conservation procedure inside the wood of the sculptures made of oak, pine, and lime wood, respectively.

The conservation process is supposed to involve replacement of water in the wood by PEG. If this is going to happen, it is necessary for water molecules to leave the waterlogged wood. This seemed to happen to different proportions in the three different wood species, oak, pine and lime wood, that have been investigated in the present conservation batch. In the oak wood sculptures it is obvious that a large part of the water molecules have diffused out of the wood without being replaced by PEG-molecules, in the pine wood sculptures this also may have happened, and in the lime wood sculptures the water diffusing from the wood, seem to have been completely compensated by PEG (table 8-LII).

The obvious starting-point for investigating the movement of the water molecules would be the waterlogged state of the wood before the conservation procedure. In order to eliminate the possibility that differences of the densities of the wood species, and differences of the densities at different depths in the wood of the same wood species, made that the water-ratios did not provide a true representation of the amount of water, these have been transformed into actual amount of water in the wood. This has been expressed by figures of water-ratio (table 8-LII), and by figures of actual amount of water in the different layers of the wood of the wood species oak, pine, and lime wood (figure 8-32).[200]

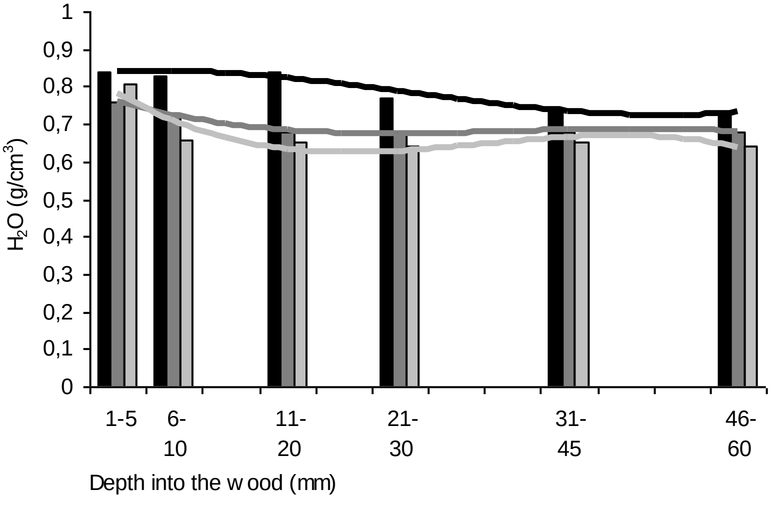

Figure 8-32. Gradients of actual quantities of water in the wood of the sculptures made of lime, pine and oak wood, respectively, before the conservation procedure. Trend-lines; least square fittings.

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[200] Esping, 1992, pp 34-35.

The calculations of the densities of the wood have been performed, based on the assumption that the water-ratios of the wood before the conservation treatment, were identical with the (u_{max}) values. It should, however, be noted that the drying method used at the Vasa conservation laboratory may have produced somewhat lower figures of water-ratio than the standard drying method, that in turn may have produced a little too high values when calculating the densities of the wood. The grand mean of the densities of the wood of the sculptures amounted for the oak wood to 0.51 g/cm^3, for the pine wood to 0.48 g/cm^3 and for the lime wood to 0.36 g/cm^3.

The calculations of the actual quantities of PEG and water in the separate layers of each of the wood species oak, pine, and lime wood have been performed by using the ratios found by analysis and the calculated densities of the wood.

In the diagram the graph representing the quantity of water in the oak wood showed the lowest values, the graph representing the pine wood showed slightly higher values and the graph representing the lime wood showed a considerably higher quantity of water than those of the oak and the pine wood (figure 8-32).

The two expected reactions, diffusion of water molecules out of the wood and diffusion of PEG molecules into the wood during the conservation procedure have been investigated. The result was that at the end of the treatment the oak wood in each layer had lost c. 60% of its amount of water before the treatment, the pine wood and the lime wood had as an average lost around 45% of their amounts of water before treatment. In these cases a little more in the layers at the surface as a gradient existed, with figures around 50% at the surface and figures below 40% in the layers near the middle of the width of the wood (figure 8-33)

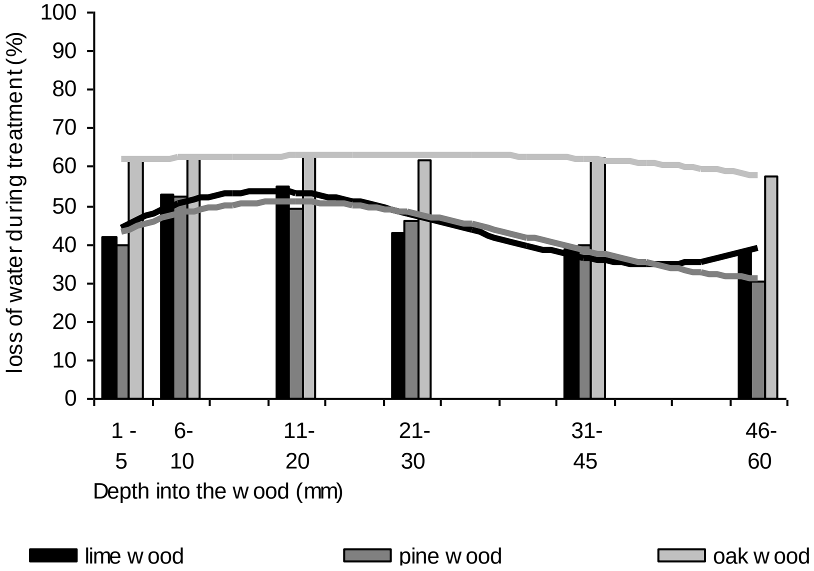

Figure 8-33. Gradients of loss of water from the wood as a percentage of the original quantity of water, during treatment of the sculptures made of lime wood, pine wood, and oak wood, respectively. Trend-lines; least square fittings.

The oak wood seemed to have lost about the same amount, 0.4 g/cm^3, of water along the wood core, leaving c. 0.25 g/cm^3 remaining at each level at the termination of the conservation programme (figures 8-34, 8-35). The pine wood had lost c. 0.3 g/cm^3 along most part of the wood core, but only 0.2 g/cm^3 at the middle of the width of the sculpture leaving c. 0.35 g/cm^3 water in the outer half of the wood core. Inwards into the depth of the wood the factual water values were increasing that ended with 0.47 g/cm^3 at the middle of the width of the sculptures (figures 8-32, 8-33). The lime wood had lost c. 0.5 g/cm^3 in the outer third of the wood core and c. 0.3 g/cm^3 in the remaining two thirds of the wood-core, leaving a rather straight graph of retained water content after the conservation procedure of 0.45 g/cm^3 in the interior levels (figures 8-34, 8-35).

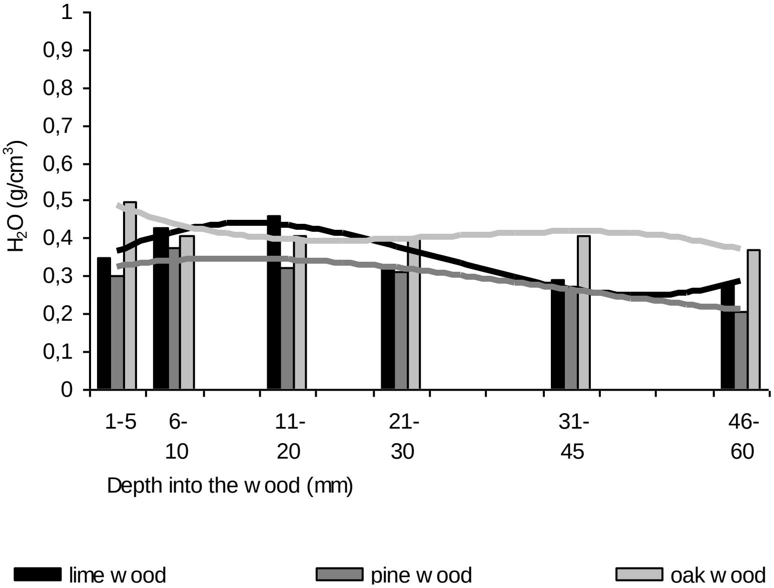

Figure 8-34. Gradients of actual loss of water from the wood during treatment of the sculptures made of lime wood, pine wood, and oak wood, respectively. Trend-lines; least square fittings.

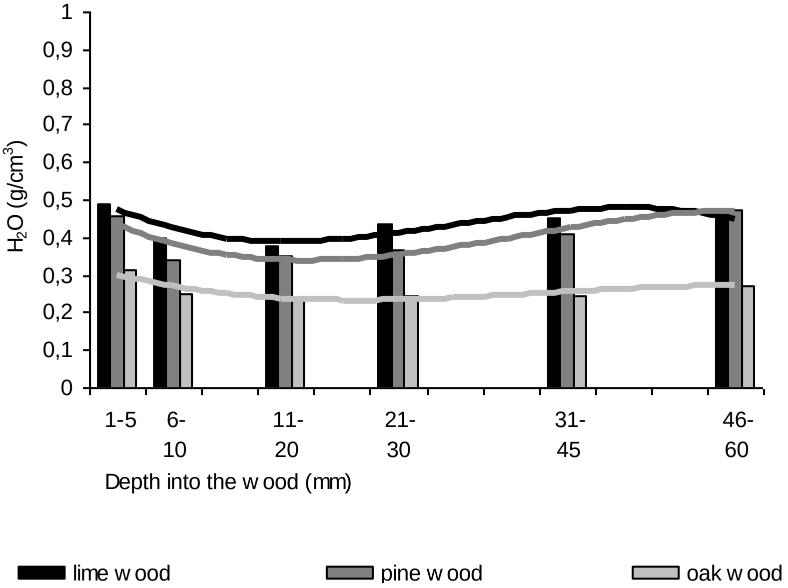

Figure 8-35. Gradients of actual quantities of water in the wood of the sculptures made of lime, pine and oak wood, respectively, after the conservation procedure. Trend-lines; least square fittings.

Some of the lost water had been replaced by PEG. In the case of the oak wood, 66 and 37 % of the lost water in the surface layers had been replaced by PEG, a steep gradient inwards showed a gradually smaller fraction of replacement. At the middle of the width of the wood only 5% of the lost water had been replaced by PEG (figure 8-36, oak wood).

PEG seems to have replaced more water than was lost from the respective 1-5 mm surface layer of the pine wood as well as the lime wood. In the layers II and III in the pine and lime woods c. 85 and 70% of the lost water had been replaced by PEG. Deeper into the pine wood the fraction of replacement decreased to c. 50% and landed on 39% at the middle of the width of the wood. In the interior layers of the lime wood the fraction of replacement rose to c. 100%, i.e. all of the lost water was replaced (figure 8-36, pine wood and lime wood).

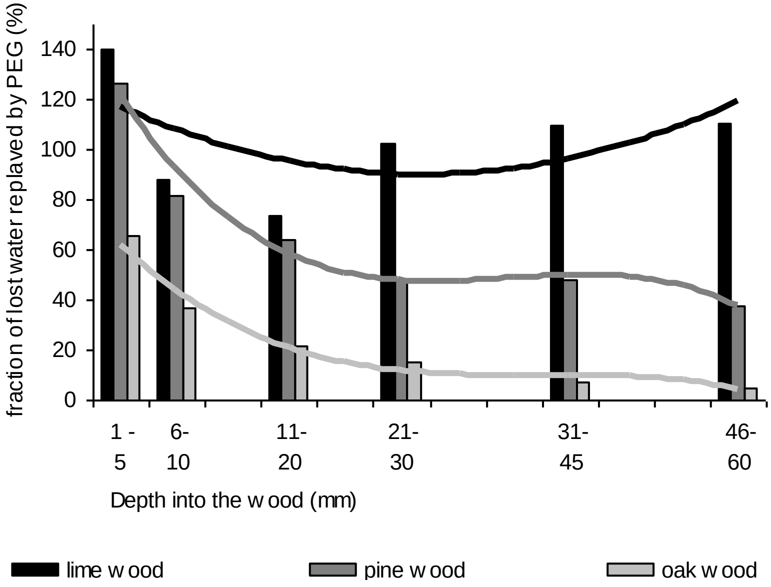

Figure 8-36. Gradients of the fraction of lost water that has been replaced by PEG in the sculptures made of lime wood, pine wood, and oak wood, respectively. Trend-lines; least square fittings.

The gradients based on the actual amounts of PEG retained in each layer of the wood showed a corresponding order of oak wood, pine wood and lime wood to the gradients of the fraction of lost water replaced by PEG (figure 8-36). The oak wood has placed itself near the bottom line especially beyond 20 mm depth into the wood (figure 8-37).

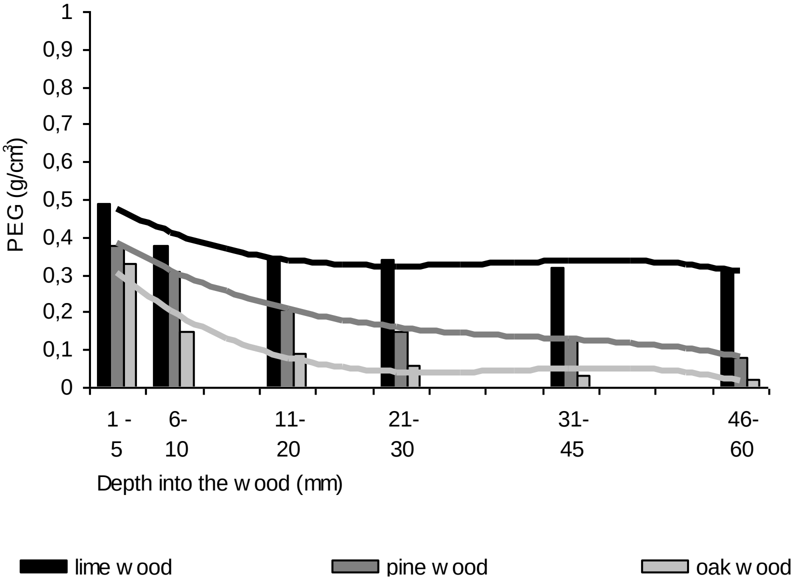

Figure 8-37. The gradients of the amounts of PEG (g/cm3) in the successive layers from the surface of the wood to the mid point of the width of the sculptures made of lime wood, pine wood, and oak wood, respectively. Trend-lines; least square fittings.

Evaluation of the diffusion of PEG and H_2O in sculptures made of oak compared to construction components made of oak

The assumption had been brought forward that the PEG molecules might diffuse more easily into the wood of sculptured oak material which contains a larger fraction of transverse surfaces compared to construction components made of oak timbers which have a rather low fraction of transverse surfaces. Since the present batch contained both of the categories the assumption may be tested.

The two categories show almost identical PEG-concentration gradients of their respective assumed PEG solutions inside the wood at the termination of the conservation treatment. Apart from PEG molecules diffusing into the wood this may, however, be obtained by a greater number of water molecules leaving the wood during a period when a lower number, or possibly no PEG molecules diffuse into the wood. A comparison of the sums of the ratios of PEG and water, that is considered as a PEG solution inside the wood, after the conservation procedure and a comparison of the water-ratios before the conservation procedure, indicate that the densities of the two categories are practically identical, which shows convincingly that there is no such difference between these two oak material categories (table 8-LIII) .

Depth	Construction oak before conservation	Construction oak after conservation	Sculptures of oak before conservation	Sculptures of oak after conservation
mm	Water-ratio (%)	Solution-ratio (%)	Water-ratio (%)	Solution-ratio (%)
1-5	270	17	260	205
6-10	150	86	125	76
11- 20	125	70	120	61
21-30	125	52	115	54
31-45	120	50	120	51
46-60	115	51	115	52

Table 8-LIII. The gradient of the water-ratios before the conservation procedure and the gradient of the ratios of an assumed PEG solution after the conservation procedure in the wood of the oak construction material and the sculptures made of oak, respectively.

The 4th conservation procedure of construction material for refitting into the Vasa hull

The batch also contained some construction material for refitting of the bow onto the Vasa hull. This part of the batch may be considered as the "fourth conservation procedure of construction material for refitting into the Vasa hull". The material for refitting had been given a rather long conservation period of 10 months from March 1968 to January 1969. At the time the material was removed from the conservation tank, the conservation programme had arrived at 25% while the actual PEG-concentration of the conservation solution was 20%.

Evaluation of the diffusion of PEG and water in the construction material for the bow during the conservation period will have to take into consideration the fact that the material before the immersion conservation treatment had been stored underneath the Vasa hull. Thus, during the storage period it had been subjected to the conservation solution that was dripping off the hull. Depending on this, PEG contamination might be suspected, that was the reason why PEG analysis of the wood cores, drilled before the immersion conservation treatment was performed.

The concentration of the assumed PEG-solution inside the 1-5 mm layer of the wood had not reached the value of the surrounding conservation solution but had increased from 9 to 15%. The PEG-concentration gradient values when moving towards the middle of the width of the wood, ranging from 4 to 1, after the conservation period, were only a little higher than the corresponding values before the conservation period (table 8-LIV).

The values of the PEG-ratio of the 1-5 mm surface layer had increased from 17 to 25% during the 10 months conservation period. The PEG-ratios from the 6-10 mm layer towards the middle of the width of the timbers ranged from 4 to 1% after the conservation procedure (table 8-LIV).

Contrary to the earlier conservation treatments of material for refitting into the Vasa hull, the material of the batch had not dried during the storage period before the immersion conservation procedure. It displayed a water-ratio in the 1-5 mm surface layer of 160% before the treatment. This value had decreased to 130% during the conservation period. The water-ratios towards the middle of the width of the timbers amounted to between 105 and 115% before the treatment and had lost as little as between 5 and 15 percentage units, i.e. c. 13% during the conservation procedure (table 8-LIV).

Depth mm	Number of cores	water-ratio (%)		PEG-ratio (%)		concentration of an assumed PEG solution inside the wood (%)	
		before conser-vation	after conser-vation	before conser-vation	after conser-vation	before conser-vation	after conser-vation
1-5	11	160	130	17	25	9	15
6-10	11	105	99	2	4	2	4
11- 20	11	115	100	2	3	1	3
21-30	11	115	100	2	4	1	3
31-45	11	110	105	1	2	1	2
46-60	11	115	101	2	1	1	1

Table 8-LIV. The water-ratio gradient, the PEG-ratio gradient and the Concentration gradient of an assumed PEG solutions inside the oak wood construction material for the bow of the Vasa before and after the immersion treatment.

Comparing the PEG-ratios the oak material of the previous batches of material for refitting into the Vasa hull (sections 8.3.1., 8.3.2., 8.3.3.), each of which was treated for a three months period. The 10 months treatment period of the present batch seemed not to have increased the amount of PEG in the wood. It may be noted that the water-ratios of the oak material of these previous batches were lower after treatment, as well as before treatments where analytical values existed.

Considering the conservation of oak construction material for refitting into the Vasa hull as representing the first half of conservation treatment and the oak construction parts of the same batch that took part in the entire procedure as representing the second half of the treatment indicates that the entire conservation process may have taken place during the second half of the conservation procedure (tables 8-XLVIII, 8-LIV) .

8.4.7. The seventh batch of material at a complete immersion conservation programme

The 2.5 m^3 tank was used for this immersion conservation treatment. Since most of the material consisted of fragments, broken from larger objects like sculptures and fitting pieces, it was important that the resulting dimensional changes would be as small as possible.

The batch consisted of 191 items, mostly parts of sculptures, fitting pieces and fragments of furniture and household objects. Most of these were rather small items that weighed between 500 g and 3-4 kg. A few items weighed c. 10 kg. The small items were tied to a wooden lattice in order not to get mechanically damaged during the conservation procedure.

PEG 4000 was chosen as preservative. In order to put as little strain as possible to the wet oak wood by the conservation procedure the PEG-increment programme chosen was, raising the PEG concentration by 1/12% increment per day, 7 days a week, during the whole treatment period. The conservation programme was continued until 73% PEG had been added to the conservation solution. This made the treatment period last for c. 2.5 years. The actual PEG-concentration of the conservation solution was 48% at the termination of the programme (figure 8-38).

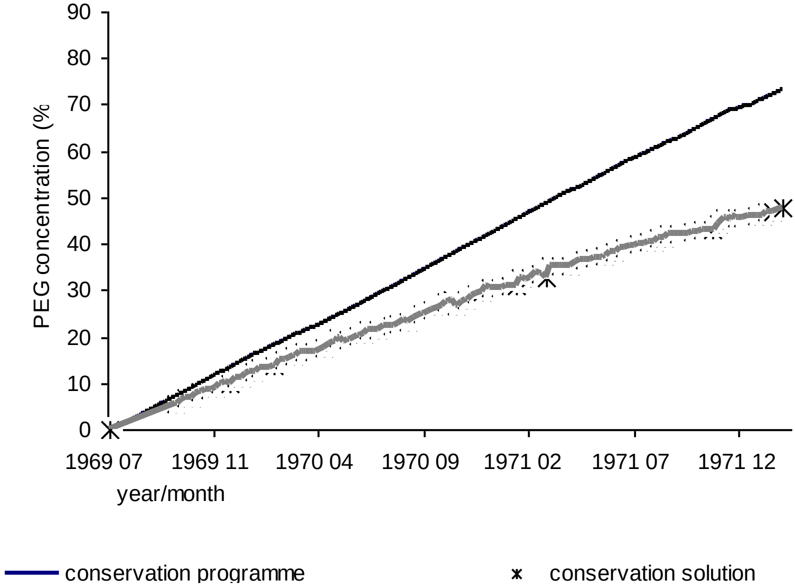

Figure 8-38. PEG-concentration of the conservation programme and the conservation solution of the seventh batch of material at a complete immersion conservation programme.

Wood-cores were drilled from 14 objects before the conservation programme was started. Nine of these were made of oak wood, three items were made of lime wood and one item was made of pine wood. This made possible comparisons between wood of the three species of oak, pine and lime wood.

Oak wood material

The PEG-concentration of the assumed PEG solution inside the separate layers of the oak wood described a gradient with a faint downwards slope from 46 to 34% from the 1-5 mm surface layer to the middle of the width of the object. Comparing these PEG-concentration values with the corresponding values for oak wood of the previous batch (section 8.4.6.), the latter values displayed more of a gradient with rather low PEG-concentrations at the middle of the width of the wood.

The PEG-ratio values inside the oak wood were quite high, and they were not distributed as a declining gradient towards the middle of the width of the wood. Deeper into the wood than the 1-5, and the 6-10 mm layers, that showed PEG-ratios of 85 and 55%, respectively, there was a stable grand mean value of the PEG-ratios amounting to c. 43%. In the previous batch the PEG-ratios described a steeply declining gradient.

After the conservation procedure the oak wood of the batch displayed a c. 20 percentage units higher grand mean of the water-ratio values than the oak wood of the previous batch (tables 8-LV, 8-XLVIII - 8-XLIX).

Depth	Number of cores	water-ratio (%)		PEG-ratio (%)		concentration of an assumed PEG solution inside the wood (%)	
mm		before conser-vation	after conser-vation	before conser-vation	after conser-vation	before conser-vation	after conser-vation
1-5	10	174	94	0.0	85	0.0	46
6-10	10	144	70	0.0	55	0.0	42
11- 20	10	127	63	0.0	43	0.0	38
21-30	10	127	59	0.0	38	0.0	32
31-45	5	139	70	0.0	48	0.0	34

Table 8-LV. The water-ratio gradient, the PEG-ratio gradient and the PEG-concentration gradient of an assumed PEG solution inside the oak wood before and after the conservation procedure.

Pine wood material

The concentration gradient of the assumed PEG solution inside the pine wood object started at 47% inside the 1-5 mm surface layer and ended at 37% at the middle of the width of the object. Comparing these PEG-concentration values with the corresponding values for the pine wood of the previous batch (section 8.4.6.), the latter displayed more of a rather steep gradient with a difference of c. 30 percentage units between the surface layers and the middle point of the wood. The concentration of the assumed PEG solution inside the pine wood of the present batch also was closer to the PEG-concentration of the conservation solution, compared to the situation of the pine wood of the previous batch (section 8.4.6.).

The PEG-ratio at the middle of the width of the pine wood was c. twice the value found in the pine wood of the previous batch although the pine wood objects were of the same width in both of the batches.

The water-ratio values of the layers inside the wood, after the conservation procedure, were of comparable magnitude to each other in both of the present and the previous batches (tables 8-LVI, 8-L).

Depth	Number of cores	water-ratio (%)		PEG-ratio (%)		concentration of an assumed PEG solution inside the wood (%)	
mm		before conservation	after conservation	before conservation	after conservation	before conservation	after conservation
1-5	1	133	76	0.0	67	0.0	47
6-10	1	125	67	0.0	58	0.0	46
11- 20	1	143	84	0.0	59	0.0	41
21-30	1	141	82	0.0	54	0.0	40
31-45	1	107	67	0.0	39	0.0	37
46-60	1	70	61	0.0	35	0.0	37

Table 8-LVI. The water-ratio gradient, the PEG-ratio gradient and the PEG-concentration gradient of an assumed PEG solution inside the pine wood before and after the conservation procedure.

Lime wood material

The PEG-concentration values of the layers inside the lime wood, after the conservation procedure, were of comparable magnitude to each other in both of this and the previous batch. The PEG-concentration values in both of the cases were also very near to the concentration of the surrounding conservation solution.

The resulting PEG-ratios remained above 70% inside the wood which was also the situation of the lime wood of the previous batch.

The water-ratio values before conservation of the lime wood of the batch seem to be a few percentage units lower than the corresponding water-ratio values of the lime wood of the previous batch. However, both of the lime wood groups showed c.100% as water-ratio values at a depth into the wood around the middle of the width of the object after conservation (tables 8-LI, 8-LVII).

Depth mm	Number of cores	water-ratio (%)		PEG-ratio (%)		concentration of an assumed PEG solution inside the wood (%)	
		before conser-vation	after conser-vation	before conser-vation	after conser-vation	before conser-vation	after conser-vation
1-5	3	260	140	0.0	137	0.0	50
6-10	3	200	120	0.0	113	0.0	48
11- 20	3	190	95	0.0	72	0.0	43
21-30	3	190	97	0.0	71	0.0	42
31-45	3	190	102	0.0	76	0.0	42

Table 8-LVII. The water-ratio gradient, the PEG-ratio gradient and the PEG-concentration gradient of an assumed PEG solution inside the lime wood before and after the conservation procedure.

Summary

The PEG-concentration of the assumed PEG solution inside the separate layers of each of the oak wood, the pine wood and the lime wood were quite similar and described a gradient with a faint downwards slope from just below 50% to 30-40% from the 1-5 mm surface layer to the middle of the width of the objects (tables 8-LV - 8-LVII).

Compared to this gradient the PEG-concentration values of the oak wood and the pine wood of the previous batch (section 8.4.6.) showed a steeper gradient, with rather low PEG-concentrations at the middle of the width of the wood. The PEG-concentration in the consecutive layers of the lime wood this batch, however, seemed to be identical with the corresponding values of the previous batch (tables 8-XLIX – 8-LI).

Since the wooden materials of both of the batches seem to have been in a waterlogged state before the treatment, the grounds for the differences between the PEG-concentration inside the wood of the two batches may have been elsewhere. Two facts namely, the size of the objects and the differences in the conservation programmes, are obvious differences between the two batches.

The differences between the two batches were for one thing that in the present batch, the mean width of the objects made of oak wood was c. 30 mm less, and the mean width of the objects made of lime wood was c. 70 mm less than the widths of the corresponding material groups of the previous batch. The object made of pine wood was of the same width in both of the batches.

The other difference was between the conservation programmes. Both of these were performed with PEG 4000 but the rate of raising the PEG-concentration in the conservation solution of the previous batch (section 8.4.6.) was doubled during the later 1/3 of the conservation period, which also made the conservation period of that batch shorter by 25%.

Evaluation of the diffusion of PEG and H_2O in oak, pine and lime wood, respectively

The situation was, that wood-cores had been drilled from a number of items of each of the three wood species oak, pine and lime wood, before as well as after the immersion conservation procedure. The fact that the wood of these items was waterlogged when brought to the conservation tank has made possible an evaluation of the diffusion of PEG and H_2O-molecules into or out of the wood during the immersion conservation procedure.

As with the sculptures of the batch described in section 8.4.6. the calculations of the densities of the wood have been performed, based on the assumption that the water-ratios of the wood before the conservation treatment, were identical with the (u_{max}) values. It should, however, be noted that the drying method used at the Vasa conservation laboratory may have produced somewhat lower figures of water-ratio than the standard drying method that in turn may have produced a little too high values when calculating the densities of the wood. The grand mean of the densities of the wood of the items amounted to 0.49 g/cm^3 for the oak wood, to 0.49 g/cm^3 for the pine wood and to 0.37 g/cm^3 for the lime wood, respectively.

The calculations of the actual amounts of PEG and water in the separate layers of each of the wood species oak, pine, and lime wood have been performed by using the PEG- and the water-ratios found by analysis and the calculated grand mean densities of the wood.

In the diagram of the graph representing the actual amounts of water at each depth in the wood before the conservation treatment, the oak wood and the pine wood showed almost identical values of c. 0.65 g/cm^3 at each depth in the wood. The graph representing the lime wood showed c. 0.10 g/cm^3 higher amount of water than those of the oak and the pine woods (figure 8-39).

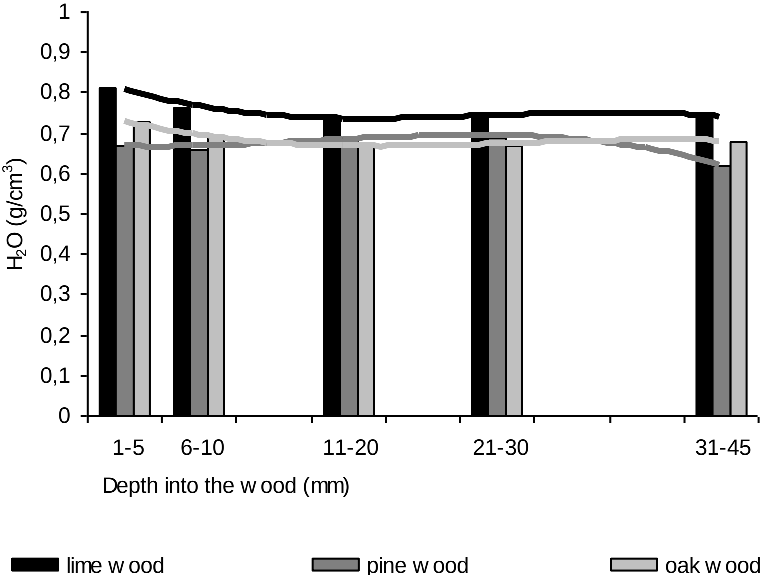

Figure 8-39. Water quantity gradients in the oak, pine and lime woods, respectively, before the conservation procedure. Trend-lines; least square fittings.

In the diagram the graph representing the actual amount of water after the conservation treatment, the lime wood and the pine woods showed almost identical values at the depth apart from the surface layers, the graph representing the oak wood showed water quantity values that were c. 15% lower than those of the lime and the pine woods (figure 8-40).

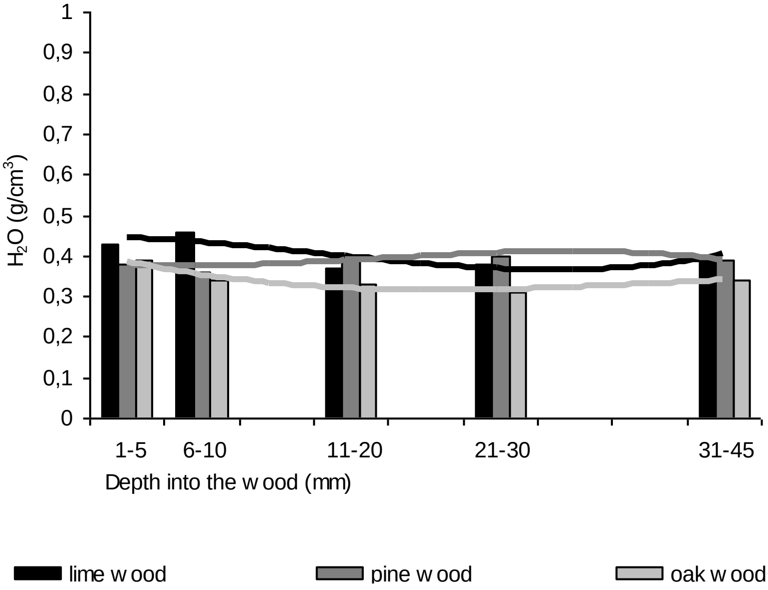

Figure 8-40. Water quantity gradients in the wood of the items made of lime wood, pine wood and oak wood, respectively, after the conservation procedure. Trend-lines; least square fittings.

This means that, from each depth, defined in the wood, during the conservation treatment the oak wood had lost c. 50%, the pine wood c. 40% and the lime wood between 45 and 50% of the water existing in the wood before the conservation treatment (figure 8-41).

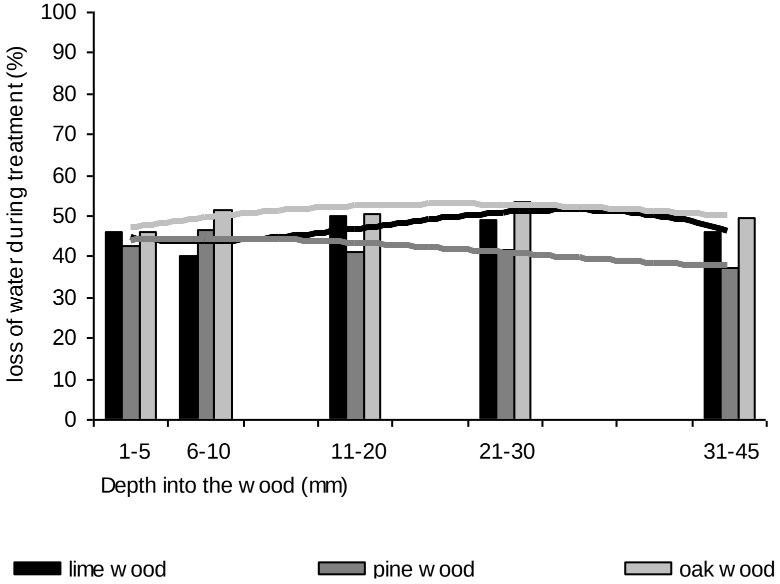

Figure 8-41. Gradients of loss of water from the wood as percentage of the original quantity of water, during treatment of the items made of lime wood, pine wood and oak wood, respectively. Trend-lines; least square fittings.

The actual loss of water from the oak wood and the lime wood at each depth in the wood, was almost identical, c. 0.35 g/cm³, while the pine wood displayed the lower figure of c. 0.29 g/cm³ of actual loss of water (figure 8-42).

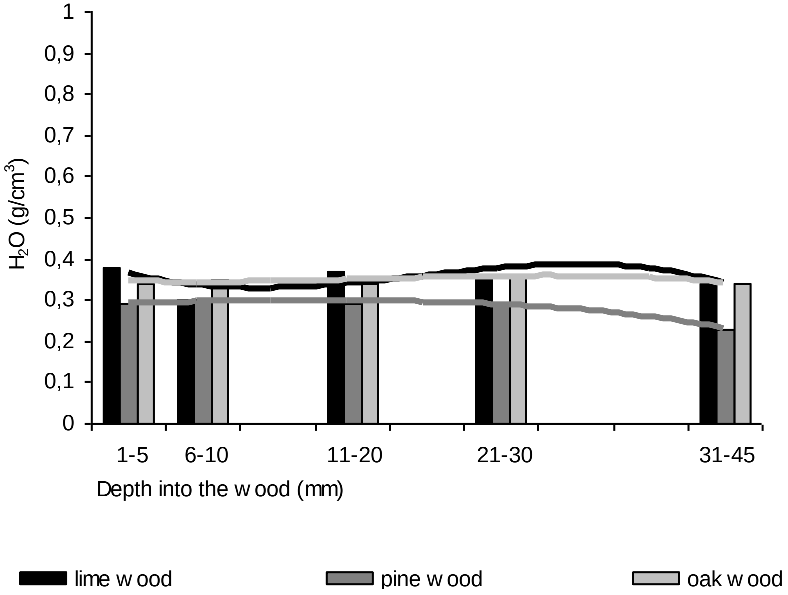

Figure 8-42. Gradients of actual loss of water from the wood during treatment of the items made of lime wood, pine and oak wood, respectively. Trend-lines; least square fittings.

Thus, the actual loss of water from the wood disclosed to be a feature that may discriminate between the hardwoods and the softwoods. The three wood species might be grouped into one group of hardwoods, consisting of the oak and the lime woods and the pine wood constituting the softwood group. Thus, the differences in actual loss of water between these groups may be attributed to the anatomical differences between hardwoods and softwoods.

The lost water had been replaced by PEG to a very high extent in the surface layers of all three wood species. In the three layers from 11 to 45 mm depth into the wood, PEG had replaced 94% of the water lost from the pine wood, 81% of the water lost from the lime wood and 65% of the water lost from the oak wood (figure 8-43).

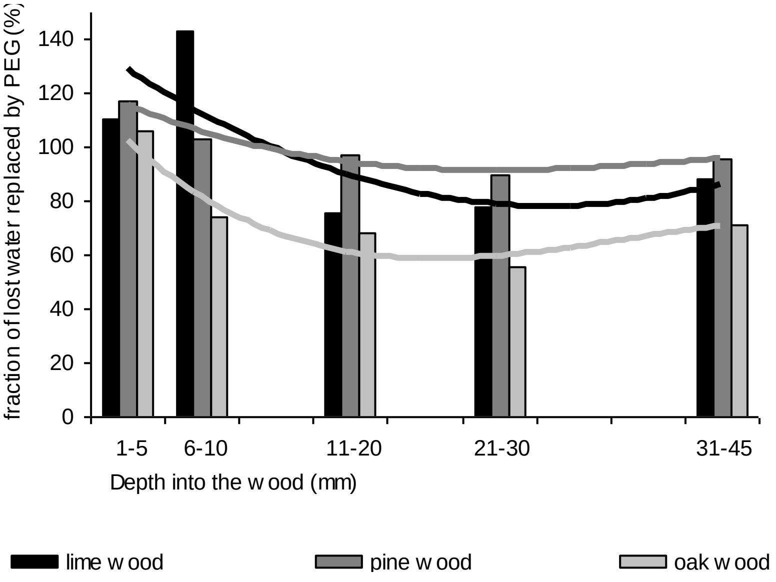

Figure 8-43. Gradients of the fractions of lost water replaced by PEG of the items made of lime wood, pine wood and oak wood, respectively. Trend-lines; least square fittings.

Considering the variation of the actual amounts of water between the species of hardwood during the conservation period the diffusion of PEG molecules from the conservation solution into the less concentrated PEG solutions inside each wood species, would, given enough time, lead to equal PEG-concentrations, but varying actual PEG amounts in the different wood species. This in combination with the fact that the oak wood displayed higher density than the lime wood may indicate an explanation to the fact that oak wood received a lower PEG-ratio than the lime wood.

The high retention of water in the pine wood, would likewise provide a high amount of PEG in the pine wood, and a higher PEG-ratio than in the oak wood of the same density.

Expressed as g/cm^3 the amount of PEG inside the inner layers of the lime wood, the pine wood and the oak wood, respectively, were 0.29, 0.25 and 0.22 g/cm^3, which expressed as PEG-ratio amounted to 73, 47 and 43% (figure 8-44).

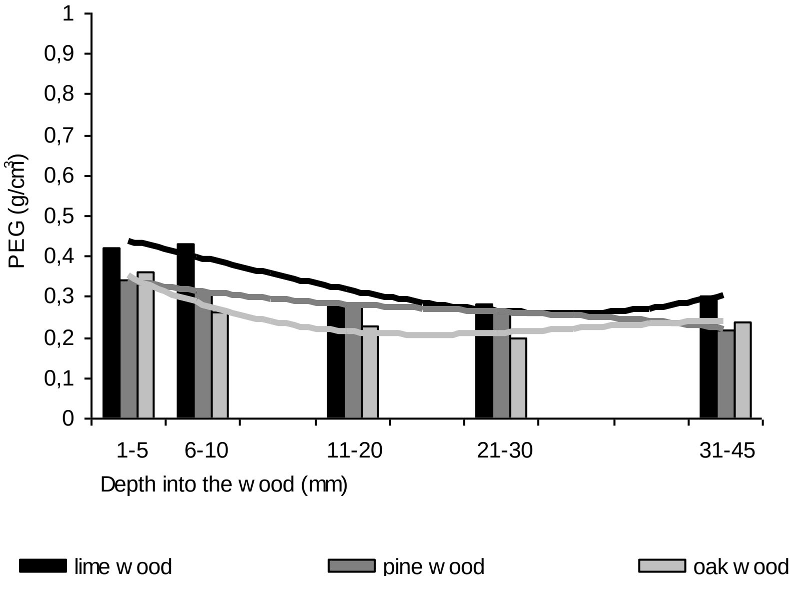

Figure 8-44. The gradients of the amounts of PEG (g/cm^3) in the layers in succession from the surface of the wood to the mid point of the width of the items made of lime wood, pine wood, and oak wood, respectively. Trend-lines; least square fittings.

Conclusion

Looking at the actual amount of PEG inside the wood instead of looking at PEG-ratios in wood of varying density might, together with the PEG-concentration of an assumed PEG solution inside the wood, provide a means of evaluating the path of PEG into the wood.

8.4.8. The eighth batch of material at a complete immersion conservation programme

The batch consisted of 286 parts of sculptures, fitting pieces and fragments of furniture and household objects. Most of these were very small items that weighed between 100 and 200 g. The items were tied to a wooden lattice in order not to get mechanically damaged during the conservation procedure.

The 2.5 m^3 tank was used for this immersion conservation treatment. Since most of the material consisted of fragments, broken from larger objects like sculptures, and other small pieces that should fit into special places, it was important that the dimensional changes would be as small as possible. The better penetration of the lower molecular weight PEG´s noted at the experimental work, inspired the choice of PEG 1000 to be added to the conservation solution during the initial half of the conservation period. PEG 1500 was added during the second half of the conservation period making the conservation solution into a mixture of PEG 1000 and PEG 1500. A small amount of PEG 800 had also been added at the very beginning of the conservation period.

Since the results of laboratory experiments had pointed to a slow pace of PEG-concentration raise as beneficial to the diffusion of PEG molecules into the wood structure, the conservation programme was performed by increments of 1/12% PEG, 7 days a week. The initial half of the conservation period continued for 13 months, and was concluded when the PEG raising programme had reached c. 35%. The actual PEG concentration was c. 28% at that time. The second half of the conservation period, when PEG 1500 was added, continued for 11 months, and was concluded when the PEG-concentration in the solution had reached 47%. The conservation programme showed that 59% PEG had been added to the solution at that time. Thus the conservation procedure lasted for c. 2 years (figure 8-45).

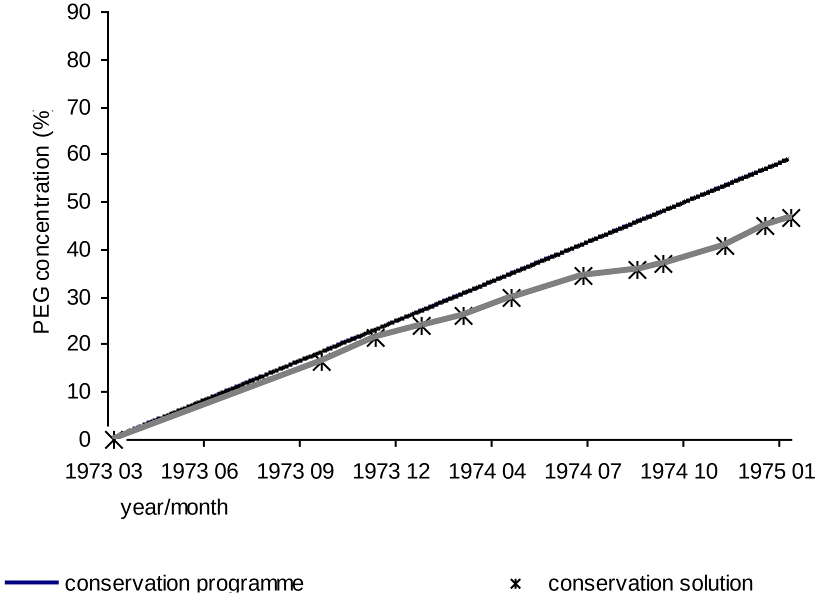

Figure 8-45. PEG-concentration of the conservation programme and the conservation solution of the eighth batch of material at a complete immersion conservation programme.

No core sampling was performed. The objects were removed from the conservation bath and were arranged for a surface coating by spray treatment.

8.5. Combined immersion- and spray treatment programmes

A vast material of small wooden items such as blocs for the rigging, staves for barrels, and small parts like fingers broken from sculptures was considered to be delicate and in need of a more cautious treatment compared to the heavy timbers and large objects. For this material a conservation programme that ended at c. 50% PEG-concentration was considered to cause less strain than proceeding to a high PEG-concentration. The duration of the immersion part of the conservation programme that had been extended to c. 2 years had now been reduced to c. 1.5 years. The immersion conservation period instead was followed by a second part of conservation treatment, consisting of a spray programme where a 45% PEG 4000 solution was sprayed, at first daily during a period of time to complete the conservation procedure, and then with a schedule of pre-set spray rounds that allowed the material to dry and also created a protective surface coating of PEG 4000. In this state the material has been stored until it was required for exhibition when the coating of PEG 4000 was removed by hot air.

Depending on that a substantial part of the material consisted of small objects vulnerable for damage by core drilling, no samples were taken from the batches of this type of material.

8.5.1. The first batch of material at a combined immersion- and spray treatment programme

The 34m^3 tank was used when starting the conservation process. The wooden objects, in total a number of 524 objects, mainly were parts of gun-carriages like the sides and bases and also wheels and axles. Considering the refitting of the gun-carriages, especially deformation of the wheels has to be avoided.

The Vasa conservation laboratory still considered the PEG 4000 as the molecular weight PEG most suitable for immersion treatment. In order to put as little strain as possible to the wet oak wood by the conservation procedure the PEG-increment programme chosen was raising the PEG concentration by 1/12% increment per day, 7 days a week during the whole treatment period. As high PEG-concentration in the conservation solution both at laboratory experiments and at conservation treatments had been found to cause shrinkage of the wood, the conservation programme would be finished when c. 60% PEG had been added to the conservation solution. This would result in a.two year period of conservation.

The conservation procedure was started and the programme had arrived at 10% PEG-concentration when there was a leakage in the pumping system and the conservation procedure had to be interrupted. The material was transferred to the 42m³ tank and the conservation procedure was continued again, after 8 months of interruption. Owing to the larger space and a reorganisation of the objects, the conservation solution was diluted to c. 5% PEG-concentration. This was not compenseted and the conservation programme was resumed at 10% PEG-concentration and continued to be finished at a PEG-concentration of 57%. Thus, instead, the PEG added to the conservation solution would in fact equalise a PEG-concentration of 52%. The conservation programme has been presented in the diagram as if no loss of PEG had occurred by the leakage (figure 8-46).

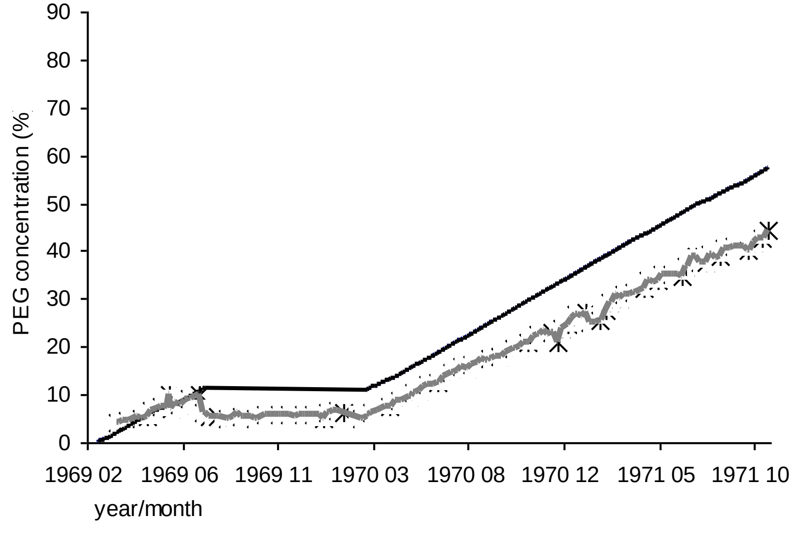

Figure 8-46. PEG-concentration of the conservation programme and the conservation solution of the first batch of material at a combined immersion- and spray-treatment programme.

Wood-core sampling was performed before and after the performance of the conservation procedure. At each time wood-cores were drilled from 26 large items, of which most of them had a width of more than 100 mm. The material had been kept submerged in water before the conservation which had prevented premature contamination with PEG. This also means that the water-ratio that had been determined before the conservation treatment had started might be equal to the maximum water content of the wood and thus present a means to calculate the density of the wood. The grand mean density of the core-sample was 0.57 g/cm^3.[201] This density value was higher by 0.08 g/cm^3 than the density value of the batch described in section 8.4.7.

The PEG-concentration gradient start with 37% in the 1-5 mm surface layer. This was a lower PEG-concentration than the 44% PEG-concentration of the surrounding conservation solution which means that equilibrium had not been reached between the inside and the outside solutions.

The remaining gradient displayed PEG-concentrations from 29 to 18%, which is the concentration that prevailed from 21 to 60 mm depth into the wood (table 8-LVIII). These PEG-concentration values were lower than the corresponding values of the batch described in section 8.4.7. (table 8-LV). It should, however, be noted that the oak wood material of the latter batch was thinner than the oak wood material of the batch.

The PEG-ratio gradient starting with 40% in the 1-5 mm surface layer and proceeding to 17% at the middle of the mean width of the objects of the core-sample were also lower than at the batch described in section 8.4.7.

The water-ratio values of the gradient of the present batch resembled the one of the batch of oak wood described in section 8.4.7. However, the actual loss of water from the wood-core sample of the present batch amounted to 0.25 g/cm^3 while the actual loss of water from the wood-core sample of the batch described in the section 8.4.7. had lost 0.35 g/cm^3.

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[201] Esping, 1992, pp 34-35.

Depth (mm)	Number of cores	water-ratio (%)		PEG-ratio (%)		concentration of an assumed PEG solution inside the wood (%)	
		before conservation	after conservation	before conservation	after conservation	before conservation	after conservation
1-5	26	110	68	0.0	40	0.0	37
6-10	26	110	64	0.0	28	0.0	29
11- 20	26	115	64	0.0	22	0.0	21
21-30	26	110	66	0.0	18	0.0	18
31-45	26	110	72	0.0	19	0.0	18
46-60	18	110	72	0.0	17	0.0	18

Table 8-LVIII. The water-ratio gradient, the PEG-ratio gradient and the PEG-concentration gradient of an assumed PEG solution inside the oak wood before and after the conservation procedure.

In the batch this loss had been almost totally replaced by PEG in the 1-5 mm surface layer, down to c. 40% replacement in the layers from 21 to 60 mm into the depth of the wood (table 8 – LIX).

The replacement of lost water by PEG in the batch described in the section 8.4.7. ranged between 74 to 71% from the 6-10 mm surface layer to the middle of the mean width of the wood-core sample with a couple of slightly lower fractions of replacement in-between (figure 8 - 43).

Depth mm	Number of cores	Lost water-ratio Gradient (%)	Fraction of lost water replaced with PEG (%)
1-5	26	42	95
6-10	26	46	61
11- 20	26	51	43
21-30	26	44	41
31-45	26	38	50
46-60	18	38	45

Table 8-LIX. The gradients of lost water and the gradient of fractions of this water replaced with PEG during the conservation procedure.

8.5.2. The second batch of material at a combined immersion- and spray-treatment programme

The 42 m^3 tank was charged with 2216 objects, minly very small items but several parts of the anchor-stocks, weighing c. 300 kg were also loaded into the tank. The main part of the objects weighed from c. 100 g to c. 2 kg. The material was mainly oak wood. In addition to the items selected for this batch some objects, that had belonged to the "first batch of material at a combined immersion- and spray-treatment programme" (section 8.5.1.), had been transferred to the "second batch of material at a combined immersion- and spray treatment programme".

The PEG 4000 was chosen for this batch of material. The PEG-conservation programme was performed by increments of 1/12% PEG, 7 days a week. The PEG-concentration development in the solution did not proceed as expected, but despite the fact that the increment programme was run to schedule, made a standstill at 10% PEG-concentration in the solution during a period of c. 4 months. No assumption as to the basis of this phenomenon has been suggested.

The programme was terminated when the PEG-concentration of the solution had reached c. 45%. During the conservation period, which lasted for 22 months, PEG equivalent to a PEG-concentration of 60% had been added to the solution (figure 8-47).

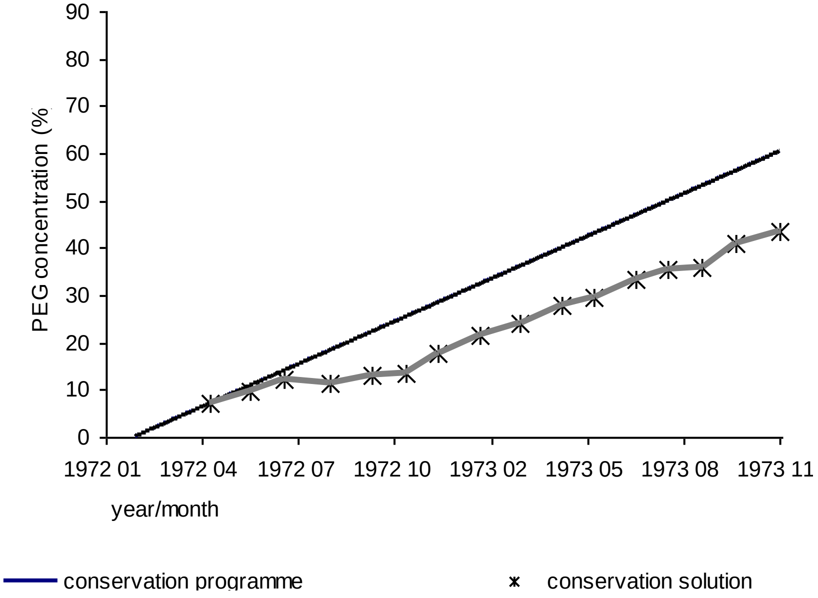

Figure 8-47. PEG-concentration of the conservation programme and the conservation solution of the second batch of material at a combined immersion- and spray-treatment programme.

Wood-cores were drilled from 4 of the large items before the conservation procedure but no core sampling was performed after the conservation treatment was finished. The objects were removed from the conservation bath and were arranged for spray treatment. This was performed with a PEG 4000-solution of c. 45% concentration.

8.5.3. The third batch of material at a combined immersion-spray treatment programme

The 42 m^3 tank was charged with 784 items, mainly parts of gun-carriages, blocks and other utensils for the rigging and staves and other parts of stave-barrels. The material consisted mainly of oak wood. The objects weighed from to c. 100 g to c. 10 kg. Some items were rather heavy, especially parts of gun-carriages, that might weigh nearly 100 kg.

The PEG 4000 was chosen for this batch of material. The PEG-conservation programme was performed by PEG increments of 1/12%, 7 days a week. The programme was terminated when the PEG-concentration of the solution had reached c. 45%. During the conservation period, which lasted for 20 months, PEG equivalent to a PEG-concentration of 53% had been added to the solution (figure 8-48).

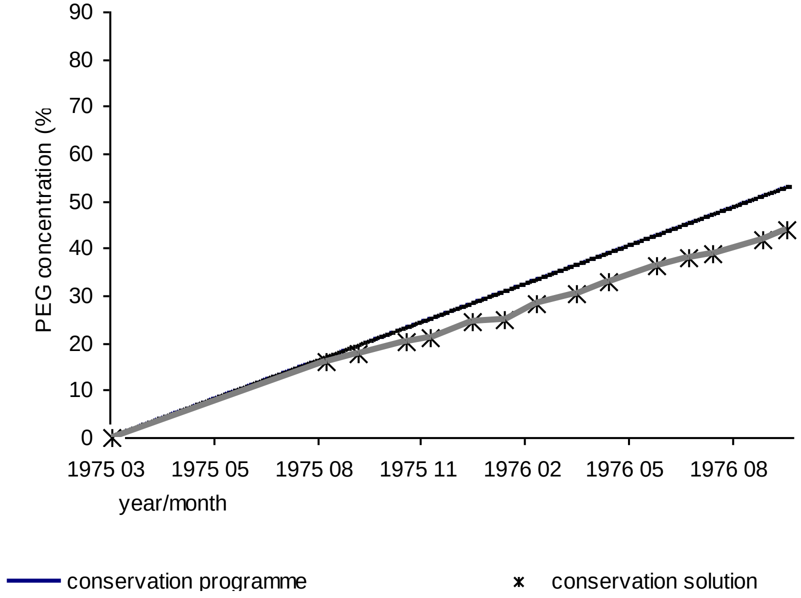

Figure 8-48. PEG-concentration of the conservation programme and the conservation solution of the third batch of material at a combined immersion- and spray-treatment programme.

No core sampling was performed. The objects were removed from the conservation bath and were arranged for spray treatment. This was performed with a PEG 4000-solution of c. 45% concentration.

8.6. Combined immersion- and spray-treatment programmes of different molecular weight PEG´s

Depending on that a PEG 600-PEG 1500 mixture from 1971 was used for the spray treatment of the Vasa hull with a growing fraction of PEG as this was the PEG that onwards was added to the tank the thought arose that even the immersion programmes might benefit from lower molecular weight PEG's.[202] The need for using lower molecular PEG's, however, was judged to be less by immersion treatment at an elevated temperature, than by spray treatment at temperatures at or below 20°C. In some cases a PEG of low molecular weight was chosen for the immersion conservation part of the programme. The spray treatment was performed with PEG 4000, or possibly with PEG 1500 if this molecular weight PEG had been used earlier for the immersion treatment. A final coating with PEG 4000 was finishing the treatment.

8.6.1. The first combined immersion- and spray-treatment programme with different molecular weight PEG´s

The 34 m^3 tank was charged with 1640 items, mainly staves, and other parts of stave-barrels, blocks for the rigging and other small wooden objects. The items were tied with soft tissue to wooden lattice in order not to get mechanically damaged during the conservation procedure. The barrel staves were built into special constructions, not to get deformed during the conservation procedure. The material was mainly oak wood. The objects weighed in general from c. 100 g to c. 3 kg. A few construction parts weighed c. 15 kg.

The PEG 1500 was chosen for this batch of material. The PEG-conservation programme was performed by PEG increments of 1/12%, 7 days a week. The programme was terminated when the PEG-concentration of the solution had reached c. 45%. During the conservation period, which lasted for 18 months, 62% PEG had been added to the solution (figure 8-49).

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[202] Håfors, 2001, p 65.

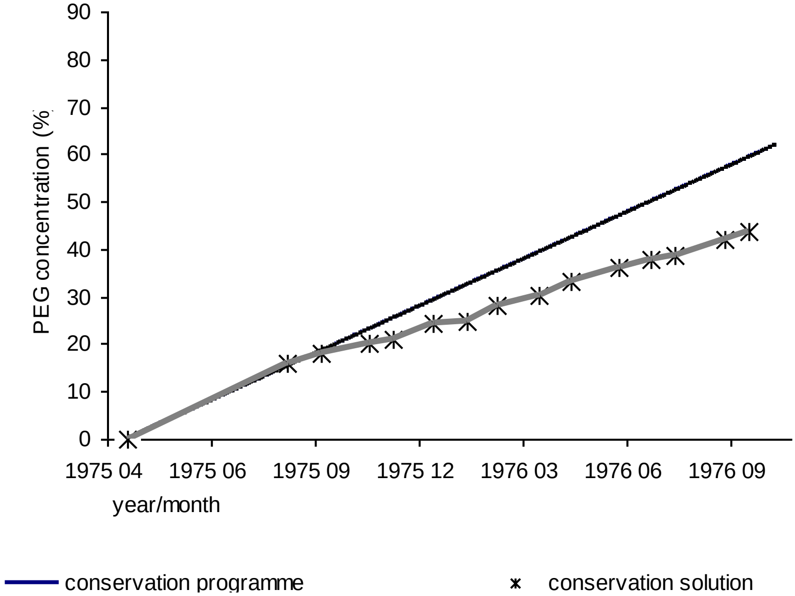

Figure 8-49. PEG-concentration of the conservation programme and the conservation solution of the first batch of material at a combined immersion- and spray-treatment programme with different molecular weight PEG´s.

No core sampling was performed. The objects were removed from the conservation bath and were arranged for spray treatment. This was performed with a PEG 4000-solution of c. 45% concentration.

8.6.2. The second combined immersion- and spray-treatment programme with different molecular weight PEG´s

The 2.5m^3 tank was charged with 191 small wooden objects, weighing between 100 and 300 g.

The PEG 600 was chosen for this batch of material. The PEG-conservation programme was performed by PEG increments of 1/12%, 7 days a week. The programme was terminated when the PEG-concentration of the solution had reached 45%, according to analysis. During the conservation period, which lasted for c. 20 months, 53% PEG had been added to the solution (figure 8-50).

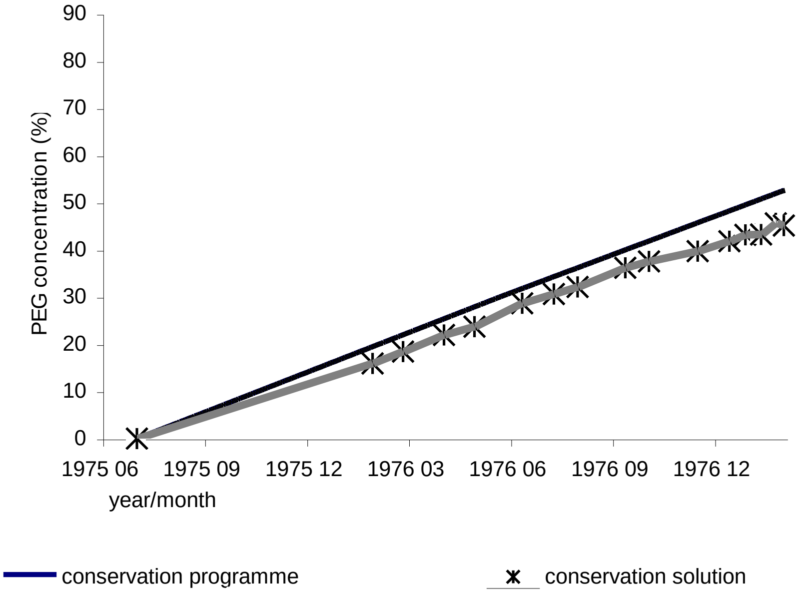

Figure 8-50. PEG-concentration of the conservation programme and the conservation solution of the second batch of material at a combined immersion- and spray-treatment programme with different PEG´s.

No core sampling was performed. The objects were removed from the conservation bath and were arranged for spray-treatment. This was performed with a PEG 4000-solution of c. 45% concentration.

8.7. Immersion treatment of loose wooden objects and timbers: conclusions

The task was to bring PEG by immersion treatment into the wet wood of loose wooden objects and timbers of the Vasa material, to an extent that would prevent or reduce shrinkage of the wood during the long-term conservation of the Vasa as a museum exhibit, and to do so without causing damage, such as extensive loss of weight meaning loss of water that may induce shrinkage or even produce measurable shrinkage of the wood during accomplishment of the treatment.

The aim was to create a “complete immersion conservation programme” that would suit all of the species of wood involved in the Vasa project.

8.7.1. The conservation procedure

The basis for the design of a conservation programme contained one temperature raising programme and one PEG-concentration raising programme for the conservation solution.

Temperature raising programmes

The temperature raising programme was implemented for the two batches, described in section 8.1. At the first conservation batch an extensive temperature programme was applied with 5°C steps from 30 to 60°C, while the PEG-concentration raising programme proceeded from 10 to 60%. The temperature raising programme of the second batch contained only three steps. It started by raising the temperature to 40°C, and used two 5°C and one 10°C step to reach 60°C, while the PEG-concentration was raised from 15 to 45% by an increment programme.

The material in the batches provided no special indication as to the effect of the temperature raising programmes. However, when the laboratory experiment of section 4.2. had been finished, the conclusion was drawn that temperature raising programmes did promote diffusion of water molecules from the waterlogged wooden objects into the surrounding PEG solution. This effect may be attributed to the fact that the raising of the temperature of the PEG solution, for a period of time produced a difference of temperature between the solution and the inside of the wood where the temperature did rise more slowly than in the solution. This may have produced a situation that promoted diffusion in the direction from the interior of the wood into the solution. The water molecules diffusing from the wood into the solution may have hampered or even reversed the diffusion of PEG molecules into the wood.

The conclusion drawn for the conservation programme was, not to apply a temperature raising programme but to raise the temperature of the chosen initial conservation solution to the highest temperature that was going to be used during the PEG-concentration raising programme and to keep the temperature stable all through the conservation procedure.

The temperature chosen for the immersion conservation treatment of the Vasa wooden material was 60°C. The temperature raising procedure of the initial conservation solution was performed during a period of 10 days.

PEG-concentration raising programmes

The PEG-concentration raising programmes contained the following three parameters:

1. maintaining a stable PEG-concentration level of the conservation solution, for a period of time, before the PEG-increment programme was started,
2. the magnitude and the frequency of the PEG-increments, and
3. the PEG-concentration at which the PEG-increment programme was to be stopped.

The first parameter, "a period at a stable PEG-concentration level of the conservation solution before the PEG-increment programme was started", was applied at the preliminary batches (section 8.1.), and at the first batch exclusively with pine material (section 8.2.1.). Application of this parameter was abandoned for reasons connected to difficulties of handling the large quantities of conservation solution at the Vasa conservation laboratory.

Since the laboratory experiments 4.2. and 4.3., that tested initial PEG-concentrations of 5, 10, 20 and 40%, indicated special benefit of applying 10% PEG as initial conservation solution, this might preferably be further investigated.

For the second parameter, "the magnitude and the frequency of the PEG-increments" 1/3, 1/6 and 1/12%, have mainly been performed for 5 or 7 days a week with development towards 1/12%, performed on 7 days a week as the programme most frequently applied. This should preferably be investigated further, with different dimensions of test specimens and different species of wood, and also different degrees of deterioration of the wood.

The third parameter, "the PEG-concentration at which the PEG-increment programme should be stopped", is difficult to accurately clarify. Since the oak wood material of the first preliminary batch (section 8.1.1.) during the 60 to 80% raise of the PEG-increment programme, had lost water but not gained any PEG the conclusion may be drawn that a PEG-increment programme should not be brought to a higher PEG-concentration value than 60%. In order to try to define a PEG-concentration for termination of the PEG-increment programme, the 13 batches listed under the designation "a complete immersion conservation programme" have been divided into one "high PEG-concentration group" containing the 6 batches, where the increment programme was terminated when the amount of PEG added to the conservation solution was between 74 and 80%, and one "low PEG-concentration group" containing the 3 batches, where the increment programme was terminated when the amount of PEG added to the conservation solution was between 52 and 67%, and a third group, containing 4 batches, where the addition of increments was stopped when the actual PEG-concentration of the conservation solution had reached 45% (table 8- LX).

Conservation rogramme final concentration (%)	Conservation solution final concentration (%)	Difference between the final concentrations of the conservation programme and the conservation solution (%)
80	58	22
80	61	19
75	48	27
75	58	17
74	52	22
74	51	23
67	56	11
65	55	10
60	52	8
60	45	15
59	47	12
53	45	8
52	44	8

Table 8-LX. Final PEG-concentrations of the PEG increment programmes and the conservation solutions, and the differences between these pairs of values.

The mean value of the final PEG-concentrations of the conservation programmes of the “high PEG-concentration group” was 76%, and the mean value of the actual final PEG-concentration of the conservation procedures was 55%. The mean difference was 21 percentage units between the PEG-concentration that might have been produced by the amount of PEG added to the solution and the final actual PEG-concentration of the conservation solution.

The mean value was 64% of the final PEG-concentrations of the conservation programmes of the “low PEG-concentration group”, and the mean value of the actual final PEG-concentration of the conservation procedures was 54%. The mean difference between the PEG-concentration that might have been produced by the amount of

PEG added to the solution and the final actual PEG-concentration of the conservation solution was 10 percentage units.

The mean value was 56% of the final PEG-concentration of the conservation programmes of the group of conservation batches that were terminated at the actual PEG-concentration of 45%. The mean difference between the PEG-concentration that might have been produced by the amount of PEG added to the solution and the final actual PEG-concentration of the solution was 11 percentage units.

The conservation solution

The PEG-concentration of the conservation solutions increased at a somewhat lower pace than the PEG-concentration of the corresponding increment programme. This was expected while the conservation process required some PEG molecules to diffuse into the wood to be preserved. However, the increase of the PEG-concentration of the conservation solution seemed to slow down and in some cases to stop between 50 and 60%, in the cases where the PEG increment programme was continued to 80%. This had been the reason why the PEG increment programmes in the first run was terminated at c. 60%. Later the actual PEG-concentration of 45% in the conservation solutions was used as the criterion for terminating the conservation procedure.

The PEG lost from the solution may have diffused into the wood aimed to be preserved. In the first case, called the “high PEG-concentration group” the amount of PEG lost from the solution was c. 20 percentage units, while the corresponding loss of PEG in the two “low PEG-concentration groups” was c. 10 percentage units. If — in this latter case — all lost PEG would be calculated as PEG-ratio for the wood of an average conservation batch (25% of the volume, occupied by wood of an average density of 0.5 g/cm^3) would equal a PEG-ratio of 60%. In the case of the “high PEG-concentration group” the loss of PEG from the solution would equal a PEG-ratio of 120%. Since the PEG-ratio, obtained by analysis, of each of the two groups was c. 20%, c. 65% of the lost PEG from the “low PEG-concentration group” and c. 80% of the lost PEG from the “high PEG-concentration group” are unaccounted for. This phenomenon has been noticed also at the experimental work (section 5.4., p 123). An explanation may be found in the possible existence of a two-phase system in the PEG-solution.[203]

The conservation result

Conditioned, that the amount of PEG lost from the conservation solution would have mirrored the conservation result expressed as PEG-ratio of the conserved wooden material, the wood-core sample of the "high PEG-concentration group" would display twice as high a PEG-ratio as each of the other two groups.

To investigate the conservation result the mean values of the PEG-ratios of the wood-core samples were compared, separately for the oak wood and the pine wood of the batches from each of the three groups. The mean PEG-ratios of the oak wood samples of the three groups of batches were 22, 19 and 21%, respectively while the pine wood displayed mean PEG-ratios of 43 and 58% corresponding to the two first mentioned values of the oak wood groups. The mean water-ratios of the three oak wood groups were 50, 59 and 68%. The two groups of pine wood displayed mean water-ratios of 84 and 105%, respectively (tables 8 - LXI, 8 - LXII).

Comparing these PEG-ratio values with the value of 60%, calculated from the loss of PEG from the solution the oak wood displayed only to have absorbed one third of that value while the pine wood closely reached the calculated value.

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[203] Cecilia Lindblad and Ingmar Persson, 2009, pp 507-516.

End-concentration of the conservation programme (%)	End-concentration of the conservation solution (%)	Concentration of an assumed PEG-solution inside the wood, mean value (%)	PEG-ratio, mean value (%)	water-ratio, mean value (%)
80	58	15	8.7	50
80	61	-	19	-
75	48	41	46	65
75	58	28	17	44
74	52	36	26	46
74	51	27	17	47
67	56	22	17	59
65	55	-	19	-
60	52	28	22	58
60	45	-	-	-
59	47	-	-	-
53	45	-	-	-
52	44	24	21	68

Table 8 - LXI. End PEG-concentrations of the PEG increment programmes and the conservation solutions, mean values of the concentrations of the assumed PEG-solutions inside the wood, end PEG-ratios and end water-ratios of the oak wood material in the conservation batches.

End-concentration of the conservation programme (%)	End-concentration of the conservation solution (%)	Concentration of an assumed PEG-solution inside the wood, mean value (%)	PEG-ratio, mean value (%)	water-ratio, mean value (%)
80	58	32	44	92
80	61	-	65	-
75	48	40	47	71
75	58	17	18	86
74	52	38	57	92
74	51	27	29	80
67	56	38	65	106
65	55	-	-	-
60	52	33	51	104
60	45	-	-	-
59	47	-	-	-
53	45	-	-	-
52	44	-	-	-

Table 8 - LXII. End PEG-concentrations of the PEG increment programmes and the conservation solutions, mean values of the concentrations of the assumed PEG-solutions inside the wood, end PEG-ratios and end water-ratios of the pine wood material in the conservation batches.

The addition of PEG 4000 to the conservation solution in order to raise the PEG-concentration of the solution from 60 to 80 % did not cause any rise of the PEG-ratios, either of the oak or the pine wood. Instead diffusion of water molecules from the wood into the solution was effected in both cases. This confirms the suitability of ending the conservation programme at or below c. 60%.

In the conservation procedures where it has been possible to split the objects into one group with larger dimensions and one group with of smaller dimensions, the group of objects with smaller dimensions showed higher PEG-ratios than the group with larger dimensions.

8.7.2. The conservation substances

The PEG 4000 was selected as preservative with most of the conservation batches. Later investigation indicated that lower molecular weight PEG's might be considered when a modification of the characteristics was desired. This has been executed by using the PEG 1500 and the PEG 600 for the 2 last batches (sections 8.6.1, 8.6.2.).

8.7.3. The wooden material for conservation

Parameters of the material

Since the conservation substance is supposed to diffuse into the wood the most important material parameter in common for all types of wet wood is that these keep a fair amount of water. It has, however, not been possible to discriminate between the conservation result of wood that keeps its maximum content of water, and the conservation result of wood that keeps quantities of water below that level.

However, the water-ratios of 12-15% at a depth of 6-20 mm into one item, and a water-ratio of 12% at 6-10 mm depth into another item, both of the items were made of oak wood, had prevented the PEG to get past these layers and proceed into the wood. In one item made of pine wood, from the same batch as the oak wood items mentioned above, with 10-16% water-ratio at 11-45 mm depth into the wood, the PEG had penetrated past this zone deeper into the wood (section 8.4.5.). Thus, a water-ratio value of c. 15% may be too low to allow for a PEG conservation of the oak wood but may be high enough for PEG conservation of the pine wood. As equal opportunities existed, the difference in penetration ability of PEG molecules into the oak and pine wood items, respectively, might be attributable to the anatomical differences between the oak wood and the pine wood.

Diffusion of water from the wooden material was another phenomenon going on during the entire immersion conservation period (section 8.4.4.). This loss of water from the wood could be compared between the items of oak wood, pine wood and lime wood in the seventh batch of material at a complete immersion conservation programme (section

8.4.7.). In this batch the actual loss of water from the oak wood and the lime wood were equal and amounted to larger amounts than the actual loss of water from the pine wood. The loss of water was replaced by PEG to a greater extent in the pine wood than in either of the oak wood or the lime wood. The order between oak wood and lime wood where replacement by PEG was considered, was lime wood before oak wood. This may be attributable to the difference in densities of the two hardwoods. However, the densities of the oak wood and the pine wood materials of the batch were equal (section 8.4.7.). Thus, the differences in actual loss of water between these groups may possibly be attributable to the anatomical differences between the group of hardwoods and the softwood, involved.[204]

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[204] Thunell, 1959, p 17; see also Greguss, 1959; Jane, 1970.

IV: Discussion and Conclusions

The selection of PEG as a dimension stabilising agent for the wet deteriorated wood of the Vasa was made with little knowledge of the ability of the substance to penetrate into the secondary cell wall to effect a long lasting stability of the dimensions of the wood. Although PEG was considered stable in the situations it had been used for up till then there was also the risk of deterioration of the molecule in the matrix of the Vasa wood. Recent Ph.D. dissertations have investigated impurities and formic acid as deterioration products emanating from PEG in the Vasa wood. [205] Calculations on the amount of formic acid predict stability of the PEG conservation for several centuries.[206]

PEG 4000 was selected depending on its low hygroscopicity that was considered to be suitable for museum exhibition. The change into PEG 1500 for the automatic spraying procedure was made as a result of technical considerations about the capacity of the automatic spraying system. This change to lower molecular weight PEG also started experimental work with such PEG´s.[207]

The fact that the capillary system of the waterlogged secondary cell wall was the target of the PEG treatment was considered. However, priority was given to the hygroscopicity aspect, and in addition PEG´s of lower molecular weight were considered too volatile for durability of the treatment.

Diffusion of water and PEG molecules have been identified as the main processes of dimension stabilizing conservation of wet archaeological wood with PEG. Since the diffusion of each species of molecule proceeds from a region of high towards a region of low concentration both the movements of the PEG and the water molecules have to be taken into account.

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[205] Fors, 2008; Almkvist, 2008.

[206] Mortensen, 2009.

[207] Håfors, 1999, pp 87-94.

Diffusion at spray treatment

Movement of PEG molecules into the wet medium inside the wood, as well as movement of water molecules towards the surface of the wood, and also water molecules even leaving the wood, is to occur when a spray treatment programme is applied. An example is the spray treatment of the Vasa hull.

Four areas of diffusion situations between a PEG-solution of increasing concentration, sprayed on the surface of the wood of the Vasa hull and the resulting PEG-concentration of an assumed PEG-solution in the outer 10 mm of the wood are described (chapter 7, figures 7-1 – 7-4). The 10 mm surface layer of the first two of the defined areas display a continuing loss of water (drying) during all four defined periods of varying PEG treatment (figures 7-5, 7-9), while the loss of water from the 10 mm surface layer of the third area (figure 7-13) ceased during the last period of treatment and the loss of water from the 10 mm surface layer of the fourth area (figure 7-17) ceased during the two later periods of treatment.[208]

The concentration of the assumed PEG-solution in the 10 mm surface layer was much lower than in the conservation solution during the two periods of rather low PEG-concentration and continuing spraying. At all four areas investigated the concentration of PEG in the 10 mm surface layer of the wood had arrived at the same value as in the spray solution at the end of the third period of treatment when a conservation solution of 35% PEG-concentration in combination with a low frequency of spraying rounds had been used for about a year. The movement of PEG-molecules into the 10 mm surface layer from the PEG-solution sprayed on the surface of the wood was succeeded by a further movement towards the interior of the wood. As deduced from the figures 7-1, 7-4, 7-5, 7-6, 7-17, and 7-18 the movement of PEG-molecules became slower after the first year of the fourth period of treatment, lasting for four years.

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[208] This dissertation, pp 233, 243-244.

During the last three years of the fourth period of treatment the proportion of PEG to water in the 10 mm surface layer became higher than in the treatment solution, which contained 45% PEG. The increase of concentration of the assumed PEG-solution inside the 10 mm surface layer ceased at c. 65% which may be regarded as an equilibrium with the RH of the surrounding atmosphere. This seems to have terminated the inwards movement of PEG-molecules in the wood.

Conclusion

A higher PEG-ratio in the Vasa oak wood would probably have been obtained by continuing the spraying programme with higher frequencies of spraying rounds during the third and fourth periods of the treatment programme.

Diffusion and osmosis in immersion situations

The experimental work was performed mainly in order to find the most suitable values for the parameters of immersion treatment with a PEG-solution. The experiments deal with temperature programmes, increment programmes, and different molecular weight PEG´s.

Osmosis creates a difference of pressure between the conservation solution and the interior of the wood. This has been noted especially where waterlogged Vasa oak wood has been immersed into PEG 4000-solutions.[209]

The actual conservation situation has made it possible to compare the diffusion of water from the Vasa oak, pine and lime woods during the conservation treatment (figures 8-32, 8-35). Although the amounts of water in the Vasa oak and pine woods seem to be rather similar before the conservation treatment had started the situation after the treatment points to substantially lower amounts of water in the oak wood compared to the pine wood. In this respect, there is a greater resemblance between the pine wood and the lime wood. If the densities of the different species of wood are considered, however, the

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[209] This dissertation, chapter 4; chapter 8.

compliance is between the Vasa oak and the Vasa pine wood both of which have a density of c. 0.5 g/cm^3, while the density of the Vasa lime wood is c. 0.35 g/cm^3.

The management of the conservation solution of immersion treatment means handling osmosis. The experiments have provided information about the influence on the conservation process of different parameters such as the molecular weight of the PEG used, the starting and end concentrations of PEG in the conservation solution, the temperature and increment programs applied.

This has resulted in less weight loss and less shrinkage during the treatment period in the following cases:

- where lower molecular weight PEG´s have been used,
- where an extended treatment period has been applied,
- where the treatment has been terminated at a PEG concentration in the conservation solution of 45 – 50%,
- where small increments of PEG-concentration have been applied, and
- where the temperature level of the conservation solution has been kept stable during the treatment period

Dimension stability of PEG-treated Vasa oak in relation to RH

To keep the PEG-treated Vasa wood stable in the permanent Vasa museum, to be constructed, a RH level of 60% and a temperature of 20°C were recommended as the most suitable values for the climatic parameters, by the chairman of the Conservation Council at the time, professor Bertil Thunell.[210] He stressed both the necessity of a rather high RH in the museum atmosphere to assist in keeping the dimensions of the wood, and warned against too high RH with regard to the hygroscopicity of the PEG 600, in those parts of the Vasa wood where

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[210] Thunell, 1985.

high ratios of PEG had been found. This mainly applied to the Vasa pine wood.

To obtain some information about the shrinkage reducing effect of the dry PEG´s the ASE values (chapter 5) have been calculated for the test specimens of experiment 5.4. after drying in a desiccator charged with silica gel (figures IV-1, IV-2).

The diagrams of the ASE values at c. 10% RH, of the radial direction of the oak wood-PEG (1500, 600) composite specimens display a high degree of similarity until the PEG concentration of the conservation programme has reached c. 45%. Above that concentration, the radial ASE curves of the PEG 1500 and 600 specimens diverge in that the ASE of the PEG 1500 specimen falls behind to lower values. The PEG-fraction in the dry matter of the wood of the specimens representing the 45% PEG-concentration level of the conservation programme stays between 25 and 29%.

The radial ASE curve of the PEG 4000 specimen remains at a lower level during the entire series of specimens of successively higher PEG-fractions in their dry matter (figure IV-1).

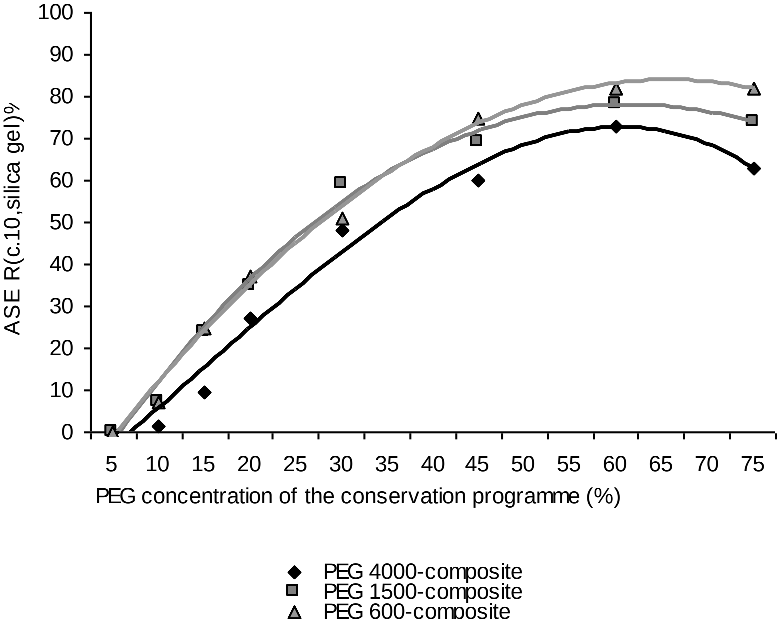

Figure IV-1. Radial ASE values of Vasa oak-PEG 4000, 1500 and 600 composite specimens at c. 10% RH.

The diagrams of the ASE at c. 10% RH of the tangential direction of all three of the Vasa oak wood-PEG composite specimens display a high degree of similarity until the PEG concentration of the conservation programme reached c. 45%. Above that value, the tangential ASE curves of the three specimens diverge when the ASE of the PEG 4000 and 1500 specimens fall behind to lower values. The PEG-fraction in the dry matter of the wood of the specimens representing the 45% PEG-concentration level of the conservation programme stays between 25 and 29%.

The tangential ASE curves place themselves in the sequence of PEG 4000, PEG 1500 and PEG 600 from bottom to top for the specimens with PEG-fractions in their dry matter between the 25-29% level and the 30-34% level (figure IV-2).

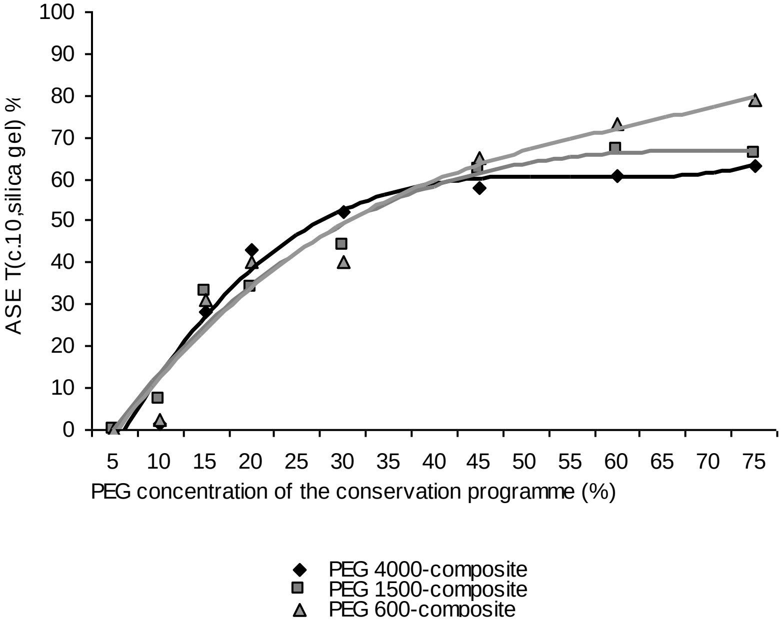

Figure IV-2. Tangential ASE values of Vasa oak-PEG 4000, 1500 and 600 composite specimens at c. 10% RH.

In order to discuss the influence of RH on the shrinkage and on the ASE, the actual shrinkage has been considered. Calculations have been performed for the Vasa oak wood-PEG composite specimens of experiment 5.4. that have reached PEG fractions of 30 to 34% in their dry matter (tables 5-V – 5-X; IV-I - IV-II, figures IV-3 – IV-8).

PEG	10% RH		55%RH		66% RH		76% RH	
	R	T	R	T	R	T	R	T
4000	63	63	64	67	71	71	78	79
1500	74	66	75	67	82	76	95	87
600	82	79	91	86	91	90	97	99

Table VI-I. ASE-values (%) of the Vasa oak wood-PEG 4000, 1500 and 600 composite specimens with 34%, 34% and 30% PEG, respectively in their dry matter, at the termination of the conservation procedure

PEG	10% RH		55%RH		66% RH		76% RH	
	R	T	R	T	R	T	R	T
4000	5.3	9.0	4.1	8.3	4.4	8.6	4.6	9.5
1500	6.6	9.4	4.9	8.5	5.2	8.8	5.6	10.1
600	6.8	11.0	5.8	10.3	5.4	10.7	5.7	11.7

Table VI-II. Actual shrinkage avoided (percentage units) as an effect of the PEG contained by the test specimens of the Vasa oak wood-PEG 4000, 1500 and 600 composite specimens with 34%, 34% and 30% PEG, respectively in their dry matter, at the termination of the conservation procedure.

The actually avoided shrinkage calculated for both of the radial and the tangential directions of the Vasa oak wood-PEG composite take their highest values at c. 10% RH for all three PEG´s. These are their lowest values as percentage of their expected maximum shrinkages (ASE-values).

From 10 to 55% RH there is a decrease in avoided shrinkage of all three specimens whereas the ASE-values were higher or remained stable. From 55 to 76% RH the shrinkage avoided of the PEG 4000 and 1500 specimens show increasing gradient while the PEG 600 specimen displays a mixed picture which paralleled the PEG 4000 and 1500 specimens where the tangential shrinkage was considered but with a further decrease of avoided radial shrinkage before an increase between 66 and 76% RH. This may be due to the fact that the ASE-values stays between 90 and 99% i. e. the shrinkage was practically totally avoided in that RH-range.

Both of the wood and the PEG are the targets of increasing RH-values. The graphs of the ASE-values of the Vasa oak wood-PEG 4000 composite specimens at increasing RH (figures IV-3, IV-4) take a common course until a fraction in the dry matter of c. 25% PEG 4000 was reached. Above that value the graphs spread apart presumably owing to hygroscopicity of the PEG.

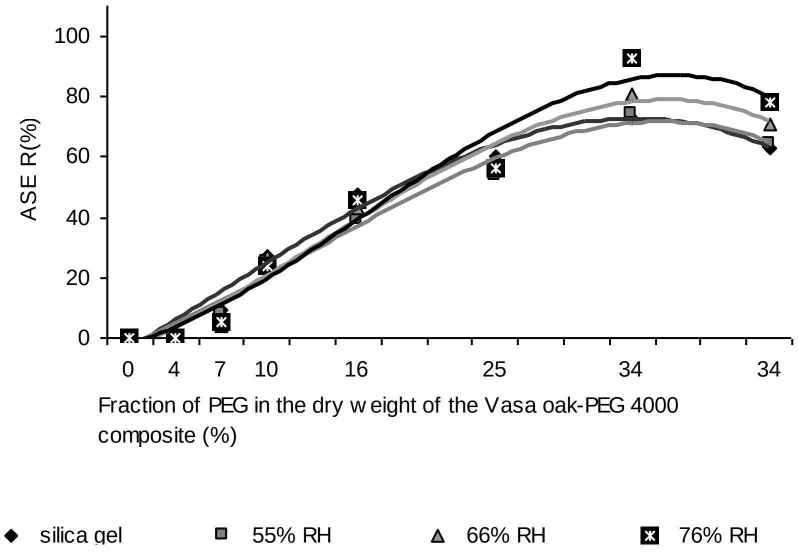

Figure IV-3. Radial ASE values of Vasa oak-PEG 4000 composites at c. 10%, 55%, 66%and 76% RH.

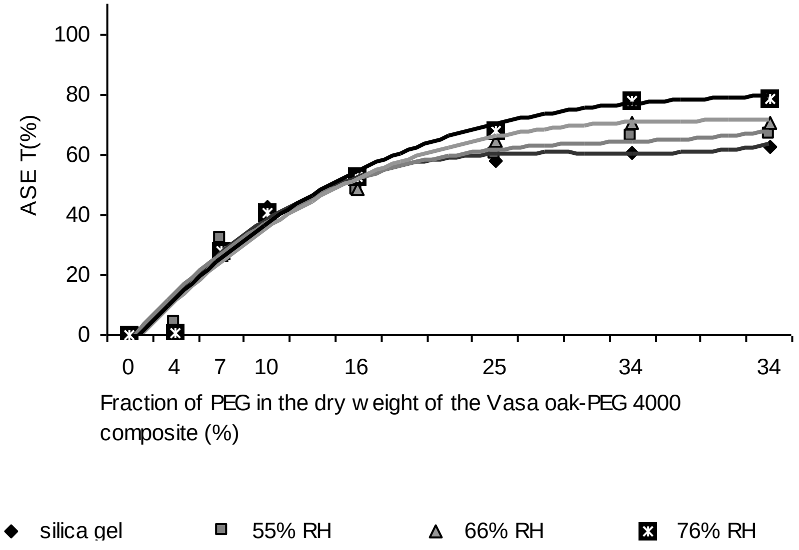

Figure IV-4. Tangential ASE values of Vasa oak-PEG 4000 composites at c. 10%, 55%, 66% and 76% RH.

The graphs of the ASE-values of the Vasa oak wood-PEG 1500 composite specimens at increasing RH (figures IV-5, IV-6) take a common course until a fraction in the dry matter of between 18 and 29% PEG 1500 was reached. Above that value the graphs spread apart presumably owing to the hygroscopicity of the PEG.

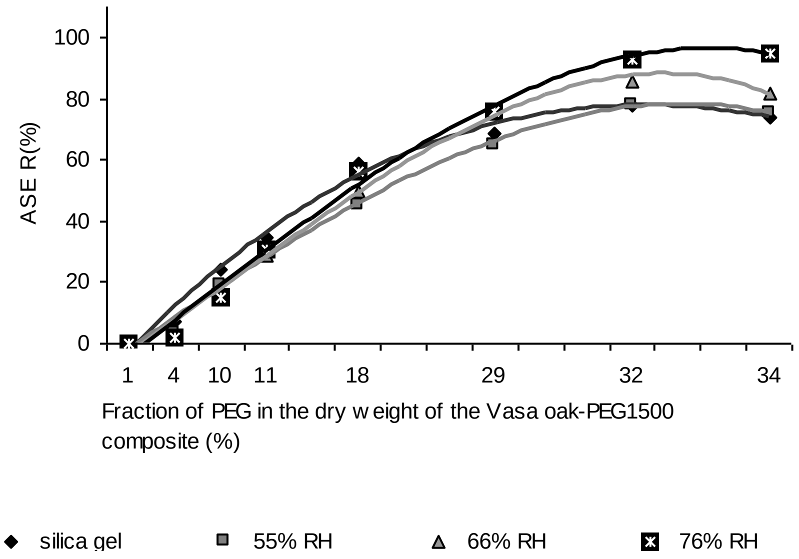

Figure IV-5. Radial ASE values of Vasa oak-PEG 1500 composites at c. 10%, 55%, 66%and 76% RH.

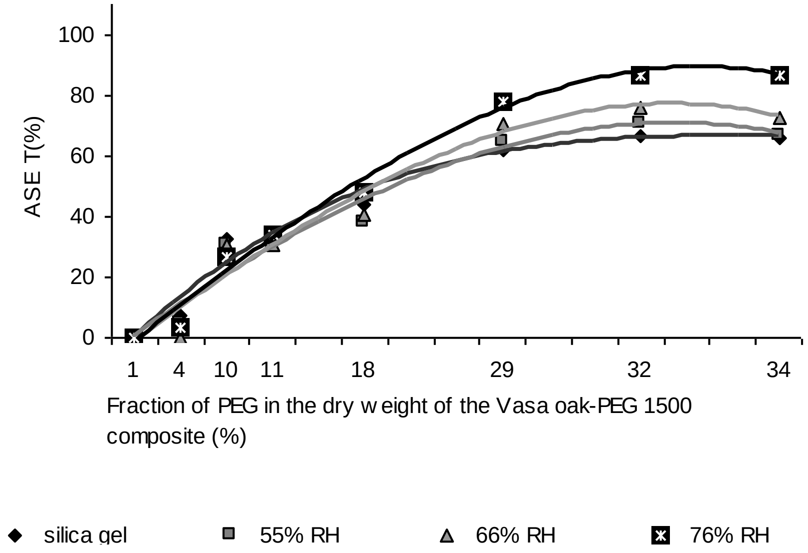

Figure IV-6. Tangential ASE values of Vasa oak-PEG 1500 composites at c. 10%, 55% 66% and 76% RH.

The graphs of the ASE-values of the Vasa oak wood-PEG 600 composite specimens at increasing RH (figures IV-7, IV-8) take a common course until a fraction in the dry matter of between 18 and 29% PEG 600 was reached. Above that value the graphs spread apart presumably due to the hygroscopicity of the PEG.

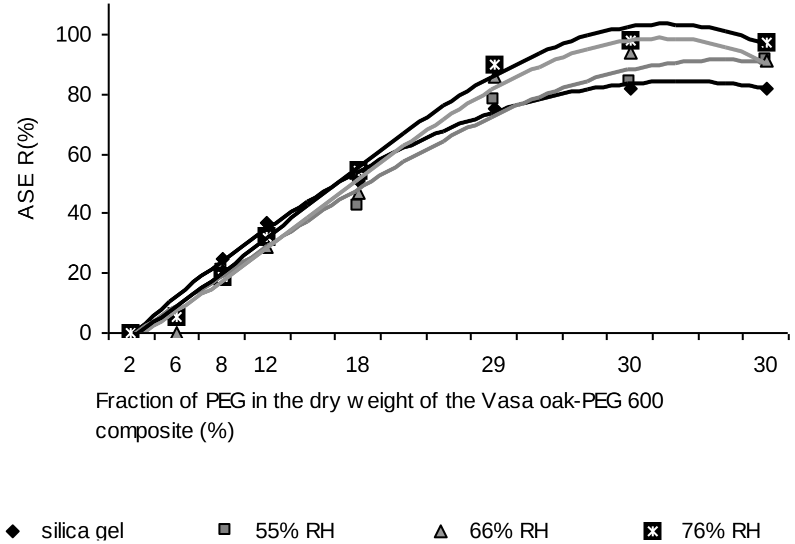

Figure IV-7. Radial ASE values of Vasa oak-PEG 600 composites at c. 10%, 55%, 66% and 76% RH.

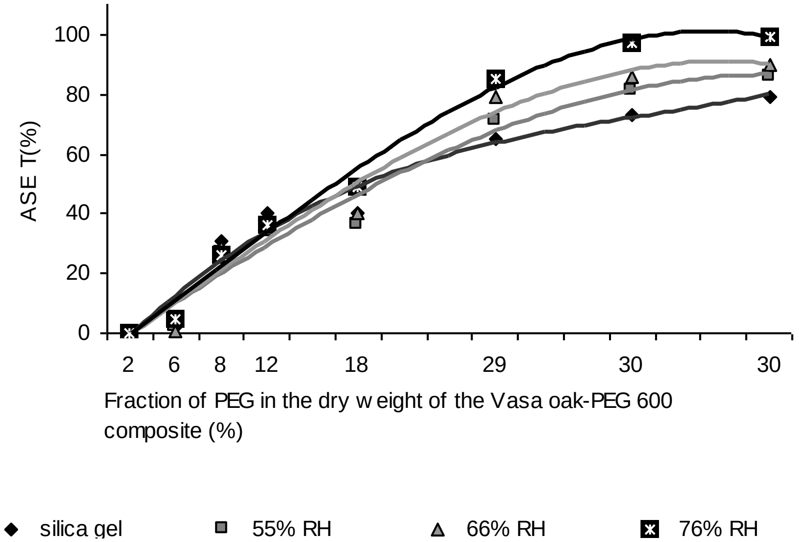

Figure IV-8. Tangential ASE values of Vasa oak-PEG 600 composites at c. 10%, 55% 66% and 76% RH.

Conclusion

The actually avoided shrinkage, calculated for the radial and tangential directions, respectively, seem rather similar for all three molecular weights of PEG from c. 10% RH to 76% RH. Since the gradients of shrinkage-reducing effect show increasing values with decreasing molecular weight of the PEG at all RH levels, the conclusion is that the difference in shrinkage reducing effect emanates from the greater ability of the lower molecular weight PEG´s to migrate into the smaller capillaries of the secondary cell wall.

A gradient of increasing RH values seem to have minor influence on the magnitude of the avoided shrinkage and the ASE-values where PEG 4000 and 1500 composite specimens are considered. PEG 600 composite specimens seem more sensitive to higher RH-values.

The secondary cell-wall as a direct target for the choice of molecular weight of PEG

The question at the outset of the conservation of the Vasa oak wood had been to investigate how to handle – in particular – a PEG 4000 solution in water, and later, solutions of some other molecular weight PEG´s to produce a dimensional stabilization of the secondary cell-wall of the Vasa oak wood. At the beginning of the 1980´s, Dr. Per Hoffmann joined the German Maritime Museum as a conservator of the Bremen cog. Instead of testing the effects of solutions of different molecular weight PEG´s on the oak wood of the cog, he investigated the oak cell-wall to be able to decide which molecular weight PEG would stabilize the multi-quality oak wood. He concluded that PEG 200 was the highest molecular weight PEG capable to fill the capillary system of the secondary cell-wall of the inner and less deteriorated parts of the wood while PEG 3000 would be needed for the superficial, more deteriorated parts of the wood.

Conservation of the Bremen cog

Based on these conclusions Hoffmann created a two-step immersion impregnation programme for the cog. The programme consisted of a first step of c. 10 years duration. The conservation programme of this step started from a 10% PEG 1500 solution in water, that was a residue from an earlier treatment programme. To this solution PEG 200 was added, raising the concentration of this component to a final 40%, at a rate of 5% per year. To proceed to the second step of the treatment programme the conservation solution of the first step of the programme had to be removed from the tank before the PEG 3000 solution could be poured in. The concentration of the PEG 3000 solution was raised from c. 50% to c. 70% during the one year treatment period of the second step. The treatment solution of the second step was heated, while the treatment solution of the first step had been kept at ambient room temperature.

During the first step of the treatment programme no shrinkage of the oak wood was observed, while a radial shrinkage of c. 1% and a tangential shrinkage of c. 2.5% were measured during the second step of the programme.[211]

Conservation of the Mary Rose

The conservation of the hull of the Mary Rose is another conservation project where PEG 200 has been applied. With this object spraying has been chosen as treatment method. The "Phase I" lasted for 12 years, during which period the treatment was performed with a solution of PEG 200. The same increment programme as with the Bremen cog was adopted for this phase of the treatment which was terminated at 40% PEG 200 concentration in the conservation solution. PEG 2000 is selected for the spray treatment during the "Phase II" of the treatment period. The "Phase II" is planned to last for c. 5 years during which period the PEG concentration of the treatment solution is planned to be increased from 40 to 50%.[212]

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[211] Hoffmann, 1997.
[212] McConnachie, 2007.

Conclusion

Conclusions about the effects of the immersion technique compared to the spray technique at the conservation treatment may be evaluated from these two objects after a substantial period of drying. The difference of approach concerning the choice of molecular weights of the PEG´s used for these two objects compared to the choice of molecular weights of the PEG's used for the spray treatment of the Vasa hull will also be an interesting parameter for future evaluation.

9. Results

Evaluation of results is primarily connected to the comprehensive assumption that polyethylene glycols (PEG's) are dimension stabilizing agents of wood from wet archaeological sites, meaning that PEG prevents or at least reduces shrinkage during the drying procedure of a PEG preserved sample from a piece of wood from wet archaeological sites compared to an untreated sample of the same piece of wood, and that this effect is remaining at a defined museum climate (RH and temperature). The museum climate chosen for the evaluation is 55% RH at 20 °C.

9.1. Shrinkage reduction effect of PEG

The PEG 4000 treated oak specimens (9 x 9 x 2.5 cm), cut from a deck-batten removed from under the lower gun-deck of the Vasa hull have shown that at 55% RH and 20 °C, c. 60% of the shrinkage anticipated in the axial, radial and tangential directions, respectively of the wood, had been prevented. The test specimens contained c. 40% PEG in the dry matter of the Vasa oak wood-PEG composite.[213]

Another experiment with oak specimens (9 x 9 x 2.5 cm) cut from another deck-batten from under the lower gun-deck of the Vasa hull involved three series of oak specimens, each including eight specimens with increasing fractions of PEG 4000, 1500 and 600 in the dry matter. Measurements of the dimensions in the radial and the tangential directions have made possible calculations of the ASE of these directions of the wood of the specimens at different fractions of PEG in the dry matter.[214]

The PEG-treated specimens have obtained dry weights with PEG-fractions of 0 – c. 30%. These PEG-fractions corresponded to shrinkage reduction effects (ASE) of 0 – c. 80% at 55% RH in both of the radial and the tangential directions.

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[213] This dissertation, section 5.3.

[214] This dissertation, section 5.4.

The ASE-R (55) values of the Vasa oak wood-PEG composites with PEG-fractions of their dry weights of 30-34%, were 88, 77 and 69%, and the ASE-T (55) values were 84, 69 and 67% for the PEG 600, 1500 and 4000 respectively.

The conclusion drawn is that *the shrinkage reducing effect is attributable to the amount of PEG in the wood and that there is also an indication that lower molecular weight PEG's may have a higher shrinkage reducing effect than higher molecular weight PEG's.*

The result of the laboratory experiments is that *PEG treatment of oak from the Vasa has prevented shrinkage of the wood by such a high percentage that PEG may be considered a dimension stabilizing agent of the Vasa oak wood.*

Thus the result of the experiment does not contradict the assumption that polyethylene glycols (PEG's) are dimension stabilizing agents of waterlogged archaeological oak wood, meaning that PEG prevents or reduces shrinkage during the drying procedure of a sample of the waterlogged archaeological wood conserved with PEG, compared to an untreated sample of the same piece of wood.

9.2. PEG surface application procedure

The surface application of PEG on the Vasa hull has resulted in the rather low PEG-fraction of 13% in the dry weight of the interior layers of the planks of the planking and the ceiling. Since the PEG 1500 and the PEG 600 were selected for the spraying of the hull this fraction of PEG may provide a shrinkage reducing effect of c. 30% at 55% RH both in the radial and in the tangential directions.

The much lower PEG content of the interior layers of the oak wood of the thicker timbers of the wales should be noted.

Even the oak wood deck-planks of the orlop deck show a very low PEG content of the interior layers while the pine wood deck-planks of the orlop deck show a PEG-fraction in the dry weight of c. 50% and even heavy pine timbers show a PEG-fraction in the dry weight of c. 13% at a depth of c. 40 mm of the interior of the timber. However, no laboratory experiment have been performed to give the ASE values of the Vasa pine wood-PEG composite.

With an intent to obtain a higher degree of stabilisation it is necessary to reach a higher amount of PEG in the wood. This may be possible by making changes in the conservation programme.

9.3. PEG immersion procedure

The immersion application of PEG to loose wooden items from the Vasa hull has resulted in a mean PEG-fraction in the dry weight of 17% of the oak wood material. Since the PEG 4000 was selected for the immersion conservation treatments this fraction of PEG may provide a shrinkage reducing effect of c. 40% in the radial direction and c. 50% in the tangential direction at 55% RH.

The mean PEG-fraction in the dry weight of the pine wood material amounted to c. 30%.

It was not — even by immersion treatment — achievable to obtain enough PEG in the oak wood to get the highest possible stabilisation.

9.4. Discussion and evaluation of results

In order to reach a higher amount of PEG in the wood than has been obtained with the spraying programme applied at the treatment of the Vasa hull, more favourable circumstances for the diffusion process would need to be created. This may affect both the initial period and the terminating period of the treatment. One change to be made in the frequency programme for the Vasa hull would be not to cut down on spraying rounds as fast as was actually done.

Since difficulties had been observed in determining the equilibrium point for the diffusion of PEG, it would be useful instead to allow for a specified time interval for each of the successively operated five percentage units higher PEG-concentrations of the conservation solution. By the Vasa surface application procedure with the automatic spraying system, that lasted for 14 years, this may have been done by splitting the spraying period into 7 intervals of equal length, each with 15, 20 …45% PEG-concentration in the conservation solution.

Since weight-loss and shrinkage during the immersion conservation experiments of the test specimens were considered harmful to the conservation results, the parameters of the conservation programmes have been adjusted from one experiment to the next, in order to avoid this shrinkage to happen.

The immersion conservation programmes have been adjusted accordingly to eventually consist of one part of immersion treatment in a PEG solution, starting with pure water and administering up to 45% PEG concentration. The other part consisted of a period of spray treatments. It might be possible to change the parameters of the conservation programmes, to obtain further increase of the PEG in the wood. Since the major part of the immersion conservation is performed with PEG 4000 it would also be profitable to try a lower molecular weight PEG which has been noted to have a higher degree of anti-shrink efficiency than the PEG 4000.

The initial conservation programme revealed that a temperature raising programme might create a temporary temperature gradient between the conservation solution and the interior of the wooden material that would raise the velocity of diffusion of water molecules from the wood and at the same time to slow down the velocity of diffusion of PEG molecules from the conservation solution into the wood.

9.5. Suggestions for further work

Since large wooden objects from archaeological wet sites are very rarely available, there are few opportunities to develop the methods of application of dimension-stabilising substances on large objects, either by spraying or by immersion treatment. This also implies the difficulties to obtain testing material of suitable quality and magnitude. In order to enable statistical evaluation of experiments it is necessary to involve a great number of test specimens. Such specimens should be cut from pieces of wood in a way that gives each of those equal anatomical structure. Each specimen should be large enough for the parameters of the conservation solution to be tested. Only recent wood from the lumberyard will have characteristics to fulfil these demands.

Testing material

Testing material should be selected from different wood species, at least from oak and pine. To obtain deteriorated wood for the test samples, a biological or a chemical method may be used.

Conservation substances

Further work on investigating PEG's of various molecular weights as dimension-stabilising agents is needed to be performed.

Sucrose may be of interest when considering other dimension-stabilising substances for waterlogged archaeological wood. In connection to this an experiment with sucrose as dimension-stabilising substance for waterlogged archaeological oak wood, performed at the Vasa laboratory and presented in 1976 at the Neah Bay (Washington) conference.[215] The result of the experiment was interesting and sucrose is used as dimension stabilising substance mainly for economic reasons. The suggestion is to proceed with systematic experimental work with sucrose. [216]

The disadvantages of sucrose, being a substrate for growth of micro-organisms, has introduced substitutes for sucrose i.e. in the group of sugar alcohols where lactitol has been tested as dimension-stabilising substance. The suggestion is that these substances would be tested parallel to one another and to PEG and to sucrose on identical testing material.

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[215] Grosso, 1976.

[216] Håfors,1976, pp 20-21.

CONSERVATION OF THE WOOD OF THE SWEDISH WARSHIP VASA OF A.D. 1628

Summary

THE CONSERVATION OF THE WOOD OF THE SWEDISH WARSHIP VASA OF A.D. 1628

The Vasa wood conservation project was conducted almost in parallel on three arenas: the analysis and research laboratory, the pontoon super structure with the spray equipment for the hull, and the conservation work-shop with the tanks for immersion treatment of wood.

The laboratory research

The main aim of the laboratory experiments was to develop the application of PEG to the wood in order to obtain an optimal long-term conservation result. Experiments were conducted both with the surface application method and with the immersion treatment technique. At the beginning only PEG 4000 was considered. With the construction of the automatic spray system, however, PEG 1500 was chosen for technical reasons for that application. This occasioned the research laboratory to involve the PEG 1500 and later also the PEG 600 and sometimes the PEG 1000 in the experimental work.

Experiments with the conservation solution

By the experiments with surface application the PEG 4000 was paralleled with carboxy-methyl cellulose (CMC) that had been in use as a shrinkage reducing preservative for waterlogged wood for as long as a decade, at the time when the Vasa was salvaged. Both substances were tested in atmospheres of high and low RH, respectively. Even though the experiments were not clearly discriminating about the effects of these two substances, the PEG was selected, partly on grounds of its high solubility in water.

The experiments dealing with development of the immersion conservation programme consisted of three main fields, i.e. temperature of the conservation solution, PEG-concentration of the conservation solution, and duration of the conservation treatment period. It was soon determined that a temperature raising programme, which was the most common way to apply temperature to a conservation solution, did in fact bring about an added tendency for water molecules to diffuse from the wooden objects into the PEG-solution. This discovery was immediately turned into practice at the immersion conservation treatments at the conservation laboratory, and the temperature raising programme was abandoned in favour of steady temperature level of 60 °C.

PEG-concentration raising programme, however, was judged to be more protective for the water molecules inside the wood the smaller the PEG increments were, and the higher the frequency was of administering the increments, and therefore promoting the diffusion of PEG molecules into the wood. This assumption was partly justified but the frequency of administering increments may be adjusted when very small increments are administered during a very long time interval, i.e. when the duration of the conservation procedure has been given a proper value. Some experiments also dealt with the issue of the PEG-concentration in the conservation solution at the start of the PEG-increment programme, as well as the issue of the PEG-concentration at which to terminate the PEG-increment programme.

Even by experiments it was noted that a large portion of the PEG that had disappeared from the conservation solution was not possible to be traced in the conserved specimens. This phenomenon was also noted by full scale conservation treatments.

Experiments for evaluation of the result of the conservation treatment

A couple of experiments dealt with characteristics of the resulting Vasa oak wood-PEG composite. For these experiments the test specimens were cut as full transverse cuts of the deck-batten (9 x 9 cm) and very short in the grain direction (2.5 cm). Movements in the radial and the tangential directions were measured on the transverse surface. The first of the experiments had a couple of longitudinally cut test specimens that enabled measurement of the movements in the grain direction.

The first of the experiments did involve no other PEG than PEG 4000. The second experiment involved three series, each composed of 8 test specimens, that were treated with PEG 600, 1500 and 4000, respectively. Since one test specimen was removed from each of the conservation baths at pre-determined occasions in the conservation programmes three series of test specimens with gradually increasing PEG-ratios were created (table I).

PEG-ratio (%) of wood-PEG 600, 1500 and 4000 composite specimens								
PEG-concentration programme	5	10	15	20	30	45	60	75
PEG 600	2	6	11	14	22	41	43	43
PEG 1500	1	4	11	12	22	40	52	48
PEG 4000	0	4	7	8	19	34	52	51

Table I. PEG-ratio (%) of the Vasa oak wood-PEG composite specimens

Measurements in the radial and tangential directions created a basis for calculation of the ASE values for the radial and the tangential directions of the wood, at each of these occasions. The ASE values at 55% RH are presented since the RH of museum atmospheres as a rule are kept at 55%.

ASE R(55) (%) of wood-PEG 600, 1500 and 4000 composite specimens								
PEG-concentration programme	5	10	15	20	30	45	60	75
PEG 600	0	3.7	21	31	42	78	84	91
PEG 1500	0	3.0	19	30	45	65	78	75
PEG 4000	0	0	8.0	25	39	54	74	64

Table II. ASE R(55) (%) of the Vasa oak wood-PEG composite specimens.

ASE T(55) % of wood-PEG 600, 1500 and 4000 composite specimens								
PEG-concentration programme	5	10	15	20	30	45	60	75
PEG 600	0	1.8	27	34	36	71	81	86
PEG 1500	0	4.6	31	30	38	65	71	67
PEG 4000	0	4.0	32	41	48	60	66	67

Table III. ASE T(55) (%) of the Vasa oak wood-PEG composite specimens.

From the two columns representing 60 and 75% PEG-concentration, according to the conservation programme, may be deduced that a shrinkage reducing effect from 64 to 91% in the radial direction corresponds to shrinkage reducing effects of 66 to 86% in the tangential direction (tables II and III). The figures obtained have been used to evaluate the results of the spray treatment of the hull and the immersion treatments in tanks.

The spray treatment of the Vasa hull

Equilibrium between the PEG-concentration in the conservation solution and the surface layer of the wood was chosen as criterion for moving to the next step of the conservation programme. The intended equilibrium, however, was difficult to define. After the hand-spraying period, the first period of the programme with automatic spraying was conducted for 5 years without the proper criterion established for the equilibrium.

At that time the originally stipulated point of time had passed, for the permanent Vasa museum to be opened. The construction of a new museum had been postponed due to lack of finance. However, the finance of a permanent museum building would be on the agenda each year until a decision had been made, which brought the museum director with the advice of the group of specialists, permanently attached to the Vasa project, to construct a time schedule for the conservation programme of the hull. This schedule worked out to give 3 years to the second period of the conservation programme, that like the first period consisted of continuous spraying. The third period lasted for 2 years only and involved both an increase of the PEG-concentration of the conservation solution conducted with PEG 600, that from this period and on, was the only PEG added to the conservation solution, and reduction of the frequency of spraying rounds. The last step, the fourth period of the conservation programme, was performed by raising the PEG-concentration of the conservation solution to 45% and making further reduction of the frequency of spraying rounds. That period lasted for 4 years.

Measurements of a fixed measuring interval at regular occasions during the conservation period have provided information that the Vasa oak wood of the planking and the ceiling had shrunk from the start of the automatic spray system, while the shrinkage started somewhat later in the heavy timbers (figure 7-29). During the first period of the spray treatment programme the magnitude of shrinkage of the planks of the planking and the ceiling was 0.3%, and during the second period of the conservation programme the shrinkage had increased to 0.5%. At the end of the third period of the conservation programme the shrinkage had increased to 1.8%, and at the middle of the forth period of the conservation programme to 4.4%. This level of shrinkage of the planks of the planking and the ceiling was maintained until January 1979 when the spraying was terminated.

Conclusions

Since the planks of the ceiling have obtained a PEG-ratio of c. 15% in their inner parts c. 30% reduction of the shrinkage expected without PEG in both the radial and the tangential directions of the wood may be expected when drying to an equilibrium at 55% RH. The planks of the planking with c. 10% PEG-ratio may have a 30% shrinkage reduction in the tangential direction while the shrinkage reduction in the radial direction may amount to c. 20% at the same conditions.

The immersion treatment of the loose timbers and objects

When the immersion conservation of loose wooden material from the Vasa was started, in 1962, the restricted amount of knowledge available about proper ways to handle a large conservation tank filled with a rather substantial volume of wet archaeological wooden material, had been derived from a test conservation executed in a 5m^3 tank during a period of seven months. Founded on the experience from the test treatment, two large tanks with capacities of 34 and 42 m^3, respectively, were started in the autumn of 1962 and in the spring of 1963. The tanks contained both oak and pine materials, and the treatments were operated in parallel for more than a year.

However, since some uncertainty still remained about the appropriateness for the wet archaeological oak material of the conservation programme applied, the conservation of the oak material was postponed and the conservation tanks were used for treating the pine material and some construction material that was selected to be refitted to the Vasa hull at an early stage of the conservation period.

When this had been done the conservation treatment of batches containing oak material for a complete conservation programme had to be regained. The terminating part of the treatment period often did not increase the PEG content in the wood, but rather removed water from the wood in the conservation tank. Therefore the PEG-concentration at which the programme was closed was gradually lowered. The raising of the PEG-concentration was finished at 45% during the terminating conservation batches of the Vasa material. The focus was instead placed on a period of spray treatment after the tank treatment. This would also allow for different molecular weight PEG's to be applied to the loose finds as well as to the hull.

Conclusions

The immersion-treated oak items have reached a mean PEG-ratio of c. 20% after the conservation. Since the PEG 4000 was the molecular weight PEG used for the major part of the immersion treatments this PEG-ratio corresponds to a shrinkage reducing effect of c. 40% in the radial direction and c. 50% in the tangential direction.

Sammanfattning

THE CONSERVATION OF THE WOOD OF THE SWEDISH WARSHIP VASA OF A.D. 1628

(Konserveringen av trämaterialet i det svenska krigsfartyget Vasa från A.D. 1628)

Konserveringen av Vasas trämaterial bedrevs samtidigt på tre verksamhetsställen, nämligen:

1) Vasamuseets försöks- och analyslaboratorium,
2) Vasaskrovets tillfälliga uppställningsutrymme, pontonöverbyggnaden, med anläggning för besprutning av Vasas skrov med konserveringsvätska
3) Vasamuseets konserveringsanläggning, som var utrustad med konserveringskar för behandling av trämaterial i bad.

Konserveringsförsök i laboratorieskala

Laboratorieexperimentens huvudsakliga mål var att utveckla metoder för applicering av PEG i syfte att uppnå optimal långtidsbevarande effekt av trämaterialet. Experiment utfördes både med ytapplicerings- och badbehandlingsteknik. Till en början övervägdes endast PEG 4000 som konserveringsmedel. Då sprutsystemet konstruerades för kontinuerlig besprutning av Vasas skrov skulle en PEG 4000-lösning på grund av dess högre viskositet kräva avsevärt större pumpkapacitet än en PEG 1500-lösning. Därför blev PEG 1500 aktuell som konserveringsmedel. Detta medförde att försöks- och analyslaboratoriet tog in PEG 1500 och senare även PEG 600 och i vissa fall PEG 1000 i sin försöksverksamhet.

Experiment med konserveringslösningar

Vid experiment med ytapplicering har testats parallellt dels PEG 4000 och dels carboxy-methyl cellulosa (CMC), som vid tiden för Vasas bärgning hade använts i c:a 10 år, som krympningsreducerande konserveringsmedel för vattenfyllt arkeologiskt trämaterial. Båda substanserna testades vid ytapplicering i atmosfär med hög respektive låg

RH. Trots att experimenten inte visade någon tydlig skillnad mellan effekterna av de båda substanserna, valdes PEG 4000 för konserveringen av Vasas trämaterial, delvis på grund av dess högre löslighet i vatten.

De experiment som rör utveckling av konserveringsprogram för behandling genom nedsänkning i konserveringslösning omfattade i huvudsak tre områden, nämligen: dels temperaturen och PEG-koncentrationen i konserveringslösningen, dels behandlingsperiodens längd. Det klargjordes tidigt att temperaturhöjngsprogram, som vanligen användes vid badbehandling, ökade tendensen hos vattenmolekyler att diffundera från träföremålet till PEG-lösningen. Så snart denna upptäckt hade gjorts övergavs temperatur-höjningsprogrammen till förmån för en jämn temperaturnivå. Denna fastställdes till 60°C och började genast tillämpas vid badkonservering i konserveringsanläggningen.

Även genomförandet av PEG-koncentrationsökningsprogram påverkar diffusionshastigheten för vattenmolekyler från det vattendränkta trämaterialet till konserveringslösningen. Denna bedömdes dämpas i högre grad ju mindre PEG-tillskotten var och ju oftare de tillfördes till konserveringslösningen. Därigenom skulle diffusionen av PEG-molekyler in i veden underlättas. Detta antagande bekräftades delvis, men det visade sig också att det fanns möjlighet att vara mindre exakt beträffande frekvensen då PEG tillfördes under en längre tidsperiod. Några experiment genomfördes för att undersöka effekten av att ha en viss PEG-koncentration i konserveringsbadet innan koncentrationsökningsprogrammet påbörjades. Även frågan om vid vilken PEG-koncentration konserveringsprogrammet bör avslutas har undersökts.

Experimenten har visat att en avsevärd del av den PEG som har konstaterats vara försvunnen ur konserveringslösningen efter konserveringsförsöket inte har kunnat återfinnas i de konserverade testkropparna. Detta förhållande har också noterats vid badkonservering i full skala.

Experiment för utvärdering av resultat av konserveringsbehandling

Två experiment behandlade egenskaper hos den genom konserveringsbehandlingen framställda Vasa ek-PEG kompositen. Testkropparna för dessa experiment sågades transversellt från en ribba med måtten 9 x 9 cm. Måttet i fiberriktningen på provkropparna var 2,5 cm vilket medförde att dessa kunde konserveras i bad utan att krympa under behandlingen. Rörelser i träets radiella och tangentiella riktningar uppmättes på den transversella ytan. I det första experimentet möjliggjordes mätning av rörelser i träets fiberriktning av ett par axialt utsågade provkroppar.

Det första experimentet utfördes endast med PEG 4000. Det andra experimentet omfattade tre serier, var och en av dessa bestående av 8 provkroppar. De tre provkroppsserierna hade konserverats med PEG 600, 1500 och 4000. Genom att ta upp en provkropp från vart och ett av konserveringsbaden vid förutbestämda punkter i konserveringsprogrammet åstadkoms tre serier provkroppar med gradvis ökande PEG-kvoter (tabell I).

PEG-kvot (%) för trä-PEG 600, 1500 och 4000 kompositerna								
PEG-koncentrationsprogram	5	10	15	20	30	45	60	75
PEG 600	2	6	11	14	22	41	43	43
PEG 1500	1	4	11	12	22	40	52	48
PEG 4000	0	4	7	8	19	34	52	51

Tabell I. PEG-kvot (%) i Vasa ek-PEG kompositerna.

Mätning i radiell och tangentiell riktning under torkningsperioden gav underlag för beräkning av ASE värdena för dessa riktningar i veden vid vart och ett av de avkortade konserveringsförloppen och därmed för olika PEG-kvoter. ASE värdena vid 55% RH redovisas då det är detta RH värde som vanligen upprätthålls i museerna.

ASE R(55) (%) för trä-PEG 600, 1500 och 4000 kompositerna								
PEG-koncentrationsprogram	5	10	15	20	30	45	60	75
PEG 600	0	3.7	21	31	42	78	84	91
PEG 1500	0	3.0	19	30	45	65	78	75
PEG 4000	0	0	8.0	25	39	54	74	64

Tabell II. ASE R(55) (%) i Vasa ek-PEG kompositerna.

ASE T(55) % för trä-PEG 600, 1500 och 4000 kompositerna								
PEG-koncentrations-program	5	10	15	20	30	45	60	75
PEG 600	0	1.8	27	34	36	71	81	86
PEG 1500	0	4.6	31	30	38	65	71	67
PEG 4000	0	4.0	32	41	48	60	66	67

Tabell III. ASE T(55) (%)i Vasa ek-PEG kompositerna.

Ur de två kolumner som representerar de konserveringsprogram som avbrutits vid 60 respektive 75% PEG-koncentration kan slutsats dras om storleken av den reducering av krympningen som kan uppnås. Den krympningsreducerande effekten är i storleksordningen från 64 till 91% i radiell riktning och från 66 till 86% i tangentiell riktning (tabell II och III). De erhållna ASE-värdena har använts för att utvärdera resultatet av besprutningen av skrovet samt konserveringen i bad.

Besprutningen av Vasa

Konserveringsprogrammet för Vasas skrov bygger på att jämvikt uppstår mellan PEG-koncentrationen i konserveringslösningen och i ytskiktet av det besprutade skrovet. Denna jämvikt var emellertid svår att definiera.

Efter perioden med besprutning för hand har den första perioden av programmet med automatisk besprutning fortgått i 5 år, utan att tydliga kriterier för uppnådd jämvikt hade kunnat identifieras.

Då hade den ursprungligen fastställda tidpunkten för öppnandet av det permanenta vasamuseet överskridits. Uppförandet av ett nytt museum hade försenats av brist på finansiering. Emellertid togs frågan finansiering av en ny museibyggnad upp varje år till dess att beslut hade fattats. Detta osäkra läge fick museidirektören att med stöd av konserveringsrådet fastlägga en tidsplan för skrovets konservering. Denna tidsplan kom att innebära en andra period på 3 år med kontinuerlig besprutning med konserveringslösning. Den tredje perioden varade i 2 år. Denna medförde både ökning av PEG-koncentrationen i konserveringslösningen, som skedde genom tillsats av PEG 600, som från och med denna period kom att bli den PEG som tillsattes konserveringslösningen. Under denna period reducerades antalet besprutningsomgångar. Sista steget, den fjärde perioden i konserveringsprogrammet bestod i ökning av PEG-koncentrationen i konserveringslösningen till 45% och ytterligera nedskärning av besprutningen. Denna period varade i fyra år.

Genom regelbunden mätning av fasta mätintervall på skrovet under konserveringsperioden har fastställts att ekplankorna i Vasas bordläggning och garnering har krympt. Denna började då den automatiska besprutningen igångsattes medan krympningen i grövre virke började något senare (figure 7-29). Under den första perioden av besprutningsprogrammet var den genomsnittliga krympningen i bordläggnings- och garneringsplankorna 0.3%. Under den andra perioden ökade krympningen i dessa plankor till totalt 0.5%. Vid slutet av den tredje perioden av konserveringsprogrammet hade krympningen ökat till 1.8% och vid mitten av den fjärde perioden till 4.4%. Denna senare nivå bibehölls till januari 1979 då besprutningen avslutades.

Slutsatser

Eftersom plankorna i garneringen har uppnått en genomsnittlig PEG-kvot av c:a 15% i de inre delarna motsvarar detta c:a 30% reduktion av den krympning som kan förväntas för ej konserverad Vasa ek. Detta gäller för både radiell och tangentiell riktning vid jämvikt med 55% RH i den omgivande atmosfären.. Plankorna i bordläggningen som uppnått en genomsnittlig PEG-kvot av c:a 10% i dess inre delar, torde ha uppnått en 30%-ig krympningsreduktion i vedens tangentiella riktning och en 20%-ig krympningsreduktion i vedens radiella riktning i samma museiklimat.

Badbehandling av löst trämaterial

År 1962 då konserveringen i bad av löst trämaterial från Vasa startade, var kunskapen liten om hur en stor konserveringstank fylld med en stor volym vattendränkt arkeologiskt trämaterial och en stor volym konserveringslösning skall hanteras. Den lilla kunskap som fanns vid konserveringslaboratoriet hade erhållits genom en testkonservering i ett 5m^3 konserveringskar under en period på sju månader. Med kunskapen från testkonserveringen som grund startades badkonservering i två stora kar med kapacitet för volymer på 34 och 42 m^3, ett på hösten 1962 och det andra på våren 1963. I båda karen placerades både ek- och furumaterial. Konserveringen i vart och ett av karen genomfördes under en period om något mer är ett år.

Då dessa båda konserveringar hade genomförts rådde det fortfarande tveksamhet beträffande lämpligheten av det tillämpade konserveringsprogrammet för det vattendränkta arkeologiska ekmaterialet. Därför uppsköts konserveringen av detta och karen användes för konservering av enbart furumaterial och för behandling av konstruktionstimmer som hade utvalts för återinsättning i Vasas skrov tidigt under konserveringsperioden.

Då detta hade genomförts var det nödvändigt att återuppta konserveringsprogrammet för ekmaterial. En iakttagelse var att PEG innehållet i veden inte ökades under den senare delen av konserveringsperioden. Den huvudsakliga effekten av denna hade varit att vatten avgått från veden till konserveringslösningen. För de efterkommande konserveringarna sänktes därför gradvis den PEG-koncentration vid vilken konserveringsprogrammet avslutades. Vid de avslutande konserveringsomgångarna skedde detta då 45 % PEG tillsatts enligt konserveringsprogrammet. För att det nedbrutna ytskiktet på veden skulle tillföras tillräckligt med PEG infördes i stället en period av besprutning av materialet med PEG-lösning efter badkonserveringen. Detta gjorde att PEG av skilda medelmolekylvikter liksom för Vasas skrov kunde användas även för det i bad konserverade materialet.

Slutsatser

De badkonserverade föremålen av ek har uppnått en genomsnittlig PEG-kvot av c:a 20%. Eftersom PEG av medelmolekylvikten 4000 hade använts vid större delen av badkonserveringarna motsvarar denna PEG-kvot en krympningsreducering av c. 40% i radiell och c. 50% i tangentiell riktning.

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Håfors Birgitta, 1968 03 07, C63I: The preservation programme was interrupted once again and part of the wooden material was removed to be refitted into the Vasa hull. As the weights of a number of objects had decreased since the start of the preservation procedure there was no regaining of the preservation programme after adjustment of the amount of PEG solution in the tank to compensate for the removed volume of wooden material.

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CONSERVATION OF THE WOOD OF THE SWEDISH WARSHIP VASA OF A.D. 1628

Abbreviations

ASE = anti-shrink efficiency
PEG = polyethylene glycol
RH = relative humidity

Terminology

This dissertation has discussed the concept of "hydro-archaeology", as a comprehensive concept.[217]

The concept of "conservation" is adopted for the process of dimension-stabilizing wood.

The term "conservation programme" is adopted for the preset parameters of managing a conservation procedure (with reference to what molecular weight of PEG to be used, what concentration raising programme, and what temperature programme to be adopted).

The term "conservation procedure" is adopted for the implementation of the conservation programme.

The term "conservation process" is adopted for the effect of the conservation procedure on the wet wooden object.

The term "green wood" denotes newly felled wood that has not been allowed to dry.

The term "fresh wood" is used with the same meaning as "green wood".

The term "recent wood" is used for seasoned wood from e.g. a lumberyard.

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[217] The concept hydro-archaeological is used in accordance with the definition suggested by Alison Gale in "Hydroarchaeology: A subject framework", The International Journal of Nautical Archaeology (1993) 22:3, pp 209-217.

The term "waterlogged wood" denotes wood, that has been dried and used for manufacturing an object or construction, and thereafter has been submerged into water and swelled to or near its highest possible degree of water content.

Ceiling: The planking of the interior of the frames, forming the inner skin of the main hull structure.

Planking: The longitudinal planks on the outside of the frames, which form the outer skin of the hull structure.

The term "density" of wood is adopted with the meaning conventional density according to ISO standard 3131, 1975.[218]

The term "moisture content" (u), of a piece of wood is defined as the weight loss a piece of wood suffers at drying to stable weight in a drying cabinet at a temperature of 103 ± 2°C, divided by the weight of the piece of wood after the drying procedure.[219]

The "theoretical maximum moisture content" (u_{max}), of a piece of wood is dependent on the density of the wood and may be calculated as follows:[220]

$$u_{max}\,(\%) = 100 \times \frac{1.56 - \varrho}{1.56\,\varrho}$$

where

$$\varrho = \frac{\text{weight in dry state (g)}}{\text{volume in swollen state (cm}^3\text{)}}$$

1.56 = density of wood fibres with no capillaries

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[218] Schniewind, 1990, p 89.
[219] Esping, 1992, p 82.
[220] Thunell, 1952, p35.

The term "water-ratio" denotes the ratio between the weight of the total amount of water in the wood and the dry weight of the wood piece less the weight of PEG (dry fibre weight) of the wood piece that contains this water.[221] (because of the sensitivity of PEG to elevated temperature the drying was performed at low pressure with silica gel (blue gel) as drying agent instead of the standard procedure of drying in a drying cabinet at 103 ± 2°C).

The term "PEG-ratio" denotes the ratio between the weight of the total amount of PEG in the wood and the dry weight of the wood piece less the weight of PEG (dry fibre weight) of the wood piece that contains this PEG.[222]

The term "solution-ratio or (water + PEG)-ratio" denotes the ratio between the weight of the sum of the total amount of water and the specified preservative in the wood and the dry weight of the wood piece less the weight of PEG (dry fibre weight) of the wood piece that contains the solution.

The term "PEG-concentration of assumed solution in the wood" denotes the ratio between the weight of the total amount of the specified preservative in a piece of wood as part of the sum of this weight and the weight of the total amount of water in the same piece of wood.

The term “mean value” is used to stress the fact that the values of each of the parameters “water-ratio, PEG-ratio, solution-ratio, and PEG-concentration of assumed solution in the wood” are distributed as a gradient in the piece of wood.

The term “grand mean” is used for the average values of the parameters “water-ratio, PEG-ratio, solution-ratio, and PEG-concentration of assumed solution in the wood” calculated layer by layer on all wood-core pieces belonging to a sample.

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[221] Håfors, 2001, p 115.

[222] Håfors, 2001, p 115.

The term "anti-shrink efficiency" (ASE) is defined by the following ratio:

$$ASE = \frac{S_0 - S_{PEG}}{S_0} .$$

S_0 is the shrinkage of the reference sample, and
S_{PEG} is the shrinkage of the PEG-treated sample that is to be compared with the reference
(the reference may be treated or untreated).

The term “outer surface” denotes the surface of the wood that is in direct contact with the atmosphere.

The term “inner surface” denotes the surface of the wood that is locked into a construction as e.g. the interior of a ships side.

TERMINOLOGY

Some nautical terms used in the text:
(reference works used: Oxford dictionary, 1946; Barkman, Lars; Sammanställning av skepps- och sjötermer, 1972; Cederlund, 2006).

beam:	horizontal cross-timbers of ship supporting deck and joining sides (Oxford dictionary, 1946).
deck-batten	board (6 ft or more long, 7in. x 2½ or less broad & thick) used for flooring (Oxford dictionary, 1946).
gun-carriage:	side part of gun-carriage. base part of gun-carriage. wheel part of gun-carriage. axle part of gun-carriage.
knee:	a L-shaped timber in which the grain follows the curvature, being used as a reinforcement on joints where two longer timbers are joined at an angle.
orlop deck	a deck above the hold and below the gun-decks, primarily for storage
riding bitts:	the heavy bitts at the bow on which anchor cables were belayed.
wale	a heavy plank or band of planking that provides longitudinal strength to the hull. Vasa has nine wales, which are about twice as thick as the normal planking

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