Some remarks on the processes used for the conservation of the " Bremen Cogg "

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We all know that the conservation of old wood involves difficulties. The reason for these lies in the enormous changes in structure, and consequently in the properties of the wood, which have taken place in the course of time. Special conservation treatments are therefore necessary to avoid damage or serious changes in the shape, and dimensions of the wood.

If we consider old wooden ships or boats, generally these have been subjected to very moist conditions for a period of some centuries. The Bremen Cogg, for instance, remained for over 550 years below the surface of the river Weser, protected by layers of sand and clay of a total thickness of 3 to 4 m. If we look at the changes which took place during that time in the physical, chemical and mechanical properties of this old, waterlogged wood, and compare these properties in their final state with the corresponding properties of normal fresh wood, we can make the following observations.

Firstly, to an extent which varies with the degree of degradation, the chemical constituents of the wood are influenced. The degradation is caused by micro-organisms, especially soft-rot and bacteria, and normally in the first stage there will be particular degradation of the hemicellulose and then of the cellulose, the most resistant component being lignin. The percentage of lignin content will therefore rise to an extent depending on the degree of degradation. In the case of the heart-wood of oak, which is very durable, the chemical properties of the old, waterlogged wood are only slightly different from those of fresh wood; however the lignin content of the sapwood — which is very perishable and had therefore suffered severe degradation — has risen to more than 65 %. Correspondingly, the cell walls of the sapwood consist of only a very thin membrane which is the original middle lamella and primary wall. This chemical degradation has a strong influence on the physical properties of the wood and adversely affects its chemical properties.

Secondly, we see that the maximum moisture-content, which is reached when all the capillaries and pores of the wood are completely filled with water, is also very much dependent on the degree of degradation. The moisture-content of the old oak heartwood is about 120 to 145 % of its dry weight, while the moisture-content of extremely degraded old oak sapwood — or old beech sapwood — amounts to 600 %, which is extremely high.

Thirdly, the changes in the mechanical properties of the old wooden parts — which are of very great importance for their conservation — are likewise very closely tied up with their degree of degradation. The strength of the oak sapwood, which is rather badly degraded, has decreased to a very low figure; thus the maximum crushing strength in the direction of the fibres is only about 10 kg/cm² (140 lbs.p.s.i.), whereas the crushing strength of fresh wood is 300 kg/cm² (4,000 lbs.p.s.i.) when saturated with water. The oak heart-wood, however, which is more durable, has lost only about one-third of its original crushing strength, if the samples are taken from the inner parts of large pieces of wood, and the crushing strength of the heart-wood when air-dried very slowly is in the same region as that of normal wood, owing to the high shrinkage and therefore higher density of the old wood. The tensile strength is more strongly influenced by degradation, and thus the maximum bending strength of this wood is only one-third to one-half that of fresh wood. It is quite evident that the much lower strength figures in the outer areas are the result of the higher degree of degradation, but on the whole we can say that the mechanical properties of the old wood in the Bremen Cogg are fairly good and that one of the conditions for the rebuilding of this very important find is thus satisfactorily fulfilled.

Fourthly, shrinkage behaviour is an extremely critical factor in the conservation of old, water-logged wood. If we compare the linear shrinkage of the oak heart-wood in the Bremen Cogg in the two important directions perpendicular to the grain with the corresponding shrinkage values of fresh wood, we see that the shrinkage of the old wood is twice as high as the shrinkage of the fresh wood; we therefore get an area shrinkage of the cross-sections of about 30 %, which is extremely high. To demonstrate this high shrinkage in the cross-sections I dried a disc of the oak-wood, which split and opened out.

In the outer areas of the structural parts of the Bremen Cogg, which are more degraded and in a more fragmentary state, the shrinkage values are far higher than in the case of the more intact inner parts. We can see this from the shrinkage values of the oak sapwood and of the old beech wood. The strength of the cell-structure of this highly degraded wood is so low that the cells are not in a condition to withstand the drying stresses and therefore the cells collapse during drying. As a result of this collapse the shrinkage of this old, degraded wood is in the region of 70 to 80 % of the original volume of the wood when in its saturated condition. This abnormal shrinkage behaviour on the part of the wood of the Bremen Cogg, and especially of the weaker and more degraded outer zones of the structural parts, which are more millimetres thick and

sometimes extend to the deeper layers, necessitates special preservation treatments to avoid buckling and breaking-up of the wooden parts during drying. The drying of old water-logged wood without a preservation treatment has given very poor results.

If water-saturated wood is brought into the atmosphere of the public galleries of a museum, the wood, as a hygroscopic material, dries to a definite moisture-content which is in equilibrium with the temperature and the relative humidity of the surrounding air. For fresh and old oak heart-wood this relationship between the equilibrium moisture-content and the relative humidity at a temperature of 20° C is shown in the chart. The drying of wood in the hygroscopic range is accompanied by shrinkage. Under normal conditions the mean value of the relative humidity of the air will be about 60 %, which means that fresh oak will dry to an equilibrium moisture-content of about 13 %, and the shrinkage which is produced by this drying is 7 % in the tangential and 3,5 % in the radial direction; consequently the area-shrinkage of cross-sections will be about 10,5 %. However, in the case of the old water-logged oak from the Bremen Cogg we can say that the hygroscopicity is increased by the long water-logging, as is to be seen from the fact that at all relative humidities the equilibrium moisture-content of the old wood is higher than that of the fresh oak, while this is particularly noticeable in the range of relative humidities above 80 %. This observation fits in with the fact that the old oak-wood starts to shrink at the very high moisture-level of 50 to 60 %, whereas fresh wood starts to shrink at a moisture-content of about 35 %. The equilibrium moisture-content of the old wood in air with a relative humidity of 60 % will be 15 %, which means that the tangential shrinkage at this moisture-content is about 16 % and the radial shrinkage about 6,5 %; again, the shrinkage of the old wood is twice as high as the shrinkage of the fresh wood.

The changes in the properties of the old oak wood which have taken place during the centuries are so serious that drying the wood without a dimensional stability treatment will lead to severe deformations, buckling and damage. But in any case conservation of the Bremen Cogg is a very difficult task, firstly because of its very large size, and secondly because an effective treatment can be possible only if the wood is stabilized throughout.

An analysis of the different methods of dimensional stabilization which we have tried out leads to the conclusion that an effective treatment which does not influence the shape and the appearance of the wood is possible only if it insolves the introduction of chemicals into the cell-walls of the wood. This means, in principle, that the volatile water in the water-saturated cell walls is replaced by an unvolatile chemical, so that the shrinkage of the wood is blocked by the bulking effect of the chemical.

Unfortunately, in the case of the Bremen Cogg it is not possible to impregnate the old wood with resins, because of the high density and the large dimensions of the wooden parts and of difficulties in hardening the resin. But a chemical which during recent years has been used with great success for the dimensional stabilization of green and water-saturated woods is polyethylene glycol, which is non-volatile but water-soluble. From experiments in the United States we know that a very effective dimensional stabilization is possible if one contrives to impregnate the wood with sufficient quantities of polyethylene glycol across its whole section; the value of the dimensional stabilization effect can be more than 95 %. Furthermore we know that the bulking effect of polyethylene glycol depends on its molecular weight, because the diffusion of the polyethylene glycol into the submicroscopical structure of the wood substance depends on the size of the molecules; the smaller the polyethylene glycol molecules the higher is the diffusion rate. On the other hand, polyethylene glycol with a low molecular weight is extremely hygroscopic in itself, which is a disadvantage, because the treated wood will attract water from the air if the relative humidity is comparatively high, so that the surface of the wood becomes wet.

From the research work which has been carried out so far, PEG-1000 would seem to be the most effective chemical. We therefore did some experiments to study the stabilization effect of this chemical on the old dense oak of the Bremen Cogg with its abnormal shrinkage values. To achieve satisfactory impregnation within a period of about three years, we used small samples, only about 5 mm long in the direction of the fibres. The results of our experiments are described below.

Fresh oak which is impregnated with a 20 % polyethylene glycol solution and dried to an equilibrium moisture-content of 10 % already shows a dimensional stabilization effect amounting to about 40 to 50 %, while treatment with a 40 % polyethylene glycol solution gives a stabilization effect of 90 to 95 %, so that the absolute shrinkage values in the tangential and radial direction are rather low, being about 0.5 %. We can therefore say that the wood practically does not shrink after this treatment. If the percentage of the polyethylene glycol solution is raised to 60 %, we already get a little swelling of the wood, so that the shrinkage is not merely compensated for but has even become slightly negative.

If we make the same experiment with old wood, likewise dried to an equilibrium moisture-content of 10 % after the treatment, we obtain the following results. The treatment with a 20 % polyethylene glycol solution gives a stabilization effect of only about 20 %, though the absolute shrinkage values are clearly reduced. With a polyethylene glycol solution of 40 % the effect of dimensional stability is improved considerably to about 60 to 70 %, and impregnation with a 60 % polyethylene glycol solution gives the remarkable effect of dimensional stabilization at 90 to 97 %; the absolute shrinkage values in the radial and tangential direction are now only 0.5 % instead of 7.5 or 17.5 %, which shows clearly that the dimensional stabilization of the old water-logged oak wood is nearly complete.

These results show that with the use of PEG-1000 dimensional stabilization of the old water-logged oak is possible, if the stabilization treatment procedure guarantees good impregnation of the wood with sufficient quantities of PEG. We have therefore developed a special treatment procedure which is based on the very valuable experience acquired in the U.S.A., and above all in the Scandinavian countries in connection with the « Vasa » and the viking ships.

Impregnation of the wood with polyethylene glycol is best achieved by the diffusion process in a polyethylene glycol-water solution. A prerequisite for this process is completely water-saturated wood without any air-inclusions, which would hinder the diffusion. When the wood is dipped into the polyethylene glycol solution, which is of a given concentration, the polyethylene glycol molecules diffuse into the wood as determined by the existing concentration gradient, while at the same time the water molecules thus replaced diffuse out of the wood. Normally, the concentration gradient would be as high as possible, so as to give a high diffusion rate, but this is not permissible in the case of old and very dense wood, because there is severe danger that the small water molecules may diffuse out of the wood much faster than the relatively big polyethylene glycol molecules can diffuse in the opposite direction; the wood would therefore "dry" and consequently shrink during the treatment. Our intention, however, was to prevent shrinkage by the impregnation treatment, not to produce it. This drying effect, which occurs if the wood is treated with a too highly concentrated polyethylene glycol solution provides the explanation for the very negative experiments sometimes made in the past.

In the old oak heart-wood in the Bremen Cogg the diffusion rates of the polyethylene glycol are extremely low, because the capillaries of the wood are filled with degradation substances and minerals. It therefore takes a long time to achieve a satisfactory impregnation of the wood perpendicularly to the grain. Impregnation tests which we made on discs showed that within a period lasting over two years the polyethylene glycol had impregnated only a very thin surface-layer a few millimetres in depth. This leads us to conclude that good impregnation of the thicker wooden parts will take as long as several decades.

It is for this reason that a different impregnation method is being used in the case of the "Vasa", a very big ship which is far too large to be submerged in a polyethylene glycol solution for that length of time. The only method which can be used for the conservation of this object with the aid of polyethylene glycol is the continual spraying method. So far the quantities of polyethylene glycol taken up by the wood are very small, but it is expected that there will be satisfactory diffusion into the wood in the course of time.

After a study of the problems involved in the use of polyethylene glycol for conservation, we have come to the conclusion that the method which will give the best and most promising results in the case of the Bremen Cogg is as follows.

The wood should be treated by submerging in polyethylene glycol-1.000 solutions, the concentration of which should be very low for the first few years. During that time the concentration should be about 5 to 10 % only, and it should then be raised very slowly, step by step, over a long period of years, until it reaches a final concentration of 60 %. This treatment will require a very long time — 20 to 30 years at least.

The separate parts of the Bremen Cogg, which are at the moment stored singly in water, are therefore to be re-assembled, in their water-saturated condition, as soon as possible. The rebuilding of the ship must be done in an atmosphere with a relative humidity of nearly 100 %, produced by spraying, to prevent any drying of the wood during the process. Reconstruction should take place in a large tank with a length of about 24 m, a width of 7 m, and a height of 8 m. The tank must then be filled with water to which has been added a water-soluble preservative for protection against micro-organisms, to prevent any further degradation of the old wood. If the walls of the tank have large windows of transparent glass the Cogg can be shown to the public throughout its subsequent conservation treatment. An important condition for this is constant purification of the water and of the impregnation solution to remove the coloured extractives leached out of the old wood during the impregnation process. Further, polyethylene glycol-1.000 possesses only a very low light-absorption capacity, so that it will be possible to add it to the water after a given leaching period and raise its concentration very slowly over several decades. By this procedure it will be possible to combine dimensional stabilization treatment with storage of the Bremen Cogg in water.

After the conservation treatment has been completed, the polyethylene glycol solution can be drained off and the wood can be dried by very careful air-drying. If treated as mentioned above, the old wood of the Brement Cogg will have a satisfactory dimensional stability and be reliably preserved; furthermore, the ship can be shown to the public throughout the process.

But before this conservation treatment could be recommended two very important problems had to be solved by experimental studies: the first of these was the gluing of the wet wood and the second the constant cleansing of the impregnation bath.

A prerequisite of the rebuilding of the Cogg in its water-saturated condition was the possibility of durably assembling its different parts and its many fragments. We all know that direct gluing of wet or moist wood is not possible because the adhesion between the glue and the wet surface of the wood will be unsatisfactory. On the other hand, the normal procedure for drying the pieces of wood is not permissible because of the abnormal shrinkage of the old wood. However, in order to secure

sufficient adhesion between the glue and the wood surface it is theoretically necessary to dry only the outermost surface-layer of the wood pieces to a low moisture-content and to see that the arrival of moisture from the wet inner regions of the wood takes longer than the glue takes to harden.

We therefore made some special gluing tests on the old oak. Before gluing we dried the outermost layer of the wood only, using infra-red heating, since by this method it is possible to warm the surface of the wood selectively in about one hour without producing surface warping. We applied resorcin-formaldehyde resin to the dried surfaces and glued the pieces by applying a low-contact pressure for about 12 hours. We then submerged the glued pieces in water once again. A study of the shear strength of the line of glue gave figures for the wet-glued oak which were remarkably high. For shear stresses in the direction of the wood fibres these figures were 40-60 kg/cm² (550 to 700 lbs. p.s.i.). The illustration shows the fracture surfaces of the shear samples, with a clean fracture in the wood, proving that the shear strength of the glue-line is greater than that of the old oak when wet. These results for the gluing of wet oak after infra-red drying thus satisfy the prerequisite for the rebuilding of the Bremen Cogg in its water-saturated condition.

We further studied the glueability of old wooden parts previously treated with polyethylene glycol solution and subsequently put back into water, using the same infra-red drying method. The shear strength of the glue-lines was only half as high as the shear strength of the untreated wood, and the surface of the shear plane showed a pure glue fracture. Nevertheless the absolute shear-strength figures were fairly high, amounting to about 20 kg/cm² (300 lbs. p.s.i.). These results show that adhesion between the glue and the wood surfaces is essentially lowered by the polyethylene glycol; but on the other hand it also shows that by gluing wet wood which has been treated with polyethylene glycol it is possible to obtain fairly strong adhesion. These results are of special importance for the gluing of those wooden parts which already show rather badly degraded surfaces and therefore cannot be dried by infra-red heating without developing severe buckling. Wood pieces with degraded surfaces should be treated with polyethylene glycol solutions for a comparatively short time, and once their surface-layers are impregnated with polyethelene glycol they can be dried by infra-red heating without danger of buckling.

The second problem involved if the Bremen Cogg is to be kept in a large tank with windows in it during the impregnation process is that of maintaining a clear and transparent impregnation bath. The old water-logged wood has the great disadvantage of containing large quantities of extractives such as tannins and humic acids, which give the water a deep black-brownish colour. Unfortunately, the leaching-out of these coloured extractives is favoured by polyethylene glycol. Special studies have therefore had to be carried out on the possibility of continually cleansing the impregnating solution; they were done with a pilot plant specially devised for the purpose by the German firm of Borsig. The clarification process works in such a way that all suspended particles and coloured substances are removed by filters of rubble and activated carbon without in any way influencing the wood preservative or the polyethylene glycol. The illustration shows how the plant functions : it consists of a polyvinyl chloride container which can hold about half a cubic metre of the impregnating solution. The latter is first pumped through the rubble filter and then through the activated carbon filter; by operating a series of valves it is possible to switch the single-filter units parallel or in a row, so that the velocity of flow and the capacity of the filters can be regulated over a wide range and under the same conditions as in the actual large-scale impregnating process. The experiments in this pilot plant were carried out with original pieces of wood from the Bremen Cogg, the ratio of the volume of wood to the volume of the impregnating solution being nearly the same as in the future impregnating process. A measure of the quality of the cleaning is the light-transmittance of the impregnating solution. This light-transmittance is expressed as a percentage of the light-transmittance of clear distilled water; if the light-transmittance of distilled water is taken as 100 %, that of a 10 % polyethylene glycol solution will be about 99 %, i.e. practically the same, and fortunately the light-transmittance decreases very slowly with increasing polyethylene glycol content. It was found that a polyethylene glycol solution at 70 % showed a light-transmittance of 97 %. The results of the clarification tests made in the pilot plant, which were carried out with very impregnating solutions, whose light-transmittance was only 20 to 30 %, have led to the conclusion that it is possible to achieve acceptable cleaning up to a velocity of filtration of 2 metres (about 7 ft.) per hour. In this process the polyethylene glycol and the wood preservative, wich consists of an organic bromide salt, pass both filters unaffected. It can be said, in short, following these pilot tests, that it will be possible to cleanse the solution on a large scale.

The solution of these two problems — that of gluing the wet wood and that of repeatedly cleansing the impregnating bath — was an absolutely essential prerequisite on the technical level for reconstruction of the Bremen Cogg and lasting conservation of the ancient water-logged wood of wich it consists.

SUMMARY

LA CONSERVATION DU BOIS DU BREMER KOGGE

Le navire marchand de Brême s'est trouvé durant des siècles dans un milieu saturé d'eau; par suite du processus de décomposition, les propriétés physiques et mécaniques du bois de chêne se sont fortement altérées. Les zones les moins attaquées, à l'intérieur des parties plus épaisses, possèdent encore environ 30 à 60 % de la solidité d'un bois frais, tandis que les surfaces les plus dégradées présentent, selon le degré de leur décomposition, une résistance beaucoup plus réduite. Le rétrécissement du vieux bois trempé est considérable : le bois saturé d'eau et asséché jusqu'à l'état sec diminue à peu près deux fois de plus que le chêne nouveau. Le rétrécissement anormal est dû à la forte dégradation des couches superficielles du bois, épaisses par endroits de plusieurs millimètres, et se prolongeant parfois, comme des nids, vers l'intérieur des zones moins atteintes. Des mesures spéciales de stabilisation sont nécessaires afin d'éviter la rupture, le détachement par feuilles et la décomposition lors du séchage. On recommande, comme traitement de conservation, une imprégnation par trempage dans une solution aqueuse de polyéthylène glycol, selon des procédés spéciaux et pour aboutir à une amélioration efficace, la concentration de la solution doit être augmentée continuellement pendant plusieurs décennies jusqu'à l'obtention d'une concentration finale d'environ 60 %. A cause de la durée considérable de ce traitement d'imprégnation, il est prévu d'assembler le navire marchand de Brême à l'état humide et de l'imprégner dans un bassin aux plaques antibuées, afin de l'étudier convenablement pendant le traitement. Ce processus a été rendu possible par la solution de deux problèmes techniques importants; primo : l'obtention d'un collage durable du bois humide avec la colle résineuse de formaldehyde-resorcine; secundo : le développement d'un procédé de préparation pour nettoyer constamment le bain d'imprégnation des substances d'extraction fortement colorantes qui se dégagent du bois au cours de ce traitement.