

# A NEW METHOD FOR DRYING WATERLOGGED WOODEN ARTEFACTS: COMPARISON OF CYCLICAL PRESSURE DROPS WITH CONVENTIONAL METHODS

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A new drying process dehydration by cyclical pressure drops (Déshydratation par Détentes Successives: DDS), was devised and developed for drying waterlogged and fresh woods. This study examines the effectiveness of this drying process compared with the standard drying processes such as hot air, continuous vacuum and freeze-drying. For archaeological specimens, parameters such as dimensional stability (directional,  $S_d$ , or volumetric,  $S_v$ , shrinkage) and colour stability are important, as well as subjective parameters such as cracks, splits and distortions. The DDS process gave satisfactory results coupled with a high drying rate. Small values of shrinkage were obtained with DDS;  $S_v$  values were in the range of 7–13% compared with 11–17% with continuous vacuum drying, 18–36% with hot air, and 8–11% for freeze-drying. It is concluded that DDS is a suitable and fast way of drying waterlogged and fresh wood.

*Keywords:* conservation; waterlogged wood; dehydration; colour preservation; dimensional stabilization; shrinkage.

## INTRODUCTION

Wood from ancient boats, shipwrecks or wooden artefacts that have lain under water for a long time, often many centuries, must be treated to obtain the well-preserved quality required for exhibition in museums. In many cases the wood has been excavated from sites under seas and lakes and has lost its rigidity as a consequence of the loss of part of its structural material (De Jong, 1972; McCawley, 1977; Foley, 1990). The treatment of waterlogged wood remains a big problem due to the high quality demanded for exhibition in a museum. Generally, the criteria used to select artefacts of museum quality are slight or no shrinking, no splits or cracks and no colour change of the artefacts after drying. Drying is therefore one of the most important stages of the treatment of waterlogged wood and has been the subject of a lot of research. Many of the above problems have not yet been overcome. Shrinkage after drying is a much bigger problem with waterlogged wood than with fresh wood.

Free air, artificial hot air (Schweizer *et al.*, 1984; Johansson, 1990; McLeod, 1987), continuous vacuum and freeze-drying have been extensively examined (Ambrose, 1990; Watson, 1984; Hug, 1984; Drocourt and M-Deladalle, 1984). Shrinkage and splitting of wood are linked to the constraints induced by the standard hot air and vacuum drying methods. For these reasons, freeze-drying was preferred. It's well known that freeze-drying gives the best dimensional

stabilization results. At the same time, freeze-drying is the more expensive process, due to the cost of the equipment and the very long drying time, which accordingly increases energy consumption. The time factor is related to the low rate at which the freeze-dryer must be operated in order to obtain the desired quality (Cook and Grattan, 1990). Therefore, there is a need for an alternative method that provides both a higher quality and a shorter drying time. An original treatment for archaeological wood conservation (Figure 1) was devised by Sanya (2000). It consisted in using starch and/or its derivatives mixtures for wood impregnation coupled with a thermal treatment and a drying. The thermal treatment had two consequences: a total elimination of bacteria and a consolidation of waterlogged wood samples.

The use of starch solutions was justified for different reasons. Starch is an inexpensive, environmental and non-volatile material. It derives from vegetables and for this reason, it appeared to be one of the best materials for safe impregnation of the wood structure.

This paper concerns the last step of the process and aims to assess the efficiency of a new drying method (Maache-Rezzoug *et al.*, 2002) for waterlogged wood, devised and developed in our laboratory: dehydration by cyclical pressure drops (DDS: déshydratation par Détentes Successives). The DDS process involves a series of cycles during which the waterlogged or fresh wood is placed in desiccated air at a

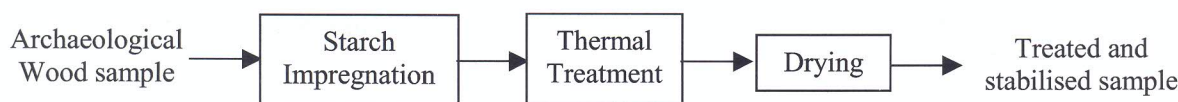


Figure 1. Sequences of the process developed by Sanya (2000) for the conservation of waterlogged woods.

given pressure then subjected to a rapid (<2 seconds) pressure drop to a vacuum ( $P_v$ ).

Among the parameters of this drying process, the high pressure ( $P_h$ ) was varied which allows us to evaluate the effect of the amplitude  $\Delta p = P_h - P_v$  since the value of the vacuum pressure  $P_v$  was fixed at 35 kPa. The experimental results obtained when drying various species of waterlogged wood and some resinous fresh wood showed that DDS was very efficient in terms of dimensional stabilization, colour preservation and drying time.

## MATERIALS AND METHODS

### Wood Samples

Several species of waterlogged wood and two fresh wood species were used in this study. Not all the species of waterlogged wood used were identified so they were labelled as samples  $ww_1, ww_2, \dots$ . Most were from *pinus* (*pinea, maritime, sylvestris*...).

Experiments were performed with samples cut from the same sections of different waterlogged artefacts. The sample dimensions in the axial i.e. fibre (a), radial (r) and tangential (t) directions were about  $40 \times 30 \times 30$  mm. Small samples were always used for the experiments because taking bigger samples damaged the wood artefacts. The samples were rinsed with ordinary water and then stored with desalting water in polystyrene bags for at least two days to allow for homogenization before drying.

Maximum water content (MWC), defined as the mass of water per mass of dry wood material, was always used to classify waterlogged wood (Table 1). Water content was determined before and after treatment by placing about 2 g of each sample in a 60-l Air Concept drying oven at atmospheric pressure and at  $105^\circ\text{C}$  for 10 to 18 hours.

Two fresh wood species, *Pinus sylvestris* and larch, both from the Limousin (France), were also investigated in this study. Bigger samples could be cut from the fresh wood than from waterlogged wood. The sample dimensions were therefore between  $40 \times 50 \times 40$  mm and  $70 \times 90 \times 50$  mm.

### Starch Impregnating Solution

The impregnating solution was composed of a mix containing two starch types: a white dextrin (2/3) and a granular cationic maize starch (1/3), both of them were available as a free-flowing white powder. The Brookfield viscosity of the impregnating solution was about 225 m Pas at 100 rpm. In this study, all the archaeological wood samples

were impregnated for 10 days and then submitted to a thermal treatment.

### Thermal Processing

The different species of waterlogged wood were divided into three groups (Table 1) according to their maximum water content (MWC). Highly deteriorated wood had a MWC of more than 500%, intermediately degraded wood a MWC in the range 200%–500% and slightly degraded wood a MWC < 200%.

Depending on the maximum water content that defines the degradation of the samples, two thermal processing methods were adopted. For MWC < 500%, the heating was performed by radiation, obtained by means of a circulation of steam at  $180^\circ\text{C}$  in the double bed of the processing chamber. The impregnation stage showed that highly degraded waterlogged woods absorbed more starch and finally contained lower residual water than the slightly deteriorated. Therefore, for MWC > 500%, we chose to use a small quantity of water which was put in the bottom of the processing chamber before closing and radiant heating to achieve conditions of high relative humidity. For all archaeological and fresh wood samples, the thermal processing time was about 1 hour. The two steps (starch impregnation and thermal treatment) were applied before all the different drying processes that are compared in this study.

### Hot Air, Vacuum and Freeze-Drying Apparatus

To compare the drying processes, some of the wood samples were dried with hot air and others using a continuous vacuum. Freeze-drying is known to be the best means of treating waterlogged wood because it ensures good dimensional stabilization (Ambrose, 1990; Watson, 1984) and was therefore chosen as a reference. A laboratory freeze-dryer, RP-2V type provided by SGD Serail (France), was used. The freezing temperature was about  $-40^\circ\text{C}$  followed by a sublimation from  $-40^\circ\text{C}$  to  $3^\circ\text{C}$  at 1.5–3 Pa.

The experimental hot air dryer was an Air Concept drying oven and the continuous vacuum apparatus was an EAV 275 drying oven, both from FirLabo Constructor (France).

### Dehydration by Cyclical Pressure Drop Apparatus

The theory behind hot air, continuous vacuum and freeze-drying is relatively well understood. We have therefore chosen only to present in this paper the principle of the dehydration by cyclical pressure drop (DDS).

Table 1. The maximum water content (MWC, %) of the different waterlogged woods used in this study.

Waterlogged wood	WW <sub>1</sub>	WW <sub>2</sub>	WW <sub>3</sub>	WW <sub>4</sub>	WW <sub>5</sub>	WW <sub>6</sub>	WW <sub>7</sub>
MWC (%)	321	343	230	281	526	184	390

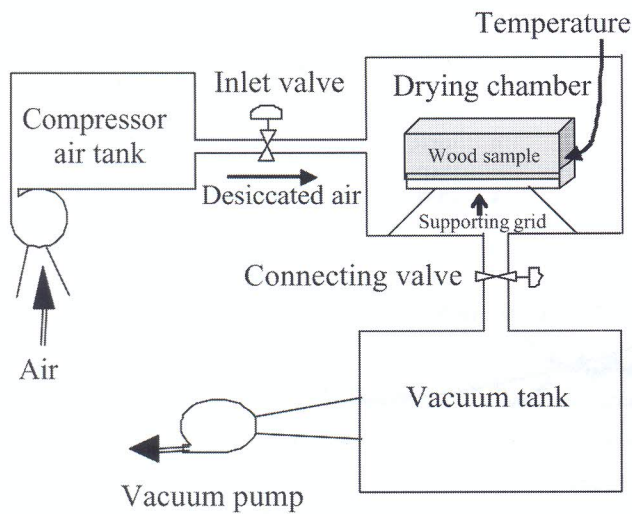


Figure 2. Schematic representation of DDS apparatus with three main parts: the treatment chamber (12l), the vacuum tank (1600l) and the valve for the connection of the two parts.

DDS consisted of subjecting a moist material (waterlogged wood samples) in an airtight chamber to cyclic variations in pressure. Each cycle consisted of alternate compression and decompression phases. The compression phase was achieved by releasing compressed air into the drying chamber (Figure 2). During this phase, an inlet air servo-valve controlled the increase in pressure to the desired level ( $P_h$ ). A compressor provided air that could, if required, be dried in an existing electrical dehydrator before releasing it into the drying chamber. The results presented in this study were obtained with dry air supplied at about 18% relative humidity measured at ambient temperature and before coming into contact with the wood sample.

The exposure to relatively high pressure is followed by a decompression ensured by a rapid release (less than 2 seconds) between the drying chamber and the vacuum tank, which has a volume (1600 litres) 130 times greater than the

volume of the drying chamber (12 litres). The fast pressure drop, which was achieved by rapidly opening the connecting valve between the two parts (drying chamber and vacuum tank), marked the end of the compression phase and the beginning of the decompression phase. The main characteristic of this phase was the drop to a vacuum.

As in the compression phase, the vacuum phase was also fixed at a determined,  $P_v$ , value (Figure 3). An appropriate 5.5 kW water sealed pump (HIBON, France), fitted to a high capacity vacuum tank connected to the drying chamber by a rapid valve, generated the vacuum. During the two phases, there is no heating source in the drying chamber.

During each pressure drop, the variation in pressure (and temperature) in the drying chamber, and thus in the immediate vicinity of the material, resulted in an alternate pressure (temperature) variation. The wood sample was then subjected to non-equilibrium conditions. Indeed, at equilibrium pressure, the water temperature is higher than the equilibrium temperature, thus leading to evaporation.

This loss of water from the moist wood had a drying effect on the sample and the same phenomenon occurred during each 'pressure increase-drop to a vacuum' cycle. The cycle period is very short compared to the total DDS drying time. In this study the cycle period was about 12 seconds (Figure 3) while the drying time was about 700 minutes (Figure 4)

Each decompression phase is accompanied by a cooling and heating effect that produced a temperature gradient through the wood measured with a K-type thermocouple. Maache-Rezzoug *et al.* (2002) who tested this drying process on collagen gels concluded that the increasing of temperature is due to heat accumulation in the form of kinetic energy during the compression phase of each cycle.

The pressure could be monitored and controlled using a pressure probe placed inside the drying chamber and connected to the data system.

The different dryers used in this study worked at temperatures in the range of 30°C to 50°C. These temperatures were controlled with a K-type thermocouples and chosen after preliminary trials. In fact we observed that higher

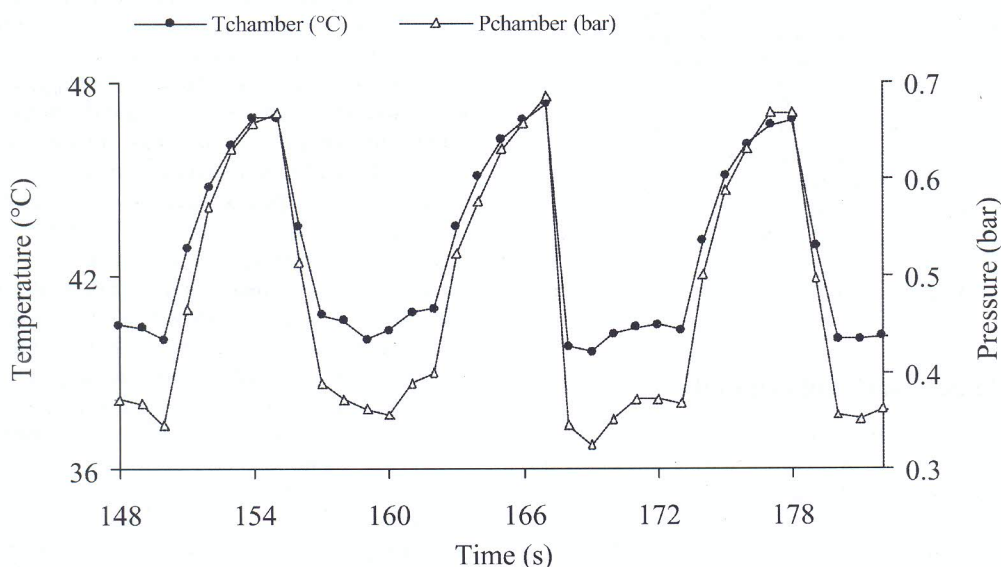


Figure 3. Typical pressure and temperature variation vs. time in DDS apparatus chamber during drying experiment.

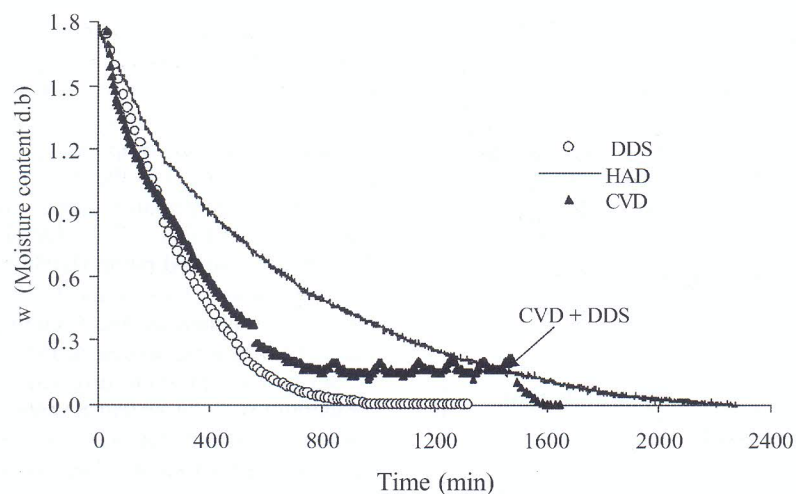


Figure 4. Comparison of moisture content vs. drying time for hot air drying at 40°C (HAD), continuous vacuum at 40°C and 12 mbar (CVD) and DDS ( $\Delta p = 0.5$  bar) processes. CVD + DDS mean that a DDS drying was performed after continuous vacuum drying. Archaeological wood: WW<sub>7</sub>.

temperatures induced more constraints, more deformations and produced dried wood of bad quality.

#### Dimensional Characterization

In all the dryers used in this study, sample weight was recorded until a constant mass was attained, at which point the dryer was switched off. The samples were then stored in polystyrene bags at room temperature (15–20°C) and a relative humidity of about 48–52%, before the final measurements of dimensions. Dimensional stabilization was measured with a 1/100-sliding calliper. The samples were measured on three positions of the parallel faces, before and after treatment. Axial (a), radial (r) and tangential (t) dimensions were measured and the percentage shrinkage in the *i*-direction ( $S_i$ ) was calculated using Equation 1:

$$S_i = \left[ \frac{D_{0i} - D_i}{D_{0i}} \times 100 \right] \quad (1)$$

where  $i = (a, r, t)$  and  $D_{0i}$ ,  $D_i$  represented the initial and final dimensions in the *i*-direction. Volumetric shrinkage ( $S_v$ ) was then calculated. In the quality control of dried fresh wood, it is generally admitted that volumetric shrinkage can be calculated as the sum of radial and tangential shrinkage since axial shrinkage is generally negligible. Axial shrinkage when drying waterlogged wood is greater and so must be taken into account. Thus, volumetric shrinkage ( $S_v$ ) for waterlogged wood was determined as the sum of the three components:

$$S_v = \sum S_i \quad \text{where } i = (a, r, t) \quad (2)$$

#### RESULTS AND DISCUSSION

The experimental results for controlled hot air drying (HAD) showed that, at the processing temperatures of 30 and 40°C, all samples began to crack and shrink before 25% of their water content had been lost. At the end of the experiments, most wood samples, and in particular those from the highly degraded class (MWC > 500%) tested at 30°C, were completely unrecognizable. This was due to the

presence of cracks and changes in dimension of the samples coupled with distortions and a change in colour. In this case, shrinkage of the dry samples was not measured. Some of the samples, including the slightly degraded wood, looked worse than those taken from the same wood and free atmosphere air-dried. It was concluded from these results that the hot air drying method was not appropriate for waterlogged wood artefacts. The quality of the dried sample was very poor and the drying time was too long compared to the continuous vacuum experiments (Figure 4). These results confirm those obtained by many authors who have studied hot air drying of waterlogged wood (MacLeod, 1987; Schweizer *et al.*, 1984; Johansson, 1990).

With continuous vacuum drying (CVD), the slightly degraded samples were of a relatively good quality at both processing temperatures (between 30 and 40°C). The intermediately degraded samples split but looked better than hot air dried samples. The highly deteriorated samples split and shrank. Most of the vacuum dried wood samples had the same appearance as hot air dried samples. In this case, it was also impossible to measure the dimensions of the samples and no shrinkage values are reported in Table 1 (continuous vacuum drying and hot air drying experiments performed with WW<sub>7</sub> archaeological wood). Nevertheless, a change in sample colour was noticed with continuous vacuum drying at both temperatures. This could be related to the lack of oxygen in vacuum drying compared with hot air drying. Shrinkage of the dried samples and drying time were reduced compared to hot air drying but DDS drying resulted in less shrinkage and a shorter drying time.

It should be stressed that with DDS, the quality of the end product depended on the processing conditions. The pressure amplitude is defined as the difference between the pressure at the end of a compression phase, i.e. the high pressure  $P_h$  (the pressure after air has been released into the drying chamber) and that attained at the end of a rapid decompression, i.e. the low pressure  $P_v$  (pressure in the vacuum tank) such that the processing pressure, or pressure drop,  $\Delta p = (P_h - P_v)$ . At relatively high amplitudes ( $\Delta p$  between 2 and 3 bar or more) thus at high values of  $P_h$ , since  $P_v$  was fixed at 35 kPa, most of the wood samples

seemed to crack and split, similarly to what was seen with hot air drying, although the deformations were not as extensive as with the latter method. At relatively low amplitudes, most of the dried samples attained the desired quality.

Based on the different results with the dried samples, we concluded that the efficiency of DDS with waterlogged wood firmly depended on the processing pressure. The results presented in this paper were obtained with pressure values of  $\Delta p$  from 50 to 80 kPa. At these low values, all of the dried wood samples seemed to be well preserved and we observed that the lower the values of  $\Delta p$ , the lower the values of the shrinkage. From Table 2, the good dimensional stability of the DDS-treated samples should be noted, since the volumetric shrinkage varied, in the majority of DDS drying experiments, between 4% and 10%.

Where the shrinkage values for DDS-dried samples were relatively high (11 to 14%), no comparable value was available for the hot air and vacuum dried samples because of their extreme deformation.

### Kinetics of Waterlogged Wood Drying by DDS

Moisture content versus time for hot air, continuous vacuum and DDS and drying rates for DDS, expressed as a function of moisture content are respectively shown in Figures 4 and 5.

Drying rate versus moisture content gave a linear relation with all the experimental conditions used for DDS. This

may indicate that the DDS drying mechanism is governed by a simple diffusion process that can be empirically modelled using an exponential equation of the form:

$$-\frac{dW}{dt} = a \cdot W \Rightarrow \frac{dW}{W} = -a \cdot dt \quad (3)$$

The solution of such an equation was commonly expressed as:

$$W(t) = W_0 \cdot \exp(-a \cdot t) \quad (4)$$

where the constant  $a$  depends on parameters such as wood characteristics and operative conditions (temperature, pressure, ...). The experimental results in Figure 5 show two DDS runs: run 1 corresponds to a  $\Delta p$  of 80 kPa and run 2 to a  $\Delta p$  of 50 kPa. As can be seen, increasing the pressure amplitude resulted in an increased drying rate but not the quality of the dried sample. In fact, drying waterlogged wood requires small drops in pressure (low pressure amplitude); higher drying rates lead to splitting and cracking and thus produce poor quality wood. The drying kinetics (Figure 4) showed that, compared to the continuous vacuum drying, the drying time was reduced by about 10% for residual moisture content below 30%. Sanya (2000) mentioned a reduction of about 1/3 for some kinds of archaeological wood.

All of the comparative experiments showed that the continuous vacuum drying method was faster than hot air drying. Freeze-drying was the slowest of the processes studied. This is clearly linked to the fact that wood samples must be

Table 2. Measured shrink values (%) for waterlogged wood (codes WW indexed) and fresh wood (FW) samples dried by different drying processes.

Sample type	Drying mode	Radial (%)	Tangential (%)	Axial (%)	Volumetric (%)
WW <sub>1</sub>	CVD (30°C)	8.99	1.76	1.29	12.04
WW <sub>1</sub>	DDS ( $\Delta p$ = 60 kPa)	3.63	4.14	0.93	8.70
WW <sub>1</sub>	DDS ( $\Delta p$ = 50 kPa)	1.71	3.83	1.28	6.82
WW <sub>2</sub>	DDS ( $\Delta p$ = 50 kPa)	1.71	2.28	0.71	4.70
WW <sub>3</sub>	CVD (30°C)	6.85	6.26	0.47	13.58
WW <sub>3</sub>	CVD (40°C)	9.17	20.81	-0.08	29.90
WW <sub>3</sub>	DDS ( $\Delta p$ = 80 kPa)	2.23	6.51	1.70	9.98
WW <sub>3</sub>	DDS ( $\Delta p$ = 60 kPa)	4.10	4.68	0.46	9.24
WW <sub>3</sub>	DDS ( $\Delta p$ = 50 kPa)	2.64	1.29	0.36	4.29
WW <sub>4</sub>	CVD (30°C)	3.90	6.16	0.01	10.07
WW <sub>4</sub>	DDS ( $\Delta p$ = 50 kPa)	3.14	2.11	0.91	6.16
WW <sub>5</sub>	CVD (30°C)	5.84	18.60	5.61	30.05
WW <sub>5</sub>	HAD (30°C)	7.23	10.74	-1.31	16.66
WW <sub>5</sub>	DDS ( $\Delta p$ = 50 kPa)	1.86	3.03	0.19	5.09
WW <sub>6</sub>	DDS ( $\Delta p$ = 80 kPa)	4.83	5.69	0.84	11.36
WW <sub>6</sub>	DDS ( $\Delta p$ = 60 kPa)	2.46	3.78	0.56	6.80
WW <sub>6</sub>	DDS ( $\Delta p$ = 50 kPa)	1.57	2.01	0.72	4.30
WW <sub>6</sub>	DDS ( $\Delta p$ = 50 kPa)	0.86	2.07	1.26	4.19
WW <sub>7</sub>	CVD (40°C)	—	—	—	—
WW <sub>7</sub>	HAD (40°C)	—	—	—	—
WW <sub>7</sub>	DDS ( $\Delta p$ = 60 kPa)	7.33	6.97	0.11	14.40
WW <sub>7</sub>	DDS ( $\Delta p$ = 50 kPa)	0.12	4.32	0.53	4.97
WW <sub>7</sub>	FZD	4.09	5.40	0.35	9.84
WW <sub>7</sub>	FZD	2.85	4.79	0.00	7.64
FW	CVD (40°C)	10.92	7.63	0.42	18.97
FW	CVD (30°C)	6.50	6.77	0.44	13.71
FW	CVD (30°C)	6.10	6.99	0.33	13.41
FW	HAD (40°C)	12.31	4.13	1.04	17.47
FW	DDS ( $\Delta p$ = 50 kPa)	4.79	6.58	0.04	11.40
FW	DDS ( $\Delta p$ = 50 kPa)	3.44	8.00	0.03	11.48
FW	DDS ( $\Delta p$ = 60 kPa)	3.83	7.74	0.19	11.75
FW	DDS ( $\Delta p$ = 60 kPa)	3.61	6.15	2.28	12.04

HAD: hot air drying; CVD: continuous vacuum drying; FZD: freeze-drying; DDS: dehydration by cyclical pressure drops.

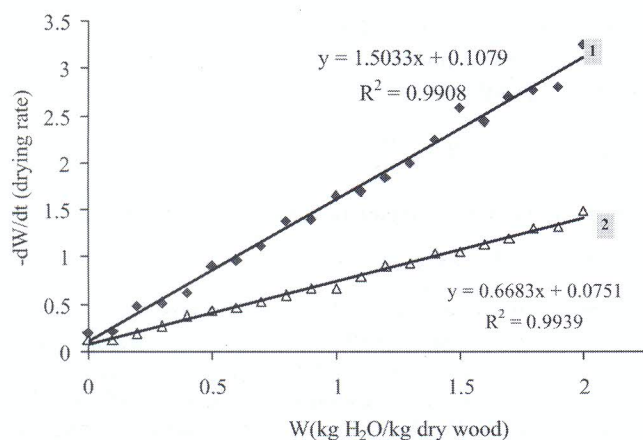


Figure 5. Drying rate vs. moisture content (dry basis) for DDS. Effect of pressure amplitude. (1)  $\Delta p = 80$  kPa and (2)  $\Delta p = 50$  kPa. Archaeological wood: WW<sub>7</sub>.

completely frozen prior to sublimation. This step in the freeze-drying method was always accomplished at the very slow rate required for ice sublimation. Freeze-drying rate was therefore too slow and could really not be compared with other drying processes.

#### Shrinkage of Dried, Waterlogged and Fresh Wood Samples

The shrinkage results (Table 2) showed that DDS was superior in this respect to the standard drying processes. It compared very well with freeze-drying for many species of wood, with values of the same order, except for highly deteriorated wood that felt very spongy. Although shrinkage resulting from DDS drying was often similar and sometimes slightly more pronounced than with freeze-drying, whether waterlogged or fresh wood was used, the overall quality achieved by using DDS was higher than that obtained with the freeze-drying, hot air and continuous vacuum methods. In addition to the good dimensional stabilization, the appearance of the surface was of high quality, with no splits or cracks.

These results are in agreement with those of Sanya (2000) who compared the final porosity (%) of archaeological samples dried by hot air, vacuum, DDS and freeze-drying. The author concluded that the final porosity of DDS dried samples (43.7%) was close to that obtained for freeze-drying (49.3%) which is a reference process, while the final porosity of the samples resulting from the two other drying processes varied from 18% to 35.1%.

#### Colour Measurements of Samples Dried with the Different Modes

Preserving the colour of waterlogged wood artefacts was another important factor to be taken into account (McLeod, 1987). We measured colour with the CIE Lab-DIN 6174 system developed for this study. The plant consisted of a Fujinon CV-M90 camera connected to a computer through an electronic conditioner-light delivery system. Atmosphere free samples air-dried at room temperature (10–20°C) were taken as a reference for the colour analyses.

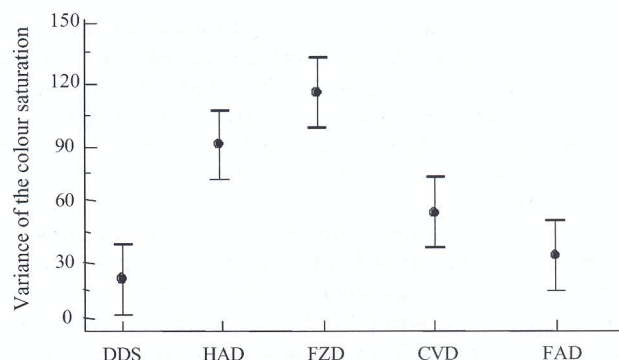


Figure 6. Colour measurements of waterlogged woods after drying with the different techniques. HAD: hot air drying; CVD: continuous vacuum drying; FZD: freeze-drying; DDS: dehydration by cyclical pressure drops; FAD: free air drying. Archaeological wood: WW<sub>7</sub>. For each technique, 10 samples were measured to determine the variance.

No colour change of DDS dried samples was observed by eye, in contrast to freeze-drying and hot air drying. The colour data obtained from the CIE Lab system analysis were processed using *Statgraphics* software. A one-way analysis of variance, based on Kruskal–Wallis statistical test and performed for variance of the colour saturation, which represents the distance between the colour of the sample and the white colour, gave the results shown in Figure 6. These show that DDS did not induce any significant colour change in wood samples at the 95% confidence level, whereas freeze-drying and hot air drying did. In fact, the colour of the DDS dried samples and to a certain degree, the continuous vacuum drying samples were similar to that obtained by free-air drying at ambient temperature, which caused no degradation of colour but took too long.

#### CONCLUSION

Freeze-drying clearly offered the most efficient dimensional stabilization for waterlogged wood and heat sensitive products compared with the other drying processes. However, some change in colour occurred when wood samples were freeze-dried. The dimensional stabilization and colour results obtained with DDS drying of waterlogged and fresh wood corresponded to the quality required for the conservation of waterlogged wood artefacts.

The dimensional stabilization results of this comparative study strongly argue that DDS should replace continuous vacuum drying as the second most efficient process after freeze-drying. The kinetics results showed that DDS was faster than continuous vacuum drying and overall it was much faster than the other processes. Thus, compared with freeze-drying, which was used as a reference in this study because of its efficient dimensional stabilization, DDS might offer a lower drying cost. This experimental study proved that DDS can compete with freeze-drying in terms of dimensional stabilization and is better at preserving the colour of wood. DDS might therefore be a powerful alternative to freeze-drying for the conservation treatment of waterlogged wood. In terms of the future prospects for DDS it might be hoped that, when there are no dimension stability requirements and the main aim is to simply dry materials, the DDS process might find wider applications. Pressure

amplitude ( $P_h - P_v$ , see Figure 3) could in this case be increased to a level suitable for the temperature best adapted for the drying of each material. This can be achieved by simply releasing air until a relatively high pressure is obtained because the pressure at the end of each compression phase in DDS determines the temperature inside the drying chamber.

Another important feature of DDS is its capacity to produce dried wood samples with a very low residual moisture content (often <6%). Such values are too low for wood conservation in atmospheric conditions because wood is a hygroscopic material that can reabsorb humidity and reach a suitable moisture content in equilibrium with its storage environment. The fact that DDS provides a low residual moisture content could be useful in the drying of many other materials, and particularly in food drying applications.

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