Week 5

THE CONSERVATION OF BOG BODIES BY FREEZE-DRYING

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Abstract—Two bog bodies, Meenybradan Woman and Lindow Man, have been conserved. The principal technique used has been freeze-drying after impregnation with polyethylene glycol 400. Preliminary tests were carried out on pigskin that had been stored in anaerobic peat slurry. Choice of consolidant was made on the basis of least shrinkage on freeze-drying. Shrinkage data are presented for the two bodies conserved and also temperature measurements during the freeze-drying process. Several novel techniques were devised for the conservation work which is described.

1 Introduction

After death, decomposition of the human body starts rapidly, but under some circumstances bodies can retain their features for hundreds or thousands of years. One reason for preservation is prevention of biodeterioration by rapid drying, as in Egyptian sand-burial bodies, or by reducing the water availability by the addition of salts, e.g. the application of natron by the ancient Egyptians [1]. Natural freeze-drying in very cold regions also occurs, but the most common cause of preservation in northern Europe seems to be burial in the acidic, anaerobic conditions which exist in a peat bog. Under these conditions bodies survive with good preservation of protein, e.g. skin and hair. However, softening or dissolution of internal organs occurs, and bone rarely survives. The conditions in the bog are such that biodeterioration is not favoured; low temperatures also aid preservation. There are 120 recorded sites in Great Britain and Ireland where human remains have been preserved in bogs [2], but undoubtedly the most famous of the European bog-burials have been found in Denmark; Tollund and Grauballe are probably the best known. Several bodies have been excavated and now reside in museums. A wide variety of conservation treatments has been used for the preservation of the bodies. This paper describes the conservation of a bog body from Lindow Moss, Cheshire, and another from Meenybradan, County Donegal, Ireland.

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Lindow Man underwent an extensive series of scientific examinations and this work is amply described [2]. However, details of the conservation and the tests done to determine a method of conservation have not been previously published.

2 Lindow Man—cleaning and excavation

Lindow Moss is a peat bog in Cheshire, England, and originally covered 600 hectares. For hundreds of years peat has been cut for fuel, but recently the peat has been cut mainly for horticultural purposes. On 1 August 1984 the remains of a human foot and part of a lower leg were found. On 6 August the rest of the body was excavated and removed, the body resting on a peat block and the whole being wrapped in water-soaked plastic foam and thin plastic sheeting. From the outset, post-excavation deterioration was minimized by cold storage of the body in a hospital mortuary.

2.1 Previous conservation methods

In the case of Tollund Man, only the head was preserved. This was placed in a solution of formaldehyde and acetic acid for six months, then in 30% ethanol, then afterwards in 99% ethanol to which industrial grade toluene had been added. Finally it was placed in toluene solution containing progressively larger amounts of wax. The total treatment time was over a year [3].

Grauballe Man was thought to be partly tanned and the conservation treatment was designed to complete the process. The body was soaked for 18 months in a slurry of oak bark which was changed three times during the treatment. After cleaning, the body was soaked in a mixture of Turkey red oil (sulphonated castor oil) and distilled water, followed by drying in air, in the course of which gradual impregnation with glycerol, lanoline and cod liver oil was carried out. Finally collodion (a solution of cellulose nitrate, usually in ethanol/diethyl ether) was injected into those parts of the body which had best retained their shape.

Possible conservation treatments for Lindow Man were discussed with conservators and curators at the Danish National Museum, Copenhagen, the Prehistoric Museum, Aarhus (where the Grauballe Man was conserved) and Silkeborg Museum (where the Tollund Man is on display). After viewing these bodies and discussing the conservation techniques which had been used it became clear that a different approach would be necessary for Lindow Man. All those consulted agreed that freeze-drying offered the best hope for a good result.

2.2 Storage of Lindow Man

After excavation, Lindow Man was stored in a shallow wooden box. The assembly was stored at a low temperature to minimize biodeterioration. This was initially done in the mortuary at Macclesfield Hospital. In late September the body was conveyed to the British Museum where a specially constructed cooled container was designed to keep the body at 4°C. The body was then subjected to numerous periods of excavation and examination.

In order to minimize deterioration it was important to keep the body cool and wet. This was achieved by intermittent spraying with cold, recently boiled, distilled water during the course of the laboratory excavation. Parts of the body not being worked on were covered with 'clingfilm' to prevent evaporation of water (Figure 1), and the body was returned to the cool-box if its temperature rose to 10–12°C. In general it was found that this temperature, measured by a thermocouple, was reached in approximately two

Figure 1 Scientific examination of Lindow Man in progress. The body was covered with clingfilm except in areas being worked on.

Figure 2 Lindow Man in his box, covered with squares of Delta Lite, being sprayed with water.

hours. The number of people in the room was restricted to those essential for whatever operation was required. An air cooler was fitted to the window nearest the body so that a cool draught passed over the working area. The body was cooled by cold packs made by freezing damp paper-towels in sealed polyethylene bags. These packs were removed to expose appropriate areas during cleaning, excavation or examination.

On occasions, one of the factors contributing to the rise of body temperature during laboratory excavation and examination was the presence of a television film crew. However, the effect of filming was minimized by using 'cold lamps' and limiting the number of people present.

One of the first tasks carried out by conservation staff after the excavation of the front of the body was to make a mount, both for ease of handling and to allow the body to be turned over to excavate the back. In the construction of the mount extensive use was made of Delta Lite and Scotchcast casting tapes, materials now used by hospitals as a substitute for plaster bandages when applying splints to broken limbs. The body was covered with clingfilm and then strips of Delta Lite, 127mm in width, were cut into squares and moulded to the body and overlapped to give strength. When all the body was thus covered, it was sprayed with water which caused the Delta Lite to become rigid in a few minutes (Figure 2). The mould was removed and further strengthened by painting on Tiranti Rigid Laminate, a polyester resin thickened with glass beads, over reinforcing strips of coarse and fine fibreglass.

Figure 3 Lindow Man covered with Scotchcast tape, pictured with Ms McCord and Mr Omar.

The mould was then replaced over the body and packed with peat in areas where it did not fit accurately. Polystyrene pellets contained in a polyethylene bag were used to pack the box as a replacement for excavated peat; then the wooden lid was fixed in position and the whole turned over. After excavation, the back of the body was again covered with clingfilm and the process of mould-making was repeated except that, in this case, strips of Scotchcast casting tape were used for the initial moulding (Figure 3). This has a larger weave and, accordingly, more flexibility for taking the contoured shapes of the body. A second layer of Delta Lite strips was subsequently applied to give more rigidity. The same steps of wetting with water and strengthening with polyester and woven fibreglass were followed. When cured, the two moulds were drilled at intervals around the edges so that they could be held together by nuts and bolts. This allowed the body to be turned onto either side (Figure 4).

Figure 4 Lindow Man encased between moulds.

The internal examination, sampling and removal of internal organs necessitated a great deal of manipulation and movement of the body. This in turn required the supporting of weak areas and loose parts. Some gaps were filled with original loose peat and elsewhere a more permanent yet easily removable support was made of wet peat enclosed in clingfilm (Figure 5). This was easily moulded to the required shape. Wedge-shaped pieces of polyethylene foam wrapped in clingfilm were also used.

2.3 Microbiological monitoring

From September 1984 to March 1985 microbiological monitoring was carried out by Ridgeway *et al.* [2, Chapter 4]. Cultures were made from the distilled water used to spray the body, the peat, and swabs from various sites on the body. The fungi isolated were of no pathogenic consequence and included a number of Pseudo-

Figure 5 Lindow Man's head being supported by peat wrapped in clingfilm.

monas spp. Various species of *Penicillium*, *Mucor*, *Vertisillium* and *Candida* were reported but none of these caused any deterioration in the state of preservation of the body. Much of the Pseudomonas contamination may have come from the distilled water. Towards the end of the monitoring period the body became colonized with small insects, possibly springtails. However, conservation processes commenced before these had time to cause any damage to the body. It was decided not to use any biocides on the body because of possible interference with radio carbon dating. However, some separated pieces of the body were treated by placing pieces of Vapona insecticidal strip (which contains dichlorvos) in the containers. The infestation was eradicated.

2.4 *Travelling*

The body was sent to a number of institutions for a variety of tests, including radiography, CT (computerized tomography) body scan and MRI (magnetic resonance imaging) scan. A system for keeping the body secure and cold was evolved, using the original wooden box made at Macclesfield Hospital. The box was lined with a heat-reflecting, metal-coated, plastic sheet designed for use by mountain rescue teams, called a survival blanket. A polyethylene bag filled with polystyrene pellets served as a cushion for the mounted body. A block of dry ice was broken up into small pieces and these were distributed around the four sides in open polyethylene envelopes. The lid was screwed to the top, allowing a thermocouple wire to pass through so that the temperature could be monitored throughout the trip.

The system proved adequate and protective and achieved all the set requirements, in particular, control of temperature and the avoidance of damage by vibration.

2.5 *Test for tannins*

Grauballe Man was found to be partially tanned when excavated and it was necessary to test whether Lindow Man was in a similar condition. Tannins are released from several types of plant material but are not generally associated with peat bogs. Three samples were examined, tissue from the inner thoracic cavity, tissue from the outer lumbar region and peat from near the body.

The test used was based on that described by Reed [5]. Samples of tissue weighing 0·02g were separately refluxed for four hours in either 1 l water:acetone (8ml) or equal volumes of 6M hydrochloric acid, acetone and water. One ml of each solution was adjusted to pH7 using sodium hydroxide solution, and 1ml of 1% ferric potassium sulphate was added. A blue or brown coloration would indicate the presence of tannins. No coloration was detected. The test was repeated using 0·15g of peat; no tannins were detected. The test gave a strong positive reaction when carried out on 0·02g of tanned goatskin. It was concluded that the skin of Lindow Man was not tanned to any significant extent.

2.6 *Choosing the impregnation materials*

Once a decision had been made to freeze-dry the body it was necessary to decide whether to use a consolidant. In the conservation of waterlogged leather, polyethylene glycol and glycerine have been used with general success. After some discussion with freeze-drying specialists' it was found that pigskin has pathological similarities to human skin and was sometimes used as a substitute for human skin for experiments in freeze-drying.

Fresh pigskin does not bear a close resemblance to the skin on a bog body. In an attempt to produce a realistic model material for the experimental work, pigskin was cut into strips and packed into peat for several months. The strips were placed in two sealable glass jars. One of the jars was topped up with distilled water and the other with a slurry of peat from near Lindow Man and distilled water. To produce anaerobic conditions, the distilled water was degassed by boiling and cooling it just before use. Further deoxygenation was brought about by bubbling nitrogen through the filled jars for ten minutes before sealing them. The jars were placed outside the laboratory for four months (January to April 1985). At the end of this period the skins were examined. The samples from the peat were firmer and browner than at the start of the experiment but those from distilled water had swelled and become gelatinous. It was decided to proceed with the experimental work using only the peat-treated skins as these were the best match to the skin on the bog body.

The skin samples were cut into rectangular shapes and their outlines drawn on pieces of

cardboard; these shapes were later used to calculate the shrinkage on freeze-drying. The cut samples were immersed in the following solutions:

10% v/v PEG 400 in distilled water
10% w/v PEG 1500 in distilled water
10% w/v PEG 2000 in distilled water
10% w/v PEG 2000 in 10% v/v PEG 400
10% v/v glycerine in distilled water

A set of untreated samples was retained for comparison.

The Organics Conservation Section of the British Museum has been freeze-drying a wide range of organic materials for several years. When PEG is used as an impregnant for leather prior to freeze-drying, satisfactory results are often obtained using 10% PEG 2000. Thus, the experiments were performed using PEG at this concentration. A mixture of PEG 400 in 10% PEG 2000 was also employed as these PEG mixtures have been used successfully on waterlogged wood.

After eight weeks the samples were removed, blotted dry and were then freeze-dried, sandwiched between stiff board to minimize warping. Pre-freezing was done in a domestic freezer at −26°C and the freeze-drying carried out with a chamber temperature of −30°C. Samples were removed from the freeze-dryer after three days, covered with polyethylene sheeting and allowed to equilibrate to ambient conditions for a week. Their outlines were retraced onto cardboard.

Although roughly rectangular, the treated skin samples had shrunk in a non-uniform manner, and the area of the sample could not be calculated by direct measurement. Tracing round the samples before and after treatment yielded pieces of card which, when cut out, had weights proportional to their areas. These pieces of card could easily be weighed and the percentage area shrinkage calculated. These shrinkages are shown in Table 1.

It is important to bear in mind that percentage area shrinkage is roughly twice that of linear shrinkage. Similarly, volume shrinkage is roughly three times that of linear shrinkage. For example, if the 10mm sides of a square of area 100mm^2 shrink by 10%, the new area is 81mm^2, 19% less than the original area.

Table 1 Shrinkage of freeze-dried pigskin samples

Pretreatment	No. of samples	Mean area shrinkage
None	5	22·9%
10% PEG 400 in 10% PEG 2000	6	21·6%
10% PEG 400	5	11·55%
10% PEG 1500	5	13·1%
10% PEG 2000	5	11·8%

2.7 Conclusions

Pigskin samples were cut from areas where the skin was seen to be uniform, i.e. away from folds in the skin, the backbone, etc. However, some samples shrank in an irregular way. Results from these pieces were used in the assessment of shrinkage. Ideally these experiments should have been repeated but, as time was at a premium, it was not possible to do this.

PEG 2000 left a white waxy deposit on the samples. If used on the body this would later have caused problems when attempts were made to remove it from areas where there was hair; depilation could result. Ellam [6] reports that PEG 400 gave good results for freeze-drying bone and notes that higher concentrations than 30% are not satisfactory. It was decided to use PEG 400 for the conservation of Lindow Man.

3 The Meenybradan bog body

After the Lindow Man body had arrived at the British Museum, the National Museum of Ireland asked whether it would be possible for us to treat another bog body. It was decided that the treatments chosen for Lindow Man would be applied to the extra body, Meenybradan Woman, to gain more experience in the chosen conservation technique. Meenybradan woman arrived at the British Museum in July 1985. She had been excavated in 1976 and subsequently stored in a domestic freezer. During transport from Ireland the body was wrapped in a survival blanket inside a wooden box packed with solid carbon dioxide. On arrival at the British Museum it was placed in a domestic freezer at −26°C. After a few days it was allowed to thaw out for examination and photography. The body was subsequently stored at 4°C.

Meenybradan Woman's body is much more complete than Lindow Man's and possessed both legs, although these were sawn off soon after the original excavation to facilitate trans-

port! The bones were in good condition. There were deposits of adipocere distributed over the body and under the skin. Adipocere is produced by the prolonged storage of animal fat under anaerobic cool conditions. No information was available on the effect of freeze-drying on adipocere so experiments had to be carried out to investigate this.

Loose fragments of adipocere of about $2cm^3$ were used for the experiments. One sample was freeze-dried without any pretreatment and retained its shape and characteristic physical properties. Another sample was soaked in 10% PEG 400 for five days before freeze-drying; this sample also responded well to treatment. It was concluded that the conservation treatment proposed for Lindow Man would be used on Meenybradan woman.

Before the main process of conservation was performed, the stomach contents were removed by a surgeon for examination, because it was believed these would not respond well to freeze-drying.

The body was bandaged to a Perspex sheet using strips of polyester bonded fabric (Tyvek). Cushions made from polyester wadding in plastic bags were used to secure limbs during immersion as they were liable to float. Stainless steel pins were fixed into the skin and bone to provide reference points for shrinkage measurements. Loose fragments were put in a bag of nylon net and the whole body placed in a bath of 15% w/v PEG 400 in distilled water. Special attention was given to the skull to ensure that no air was trapped there. After soaking for four weeks the PEG was drained off, a thermocouple inserted in the body and it was wrapped in clingfilm. The body was then placed in a freezer at −26°C. After three days it was transported to the English Heritage Laboratories, the clingfilm was removed and [illegible] the freeze-dryer where it was trolled at −32 C. When the body had reached an equilibrium temperature of −32°C the vacuum was applied.

The process was monitored by weighing one of the legs and measuring the body temperature. The process was deemed to be complete when body temperature rose to −5°C (Figure 6). After 31 days of freeze-drying the body was removed from the freeze-dryer, wrapped in a survival blanket and placed in a wooden box with dry silica gel (to prevent condensation). The body was returned to the British Museum; ideally it would have been allowed to reach ambient temperature in the freeze-dryer but operational difficulties prevented this. Figure 7 shows the body after freeze-drying.

After a week of acclimatisation of the body to ambient conditions the survival blanket was

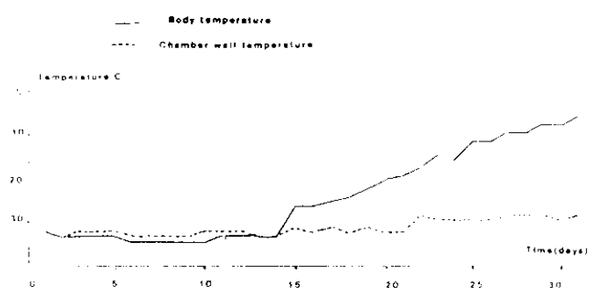

Figure 6 Temperature versus time graph for the freeze-drying of Meenybradan Woman.

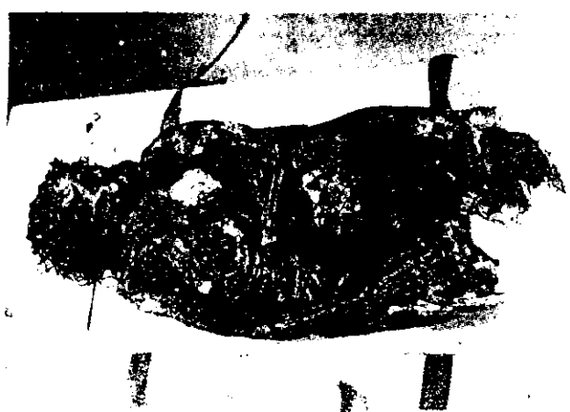

Figure 7 Meenybradan Woman before conservation.

Table 2 Linear shrinkage measurements during conservation of Meenybradan Woman

Position	*% shrinkage*
Left leg, bone	5·6
Left leg, skin	1·8
Ditto at 90° to the above	1·3
Left hip	1·2
Between hips	0·6
Left hand, bone towards abdomen	1·3
Left hand, bone towards the head	2·3
Left hip, longitudinal	0·0
Left hip 90° to above	0·0

removed. Shrinkage of the body was generally small: between 1 and 2% (see Table 2). Skin texture and details became much easier to see e.g. eyelashes and eyebrows became visible. The skin was supple and the peat that remained on the body was easy to remove. The hair was rather tangled at the end of the treatment and was interspersed with a dried-out scum from the impregnation solution. This was later removed by careful rinsing with 1:1 IMS and water.

Generally, the result was very good and there was no reason to suppose comparable results would not be obtained on Lindow Man.

4 Consolidation and freeze-drying

Lindow Man was cleaned as much as possible and then placed on a Perspex sheet; strips of polyester bonded fabric (Tyvek) were used to secure the body to the mount. Pressure from the strips was evenly distributed over the body by using polyethylene bags filled with polyester wadding between the body and the fabric strips. Stainless steel pins were stuck into various parts of Lindow Man in order to monitor shrinkage after conservation. Ten pairs of pins were put into position (see Figure 8).

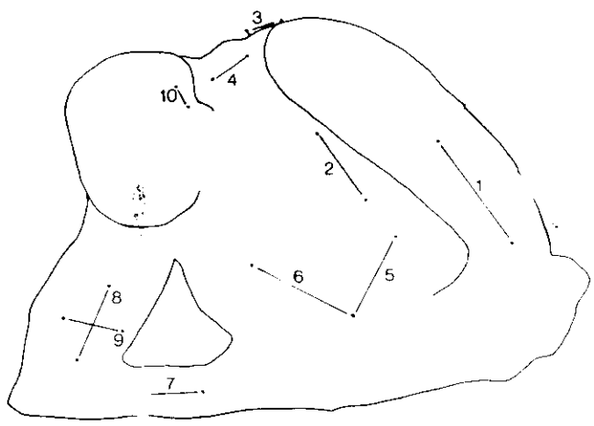

Figure 8 Pin positions for measuring the shrinkage on Lindow Man.

The body was immersed in a 15% v/v solution of PEG 400 in distilled water, and glass weights were added to the mount to keep the body and Perspex submerged. It had been decided to increase the concentration of PEG from the 10% used in the pigskin experiment, so that bone shrinkage would be minimized.

After four weeks immersion the body was removed from the PEG 400 solution, drained, and the fabric strips removed. Polyester wadding was placed inside the abdomen to maintain the body contours, and clingfilm wrapped round the body to avoid drying during transport to the English Heritage Laboratories where freeze-drying was to take place.

Thermocouples were placed in the skull and abdomen. The body, still on its sheet of Perspex and wrapped in clingfilm, was placed inside the freeze-drying apparatus. For five days the chamber walls were refrigerated at −28°C; at the end of this period the thermocouples registered a temperature of −24°C in the skull and −20°C in the abdomen. The clingfilm was removed and the vacuum applied. A pressure of between 100 and 200 millitorr was maintained during the freeze-drying. Figure 9 shows how the temperatures varied during the course of treatment. After 23 days the body was weighed daily. The treatment was considered to be complete when negligible weight loss occurred; this happened on the 29th day and the refrigeration was turned off. After three more days the body had warmed up and the temperature was stable. The body was removed, covered with Tyvek fabric sheets and placed in a wooden box containing dry silica gel. On its return to the British Museum the body was left to acclimatise to ambient condition for seven days before any further conservation work was done.

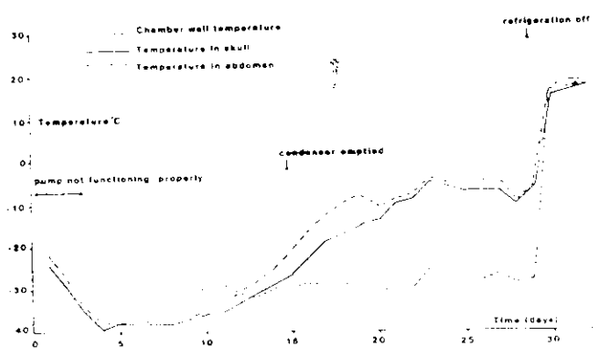

Figure 9 Temperature versus time graph for the freeze-drying of Lindow Man.

5 Results of treatment

Generally the skin had become lighter in colour.

Table 3 Shrinkage of Lindow Man after freeze-drying

Reference no.	*Position*	*Distance between pins (in mm)*		*% linear shrinkage*
		Before conservation	*After conservation*	
1	Left arm	123	117·5	4·47
2	Chest	70	67·6	3·43
8	Right arm	85	83·8	1·41
9	Right arm	107	105	1·61
10	Ear	46	44	4·30

However, lighter and darker marks could be seen on some areas of the skin which were reminiscent of the folds of clingfilm. The cause of these marks is unclear but may have been caused by a surface morphology change during freezing or absorption of plasticiser from the film.

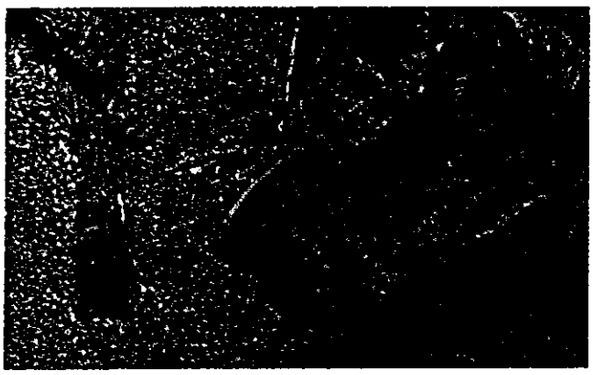

Figure 10 Lindow Man after conservation.

Freeze-drying enabled the last traces of peat to be removed easily and the excellent preservation of parts of the body was revealed (Figure 10). The skin texture was still very good over most of the body. The skin had become stronger and more rigid than in the wet state but was still flexible and could be handled with greater ease. There was no smell from the body.

Some of the stainless steel pins inserted to monitor shrinkage had come out during the freeze-drying and it was impossible to relocate them. Only five shrinkage measurements were made (Table 3).

Linear shrinkge was less than 5% which was similar to the linear shrinkage obtained in the preliminary experiments. The conservation treatment was considered very successful. At the time of writing the body has been conserved for over a year and shows no sign of deterioration. A specially constructed showcase has been built for the body and the following environmental conditions are maintained: RH 55 ± 5%, temperature 19° ± 2°C, illuminance 150 lux, ultraviolet level less than 75 microwatts/lumen.

No attempt was made to reconstruct the one remaining hand but a detached residual armbone was secured using 75% Mowilith 50 poly(vinyl acetate) resin in acetone. The elbow was too heavy to fix with adhesive alone and was dowelled to the upper armbone with a small section of wooden cocktail stick.

Acknowledgements

We would like to thank Dr C. Price of English Heritage for allowing us to use their freeze-dryer, and especially Miss J. Watson for supervising the freeze-drying process, taking measurements and being generally inconvenienced by the conservation.

Materials used

Scotchcast (fibreglass casting tape): 3M (UK) PLC, Orthopaedic Product: Division, Morley Street, Loughborough, Leicestershire, UK.

Delta Lite Strips (fibreglass casting tape): Johnson and Johnson Products Inc., New Brunswick, NJ 08903, USA.

Tiranti Rigid Laminate: Alec Tiranti, 70 High Street, Theale, Berkshire, UK.

Polyethylene glycol 400: CSD, Hall Lane, Rookery Bridge, Moston, Sandbach, Cheshire CW11 9QQ, UK.

Tyvek polyester bonded fabric: WM Supplies (UK) Ltd, Park Mill, Bleasdale Street, Royton, Oldham, Lancashire OL2 6BR, UK.

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Résumé—L'article décrit le procédé de conservation appliqué à deux corps—un homme et une femme—trouvés dans des marécages. La principale technique utilisée a été le séchage cryogénique après une imprégnation au polyéthylène glycol 400. Des tests préliminaires avaient été conduits sur une peau de porc conservée dans un bain de tourbe anaérobique. On a choisi le consolidant en fonction de sa moindre contraction au séchage cryogénique. On présente les mesures de contraction pour les deux corps conservés, ainsi que les mesures de température pendant le processus de séchage par le froid. Plusieurs nouvelles techniques ont été envisagées pour ce travail de conservation.

Zusammenfassung—Der Beitrag beschreibt die Konservierung zweier Moorleichen. Als Konservierungsverfahren wurde dabei Gefriertrocknen nach einer Imprägnierung mit Polyethylenglycol 400 eingesetzt. Voruntersuchungen wurden an Schweinehäuten durchgeführt, die unter Luftausschluß in Torfschlamm gelagert worden waren. Das Festigungsmittel wurde unter dem Aspekt eines möglichst geringen Schrumpfens während des Gefriertrocknens ausgesucht. Der Beitrag liefert Daten, die die Schrumpfung der beiden konservierten Moorleichen und den Temperaturverlauf während des Gefriertrocknens beschreiben. Mehrere neuartige Techniken werden vorgestellt, die für die beschriebenen Arbeiten geeignet erscheinen.