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# MONITORING MOISTURE IN THE *BATAVIA* TIMBERS

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## SUMMARY

A series of twelve sets of stainless steel probes were hammered into the timbers of the *Batavia* (1629) reconstruction at the Western Australian Maritime Museum and used to measure the electrical resistance (R) of the selected planks, ribs and transom beams. Despite the unsophisticated nature of the method it has been possible to observe the way in which the timbers have responded to the environment in the airconditioned display gallery. The proximity of the probes in the 7 x 12 metre structure to the outlets of the airconditioning ducting is important in explaining the variations in the rates of change of resistance of otherwise identical timbers. The sensitivity of the timbers to changes in the environment were determined by the slopes of plots of resistance against time. Different responses of the timbers were found to be dependent on the depth of penetration of the probes and on the cube root of the thickness of the timbers. The pH of the PEG 1500 treated oak surfaces also affected the relative rates of drying of similar sized timbers. The sensitivity of the conserved archaeological timbers to changes in the relative humidity in the gallery has also been demonstrated. Micrometeorological monitoring of the timbers has provided data on the variability of conditions within the gallery and on the effects of display lighting. Insertion of the resistance probes to a standard depth would greatly increase the ease of interpretation of the data obtained from the monitoring program.

## INTRODUCTION

On June 4th 1629 the Dutch East Indiaman *Batavia* was wrecked on Morning Reef in the Houtman Abrolhos Islands some 500 km north of Perth in Western Australia[1]. The timbers were recovered in a series of excavations in the 1970's and treated with solutions of PEG 1500 over a period of twelve years in a batched process[2-4], before being dried in a dehumidification chamber and placed in a display gallery at the Western Australian Maritime Museum. The presence of thousands of cannon balls in the stern section of the vessel resulted in many of the timbers being impregnated with iron corrosion products.

Subsequent anaerobic microbial activity under the protective coralline concretion layer[5] caused the soluble iron chlorides to precipitate as iron sulphides. The problems associated with the oxidation of pyrite, $FeS_2$, have been previously reported in terms of the nature of the oxidation products and the neutralising treatment given to restore the archaeological materials to something

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approaching neutrality[6]. Oak timbers that have been subjected to the oxidation of pyrite in their structures are significantly impaired with regard to mechanical strength and require consolidation. The use of Luviskol N-90, a polyvinyl pyrrolidone, in solutions of n-butanol to strengthen the neutralised timbers has been reported and the results are most encouraging[7].

Part of the regular monitoring of the environmental conditions in the *Batavia* gallery involved the inspection of charts from a thermohygrograph which was placed on the steel support structure at the top of the reconstruction, some seven metres above the floor level. Where excursions into regions of high (>60%) or low (<45%) relative humidity were noted calls to the plant officers, located some thirty kilometres from the museum, were made and attempts to adjust the airconditioning plant on the roof normally restored the desired conditions of 54±3% relative humidity(RH). Being acutely aware of the sensitivity of the timbers to times of high relative humidity it was deemed essential to have some form of early warning system to alert us to any significant change in the nature of the timbers. A regime of regular monitoring of timber acidity, using a flat surface pH electrode, was established in conjunction with a series of electrical resistance probes to monitor the moisture content (figure 1).

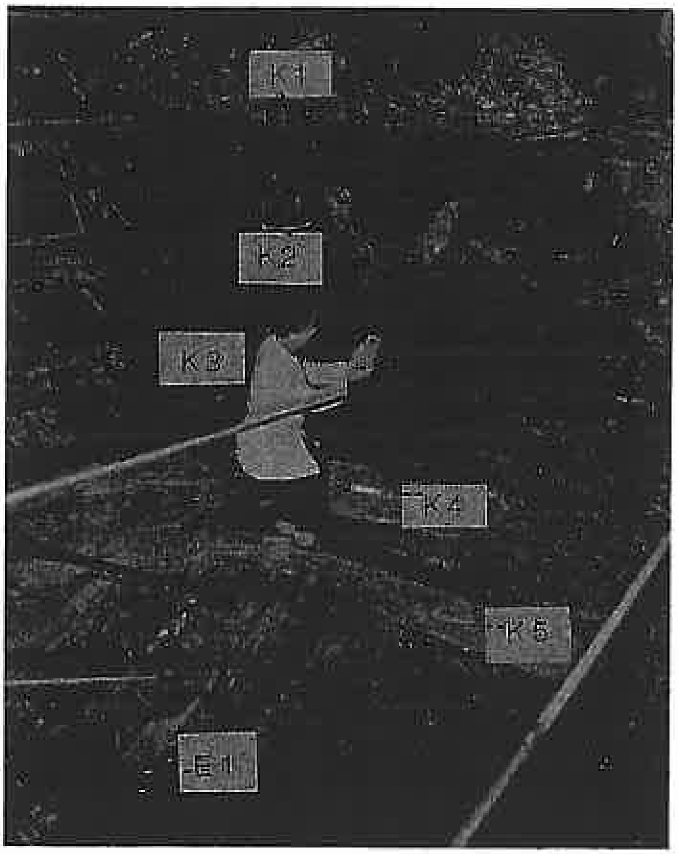

Figure 1. Location of resistance probes in the stern of the *Batavia* reconstruction.

## RATES OF CHANGE IN THE RESISTANCE OF ARCHAEOLOGICAL TIMBERS

A series of twelve sets of resistance probes were manufactured by grinding a sharp point at a 30 degree angle onto the tip of 3.2 mm diameter, 200 mm length of 316 stainless steel rod. Near the end of each rod an insulated multistrand copper cable was silver soldered to the shaft and a *banana* plug was soldered to the other end of the wire. All the probes were separated by a distance of 200 mm using pre-drilled perspex sheet which had the dimensions of 250 x 25 x 3 mm. After an initial trial period on two main structural timbers the other probes were hammered, as far as possible, into the reconstruction and monitoring commenced.

Reproducible readings of the electrical resistance of the timbers were made by following the polarisation behaviour of the probes. After the banana plugs were connected to the digital multimeter, the resistance would fall to a minimum value before the reading would increase. The minimum value was reproducible to within 5% of the reading during repeated measurements at intervals of ten minutes. Resistance readings were generally in the megohm range on the Hung Chang 7012 or Escort EDM-82 digital multimeters. The choice of locations of the probes was determined by the need to collect data on a number of similar types of timbers in a variety of locations on the reconstruction (see figures 1 & 2).

**Figure 2. Location of resistance probes in the forward section of the *Batavia*.**

Several of the heavily iron-impregnated timbers that had previously been treated with ammonia were chosen because they were inherently most at risk. Once pyrite has been oxidised the remaining mineral surfaces are more susceptible to attack at times of high relative humidity. The probes were inserted into four of these timbers ($B_2$, $F_5$,$F_2$ and $F_0$) so that any differences associated with the varying degrees of degradation could be assessed. The five transom beams ($K_{1-5}$) were also chosen because of the need to see what effect the size of the timbers had on the resistances and on the rate at which the readings changed. One rib ($R_{15}$) was selected along with one plank high in the structure ($E_6$), near the first gun port and one plank ($E_1$) near the return of the fashion piece at the stern since it was "sheltered" by the surrounding timbers. The exposed surface area of this plank was small in comparison with other planks.

The resistances were measured at intervals ranging from weekly to bi-monthly except when there had been a significant change in the gallery conditions. Events such as an increase in temperature from 22 to 24.5°C, an increase in relative humidity from the set point, 55%, to 60% or a decrease down to 45% would initiate a greater frequency of readings in order to obtain data on the way in which the timbers responded. Under conditions of 54±3% RH and a temperature of 22±1.5°C the resistance of the five transom beams $K_{1-5}$ showed a steady increase with time, apart from times when the air conditioning plant was malfunctioning, until 240±25 days when the resistance readings seemed to plateau. Plots of the R values against time are approximately linear and so the rates of increase in the value of R can be regarded as a measure of the rate of response to changes in the microenvironment of the timbers. The rates of change in the resistances of the timbers, $k_1$, are measured in kΩ.day$^{-1}$ and are shown in table 1.

Table 1 : Resistance changes,pH, timber thickness and depths of probes in *Batavia* archaeological timbers.

| Location number | $k_1$ kΩ.day$^{-1}$ | $pH_{old}$ 23-08-91 | $pH_{new}$ 11-06-93 | Thickness of timber, mm | Mean depth of probes, mm. |
|---|---|---|---|---|---|
| $K_1$ | 6.1 | 5.3 | 5.83 | 580 | 45.8±15.9 |
| $K_2$ | 59.5 | 5.1 | 5.39 | 440 | 29.3± 3.9 |
| $K_3$ | 11.0 | 5.1 | 5.58 | 320 | 23.5±19.1 |
| $K_4$ | 19.0 | 5.2 | 5.85 | 310 | 42.3±32.2 |
| $K_5$ | 12.1 | 5.3 | 5.75 | 290 | 25.1± 6.9 |
| $E_1$ | 0.61 | 5.2 | 5.46 | 50 | 26.8± 3.2 |
| $E_6$ | 49.0 | 5.7 | 5.41 | 55 | 22.0± 6.4 |
| $R_{15}$ | 14.0 | 5.0 | 5.29 | 170 | 35.5± 2.1 |
| $B_2$ | 18.1 | 4.4 | 4.0 | 75 | 24.5± 3.5 |
| $F_5$ | 17.0 | 4.7 | 5.11 | 64 | 16.4± 1.3 |
| $F_2$ | 3.8 | 4.2 | 3.71 | 68 | 44.5± 6.7 |
| $F_0$ | 3.25 | 3.8 | 3.70 | 54 | 46.0± 4.2 |

The attainment of constant resistance values for the timbers is seen as a sign that the material has reached a steady-state in the dynamic equilibrium with the local environment.The rate of increase in resistance for rib $R_{15}$ was 14 $k\Omega.day^{-1}$ which is similar to that found for transom beams $K_4$ and $K_5$ and the acid affected planks $B_2$ and $F_5$ - see table 1. The two planks with the lowest average surface pH values, $F_2$ and $F_0$, had about one quarter the $k_1$ values as found for the previously mentioned timbers. The "sheltered" plank $E_1$, which had a very small exposed surface area, showed the slowest rate of increase in resistance. The rate of change in resistance was greatest for the plank $E_6$ and the transom beam $K_2$. Their $k_1$ values were roughly three times the values found for the rib and three of the other transom beams. During the routine measuring programme it was noted that strong air movement, from the vents in the air conditioning duct, was felt at the location of the probes on the timbers $K_2$ and $E_6$.

**EFFECTS OF PROBE PENETRATION ON RESISTANCE**

The depth to which the stainless steel probes were embedded into the *Batavia* timbers varied considerably not only from section to section of the reconstruction but also between some of the probes in individual timbers. The extent of the variation is shown in table 1. Nine of the timbers had probe penetration depths($x$) that were within 5mm of each other. For these timbers the similar depths of the probes is an indication of similar degrees of degradation at the points of attachment to the structure. The transom beams $K_1$, $K_3$ and $K_4$ showed considerable variation in the depths to which the resistance pins were hammered. The greatest variation was found in $K_4$ which had one pin at 19.5mm and the other at 65mm. The large structural beams are known to exhibit a wide range of degradation within the one piece of timber - the variations in the depth of penetration of the probes is a reflection of this reality. A plot of the resistances of the timbers after 265 days of equilibration with the local environment is shown in figure 3 as a function of $x$, the depth of penetration of the probes.

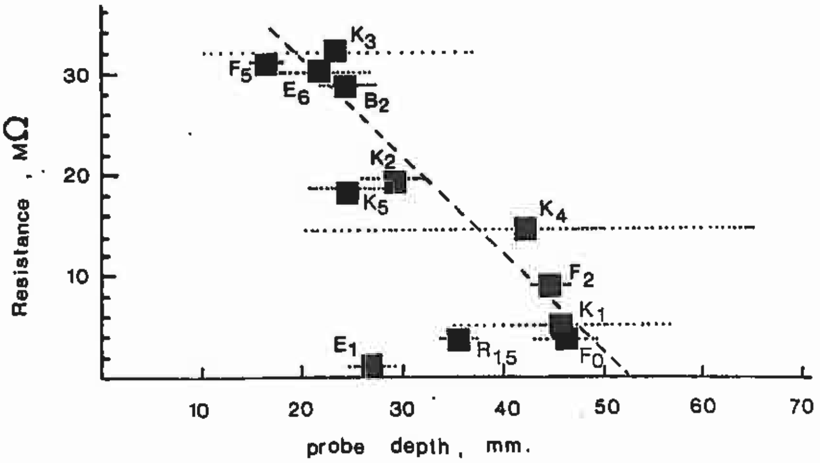

Figure 3. The resistance of *Batavia* timbers as a function of $x$, the depth of penetration of the stainless steel probes.

The error bars on the x axis reflect the standard deviation associated with the mean depth of penetration. As previously discussed, the large variations in $x$ values associated with some of the timbers is associated with variations in the localised degrees of degradation. This variation will naturally affect the overall value of the resistance between the steel probes. Analysis of the slope of the graph in figure 3 gives a fall of 0.96 MΩ for each millimetre of increased depth of penetration of the probes. The decrease in resistance by approximately one megohm per mm of probe depth in the timber is not surprising since the common 200mm separation of the probes means that the greater the surface area of probes buried in the timbers, the less the resistance. It is noted that the "sheltered" timber $E_1$ does not follow the general trend of the other eleven sets of data.

## EFFECTS OF TIMBER THICKNESS

The rates of changes in resistance are seen to vary from high $k_1$ values of 59.5 $k\Omega.day^{-1}$ for the second transom beam $K_2$ and 49 for the plank $E_6$ to low values such as 3.8 for the acid affected plank $F_3$ and 0.61 for the "sheltered" plank $E_1$. Changes in the moisture content of the timbers will be dependent on the rate at which water can diffuse out of the surfaces that are exposed to the air conditioned space in the *Batavia* gallery. Trying to find correlations between the timber thickness and the varying responses of the timbers to changes in the environment is fraught with difficulty owing to the complex nature of the reconstruction. Previous studies of the drying rates of timbers by Grattan et.al.[9] had found that the cube root of the weight during drying should be proportional to the time of drying. Given that the *Batavia* timbers have been in an air conditioned gallery for periods of eight to twelve years it is likely that they are effectively dry and that the changes in moisture content, as reflected in the changing resistance values, are a reflection of the dynamic equilibrium between the timbers and changes in the environment. Since we cannot monitor the weights of the timbers with time, we can use the rates of change in resistance to act as a measure of the way in which the timbers respond to the local environment.

Since timber thickness in the reconstruction varies by more than a factor of ten, from 580-54 mm, it is not unexpected to find that there is a large variation in the rate at which the resistances of the timbers increases with time. The effective "sensing zone" of the stainless steel probes inserted into the timbers will also be dependent on the relative depth of penetration compared to the thickness of the timbers. This in turn will affect the rates at which the resistance of the probes will change with time. Attempts to find an empirical relationship between the $k_1$ values, the depth of penetration $x$ and the thickness of the timbers $d$ resulted in the relationship given in equation 1,

$$k_1 = 3.04\ x/d^{1/3} + 0.33 \qquad \ldots\ldots\ldots\ 1$$

where the rate of increase in the resistance of the timbers($k_1$) is dependent on the depth of penetration of the probes divided by the cube root of the thickness of the timbers. A plot of the data is shown in figure 4 where the mean depths of the probes are used for the $x$ values and the error bars are associated with the variations in the depth of penetration of the individual probes into the timbers. Inspection of the plot shows that the second transom beam $K_2$ and the plank $E_6$ have much higher $k_1$ rates than would be predicted on the basis of equation 1. The increased $k_1$ values for these two timbers is primarily due to the effects of increased air flow associated with proximity to the outlets of the ducted air conditioning. The increased "sensitivity" to changes in the environment is a factor of five for $K_2$ and 2.7 times for $E_6$. The upper transom beam $K_1$ fitted onto the plot at the extreme point of the range of $x$ values while the rib $R_{15}$ and the plank $F_5$ came close to the line defined by equation 1.

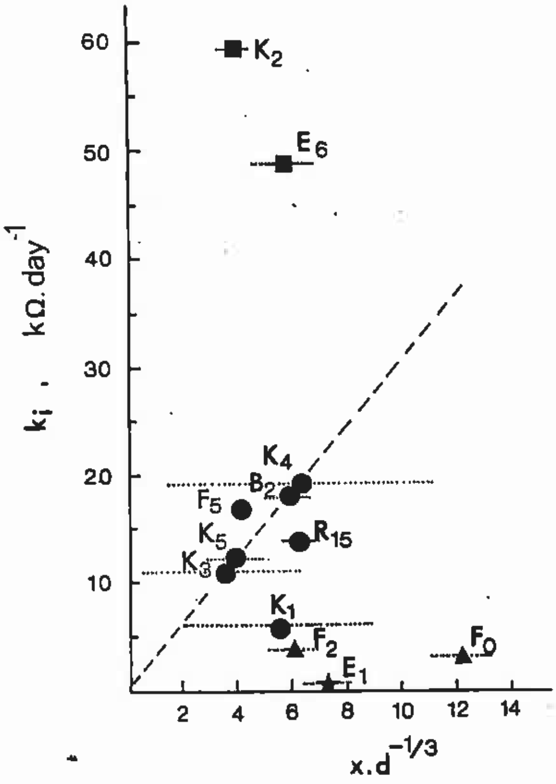

Figure 4. Values of $k_1$ as a function of the depth of the resistance probes and the cube root of thickness of *Batavia* timbers.

The plank $E_1$ falls well below the value expected on the basis of the depth of the probes and the thickness of the wood. It has been previously noted that this timber has a very small surface area exposed to the gallery air flow and so the low $k_1$ value is not unexpected. The two other planks that fall below the predicted $k_1$ value are the acid-affected planks $F_0$ and $F_2$. Both these timbers are badly degraded and this is partly reflected in the average surface pH values of 3.75 and 3.96 respectively. However other timbers, such as $B_2$, which have similar average surface pH values of 4.2 follow the relationship in equation one. One major difference between $B_2$ and the other acidic timbers is the ratios of $x/d$ (probe depth/timber thickness) for $F_0$(0.85) and $F_2$(0.65) are much higher than the value of 0.32 for $B_2$. The relative depth of penetration of the probes in $F_0$ and $F_2$ is apparently too great to permit the resistance kinetics to conform to the parameters that control the rates of change in resistance in the other timbers. Another factor influencing the low $k_1$ values may be the location of the timbers in the reconstruction - see figure 2. Both planks $F_0$ and $F_2$ are close to the floor on the far side of the reconstruction and the furthest removed from the source of the return air.

## EFFECTS OF pH ON RESPONSE RATES OF TIMBERS

One of the problems of dealing with the conservation of degraded archaeological timbers is that the material comes in varying degrees of degradation and that the timbers vary considerably in size owing to the different structural functions they had in the original vessel. The data outlined above has shown that the kinetics of dehydration, as measured by the rate of increase in the resistance, is inversely dependent on the cube root of the thickness of the timber and directly dependent on the depth of the probes in the timbers. In order to ascertain what effect the surface acidity has on the drying of the timbers, it was decided to "normalise" the $k_1$ values for the individual timbers to a common thickness, using equation 1, to effectively remove the variable of the differing thicknesses of the timbers. The calculated $k_1$ values used the experimental values of $x$ and common timber thickness.

The calculation was performed for the timbers that conformed to the relationship defined by equation 1. The chosen values of timber thickness were at the extremes of the range i.e. 580mm and 54mm. Plots of the difference between the "normalised" and actual $k_1$ values against pH showed that the rates were dependent on the surface pH, as shown in figure 5. The data used in the plots takes into account the range of surface pH readings (see table 1) and the variations in the depths($x$) of the probes. For the timbers that had experimental $k_1$ values that fitted equation 1, the slope of the graph of the difference between the calculated and experimental $k_1$ as a function of pH had a value of 6 $k\Omega.day^{-1}.pH^{-1}$ for 580mm thickness and 8 $k\Omega.day^{-1}.pH^{-1}$ for the 54mm timber calculation. In simple terms this means that the more acidic timbers had a slower rate of responding to "drying" than those with more alkaline surfaces. It should be noted that the surface pH may not necessarily be a true reflection of the acidity in the timber. Typical data of the pH profiles of *Batavia* timbers is given in table 2 which shows differences of up to 2.2 pH units between surface pH and core levels[10].

Table 2 : Acidity readings for *Batavia* timbers.

| Registration number | Surface pH | pH at 10-15 mm |
|---|---|---|
| BAT 6091 | 4.2 | 4.3 |
| BAT 6102 | 4.0 | 1.8 |
| BAT 6038 | 3.9 | 2.4 |

In the light of this information it is wise not to try and read too much into the data shown in figure 5. The main point to note is that the rate of response of the timbers to the conditions in the display gallery is, in part, dependent on the pH of the timbers. The lower response rates for the acid affected timbers $F_2$ and $F_0$

have been previously noted in terms of their location on the reconstruction. The lower than expected $k_1$ values for these timbers is also partly explained by their surface pH values. The presence of acidic and hygroscopic corrosion products such as bilinite $Fe_3(SO_4)_2.22H_2O$, butlerite $FeSO_4(OH).2H_2O$ and romerite $FeFe_2(SO_4)_4.14H_2O$ will appreciably slow down the rate at which moisture can be removed[6].

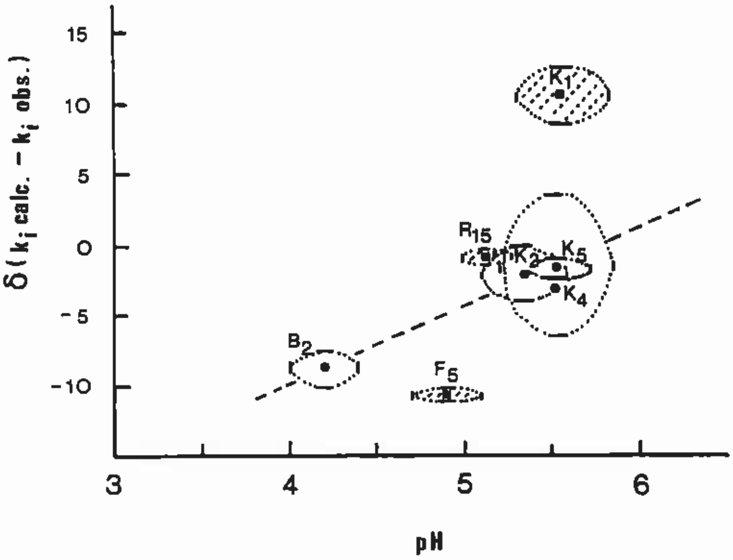

Figure 5. Surface pH versus the difference between observed and calculated $k_1$ values for *Batavia* timbers at 580 mm thickness.

## EFFECTS OF TEMPERATURE ON TIMBER RESPONSE RATES AT CONSTANT RH

Despite the best efforts of the maintenance team, the *Batavia* gallery is subject to periodic excursions outside the normal range of set conditions. Such events are normally signalled in the conservation laboratory by a loud and piercing alarm which causes the conservators to re-set the control panel and to contact the refrigeration technicians. During the period of the experiment there were several incidents when the conditions were either too humid, too hot or too cold. Monitoring the resistance of the timbers after these events gave valuable data on how the PEG 1500 treated timbers responded to such changes.

An increase of 3°C was sustained over a period of thirty four days, from day 172-206, during the breakdown of one of the main chillers. During this time the timbers showed an increase in their $k_1$, the rate of change in the resistance, as measured from the change in the slope of the plots of the resistance against time. Thinner timbers showed the most marked increase in rate with typical ratios of $k_1$ at 25°C/22°C being 16.1±0.5 whilst the thicker transom beams had ratios of 6.4±0.4. The quality of the data is not sufficient to allow accurate interpretation of the effects of the temperature on the response rates. However, the smaller increase in $k_1$ values for the larger timbers is probably a reflection of the different ratios of surface area to volume of the various timbers. During the time of elevated temperature the RH in the *Batavia* gallery was fairly constant.

In order to gain an insight into the way in which the gallery conditions varied in normal operational mode, a series of temperature and humidity probes were attached at $F_2$, $B_2$, $E_6$ and $K_1$. The data was collected at $F_2$ using a *Smart Reader 2* and at the other sites using a multichannel *Data Taker* DT 100F. The temperature and humidity probes were calibrated using a Novasina MIK 3000 humidity and temperature sensor. During the logging period of two weeks the gas-fired boiler extinguished, the temperature fell by 5.5°C over an eight hour period and the relative humidity at $F_2$ soared from 52% to 75% as shown in figure 6. One of the reasons why the loss of heating causes such marked changes is that the gallery is essentially a "closed system" with 95% return air. The timbers remained at this dangerously high RH for eight hours until the boiler was refired by the conservators in the morning. It should be noted that the sensors of the data loggers were placed adjacent to the timber surfaces and not inside the wood. Measurements of the resistance at $F_2$ showed a 7.3% fall but this was not recorded until 24 hours after the boiler extinguished.

## EFFECTS OF HUMIDITY INCREASES

Because of the problems associated with the oxidation of pyrite at relative humidities greater than 60%[6], it has not been possible to have the timbers at an elevated RH for a long period to monitor the response. The acquisition of data on the effects of increases in RH is essentially opportunistic. During a one week period, between days 207-214, the dehumidifier broke down and the ambient conditions increased to 65% RH. The following discussion is based on two measurements for each timber, i.e. one before the increased humidity and one just before the plant was repaired. The uptake of water by the *Batavia* timbers was reflected in dramatic falls in the *R* values of up to 50%. The response of the transom beams was different to that of the planks in that they were more sensitive to the increase in RH. The percentage decrease in *R*, $\delta_{\underline{R}\%}$, for $K_1$, $K_2$,$K_4$ and $K_8$ was given by equation 2,

$$\delta_{\underline{R}\%} = 17.1\, d^{1/3} - 92.3 \qquad \dots\dots\dots\dots 2$$

The relationship that described the fall in resistance of the planks $E_6$, $F_8$, $F_0$ and the rib $R_{15}$ is given by equation 3,

$$\delta_{\underline{R}\%} = 9.1\, d^{1/3} -17.9 \qquad \dots\dots\dots\dots 3$$

The greater percentage fall in resistance of the larger timbers is probably related to the relative amount of exposed area in the reconstruction, when compared with the planks. Data from the logging experiment shows that at times of elevated RH, the mean value of the relative humidity at the transom beam $K_1$ was 67.9±0.8 while the mean value of the plank at $B_2$ was 63.6±1.2 over an eight hour period. The difference of 4.3% in RH between the two locations also explains some of the apparent differences in sensitivity to changes in gallery conditions. The timbers nearer the source of the return-air tend to experience a greater variation in conditions than those near the floor. Given that the $k_1$ values for the timbers were found to be dependent on $x/d^{1/3}$ (equation 1) it is not surprising to find that the fall in resistances were also dependent on $d^{1/3}$. The results clearly indicate that the timbers are very sensitive to changes in the gallery conditions. The cause of the different behaviour of the thinner timbers showing greatest sensitivity to changes in resistance with temperature, at constant relative humidity, and showing less sensitivity to increases in RH, at constant temperature, is not understood.

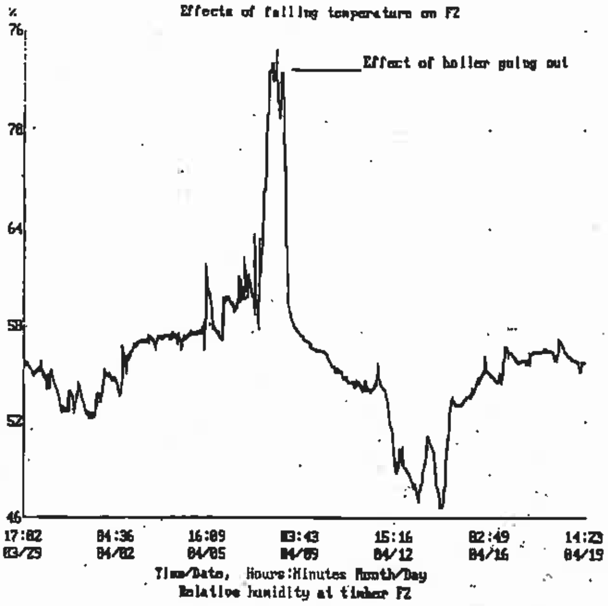

Figure 6 : Plot of the relative humidity at $E_2$ in the *Batavia* gallery during a boiler shut-down.

In the past three months a new computer-run control has been installed for the air conditioning plant and two temperature and humidity probes have been inserted into timbers (not at the locations of the existing resistance probes) and the key-holes sealed. The effectiveness of the seal is doubtful since during a 23 hour period when the gallery RH increased up to 57.81 the RH of the timbers reached a maximum of 58.3% during the same five hour time interval.

Previous observations on the PEG-treated waterlogged wood, that formed part of the International Comparative Wood Treatment Project, indicated that the extent of degradation, as measured by the $U_{max}$ values, was one of the factors determining the relative sensitivity of the archaeological timbers to changes in relative humidity[8]. Greater degradation leads to more PEG being incorporated into the timbers and this in turn renders them more "sensitive" to changes in the environmental conditions. The range of $U_{max}$ for *Batavia* timbers[11] is 165-576 wt% and so the sensitivity of the *Batavia* timbers to increases in RH is not unexpected. Given that some of the PEG 1500 will have degraded during the treatment programme the average molecular weight will be below 1500 and so the timbers will naturally be more sensitive than might otherwise be expected.

Logged temperature and relative humidity measurements at the surface of the timbers showed up interesting behaviour during another incident. Prior to the plant failure the conditions were as desired, see table 3, but within one 15 minute recording interval the RH increased by 19% with no increase in temperature. In the next three hours the temperature increased by 5°C to 25.5°C and the RH remained at 66.5±2.3°C. After eight hours the plant was repaired and the temperature and relative humidities returned to previous steady values in forty seven hours.

Table 3: Environmental conditions in the *Batavia* gallery during normal operations of the air conditioning plant.

| Location | Relative Humidity | Temperature | Lux |
|---|---|---|---|
| $B_2$ | 49.43±0.49 | 21.51±0.68 | 350 |
| $K_1$ | 50.67±0.59 | 21.37±0.78 | 175 |
| $E_6$ | 49.91±0.66 | 21.25±0.74 | 88 |

An insight into the possible effects of the varying light levels on the rate of change in the resistances was obtained when comparing the light levels and logged temperature at various locations(see table 3). The plank $B_2$ received 350 lux while the light levels at $K_1$ were 175 lux and 88 lux at the plank $E_6$, both of which are six metres higher in the gallery than $B_2$. Analysis of the logged data showed that $B_2$ was systematically 0.14°C hotter than $K_1$ and 0.26 °C hotter than $E_6$ which had the lowest light level. Inspection of the data in table 3 clearly shows a definite relationship between the lux levels from the display lighting and the differences in surface temperature over the reconstruction. The temperature differences will also be reflected in different $k_1$ values for the timbers.

## CHANGES IN SURFACE ACIDITY

Although the pH values listed for the timbers in table 1 were obtained using a flat-surface pH electrode, cored samples of the timbers often have lower pH values, as seen in table 2. During the eighteen months between measurements the pH increased for all five transom beams and the planks $E_1$, $F_8$ and the rib $R_{18}$. With the increased resistances indicating significant drying of the PEG impregnated timbers, the increased pH is probably a reflection of lower water activity and this is manifested in a lower level of activity for the hydrogen ions. There is growing concern for the continued gradual decrease in the pH of the planks $F_2$, $F_0$ and $B_2$ as these are areas where there were the most significant previous levels of acidity associated with the oxidation of pyrite. It should be noted that the surface pH at plank $E_6$ decreased over the period of monitoring. Continued vigilance and regular monitoring are needed to ensure the survival of these fragile parts of the *Batavia* reconstruction.

## FUTURE MONITORING

Adoption of a standard depth of penetration would undoubtedly improve the ability to unequivocally interpret the changes in resistances of the timbers. The use of a commercial four probe AC based *Megger* system, such as are used commercially for measuring soil resistances, would be more accurate and would overcome some of the polarisation problems associated with the DC two probe method used in this pilot study. Given the variability associated with the degree of degradation of waterlogged wood, the more sophisticated methods may well not prove to be cost effective since our crude apparatus has provided us with useful information. Because the resistance probes and data loggers have shown how sensitive the timbers of the *Batavia* reconstruction are to changes in relative humidity, the set conditions for relative humidity in the gallery are now 52±2% RH and 22±2°C. The lowering of the RH should go a long way to minimising the damage that occurs during plant breakdowns.

## CONCLUSION

The use of simple and inexpensive stainless steel probes hammered into the *Batavia* timbers has provided a useful set of data on the rates at which the reconstruction is responding to the local environment. The measurement of electrical resistance was carried out using a digital multimeter and a set of two probes at each location. From plots of the resistance against time it has been possible to obtain results that show the "drying" rate of the PEG 1500 treated timbers is linearly dependent on the penetration depth of the probes and inversely dependent on the cube root of the thickness of the wood. The surface pH also controls the rate of drying with less acidic surfaces having a faster rate of water removal. Differences in response rates can also be interpreted in terms of the local microenvironment where the amount of air movement and proximity to display lighting can have a major impact on the rates of moisture exchange. Uptake of moisture is surprisingly rapid and this highlights the necessity of having good climate controls and an appropriate backup system to cope with normal downtime of the main air conditioning plant.

## ACKNOWLEDGMENTS

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**ADDENDUM**

Following the conference this excellent paper by David Grattan was drawn to the attention of the authors.

Grattan D.W., 1989 "Permanent probes for measuring moisture in wood", *Association for Preservation Technology Bulletin*, XXI(3/4) 71-78.

**Quoc Khoi Tran:** Did you actually try [measuring] the conductivity?

**Ian MacLeod:** No, because we didn't have the money to buy a probe.

**[-]:** Most schools have the equipment and will lend it possibly?

**Ian MacLeod:** By the time I got around to thinking about this my whole concentration was on doing or trying to interpret the results. With the AC system in fact there are nice relationships that you can use depending on the depth of the probes. You can actually calculate how far in your probes are sensing; this is one of the things that we would really like to know. Is this more or less just a response of the change in resistance in the surface layers of the timbers or how far in the probes are sensing? But, given that some of them went in 16 mm and 45 mm into the timber I think we are getting a reasonable field. Also, you can't have your probes deeper than the 25% of the separation distance without getting funny effects. That is the reason that some of the points didn't fit onto that relationship between depth of probe and cube root of thickness of the timber. The timber was so degraded and the probes went in so far that the boundary conditions of diffusion of moisture in and out of that environment broke down and didn't fit with the model of the rest of the structure. No, we didn't measure the conductivity but what we are going to do is use AC measurements in the future with other timbers that we are modelling. The main thing is that it really did prove to us how sensitive the timbers are to changes in conditions. With data loggers and humidity and temperature probes all around the reconstruction we are able to show that the closer you are to the air-conditioning ducts the bigger the deviation from the set conditions there are when the plant goes off. So the timbers that were near the top of the reconstruction got a far worse deal than those down at the bottom. We were able to rationalize some of the changes that would otherwise appear to be anomalous.

**David Grattan:** Cliff [Cook], could you comment on the time you used electrodes like that with a Delmhorst meter for moisture gradients when drying waterlogged wood?

**Clifford Cook:** This is something that I got from Dave. We used stainless steel screws driven into a set depth of about an inch and a quarter. We monitored a profile from the pith, in the centre, and out along an end grain. The screws were the same distance apart as the meter probes. There was some concern about insulation of the screws and it turned out it didn't matter. I was using a slow drying process to try and maintain a flat gradient between the interior of the timber and the exterior surface. We used alligator clips on the end of a piece of lamp cord to connect onto the meter and we used one pair of screws to measure the values. Your value decreases to a minimum. We set a standard length of time and then used that time to take a reading. You could plot quite precisely the gradient across and the time. You could measure very small changes in humidity in the interior of the wood by playing with the RH levels in the environmental chamber. It is a much more sensitive method than weighing timbers which is the traditional way of doing it for slow drying. The advantage is that you don't have to have a sling around the timber that might weigh a few hundred pounds, as well as dealing with all that aggravation. One thing that I worried about was we only monitored about an inch and a quarter into the end grain. What was happening in the core, the interior, of the timber, I have no guarantees that it would parallel the end grain. I would hope it would, because with wood most of the drying happens in the end grain anyway, so I was hoping that's where my greatest moisture loss would be. It just gave me much better control of the humidity inside the wood than I could get by weighing. It worked quite well. It was quick and easy.

**Ian MacLeod:** Before there was a change in environmental conditions where we lowered the RH in the gallery we got steady resistance readings. At that stage those surface layers of the timber were equilibrated with the external environment. We dropped the RH down by another 3% and again the resistance changes took off. It is really quite a sensitive thing. By having those differences of surface temperatures and light levels it has enabled us to convince the Maritime Archaeologists in charge of the display that they need to seriously look at getting softer lighting. At the moment, with the floodlights you get a difference of a ⅛° C. You may not think that is much but in an air conditioned environment with a reasonable turnover of air that is a significant difference in microenvironment.

**Clifford Cook:** Going back to the moisture probe monitoring, when a convent chapel was installed in the National Gallery. Dave, [Grattan] installed several probes and ran wires from the stainless steel screws down to a central piece of plywood. He did not have to clamber over the structure once he had set up all the screws. He could just clip onto the stainless steel screws. The resistance of the wire was trivial compared to the resistance of the timber. It means in any size of structure once you have your probes and wires placed you can just stand in one place and take your measurements. You can save an awful lot of time in monitoring.

**Ian MacLeod:** Also, it is quite tricky climbing over the "Batavia" reconstruction. I have had a couple of near falls and since the top probes are about 8 metres above the concrete it is a reasonably bumpy ride down.

**Chris Caple:** Did you monitor the thermal couples at all?

**Ian MacLeod:** Some of the probes are in timbers which we know are loaded with pyrite. Some of them seem to have, initially, quite different responses to changes in RH. But, it turned out that it was more a reflection of the depth of the probes relative to the thickness of the timber, the inherent acidity of the surface, and the corrosion of the pyrite oxidation products.

**Chris Caple:** You are equating the pH to the pyrite level?

**Ian MacLeod:** No, the pH change is a result of varying degrees of oxidation of pyrite, when we had times of high RH.

**Chris Caple:** But since you didn't measure the pyrite you don't know how much was present?

**Ian MacLeod:** Well pyrite itself is inert. It has a neutral pH.

**Chris Caple:** How does this relate to the long term stability?

**Ian Macleod:** With many of the timbers that appear to be stable we have done analysis of the pyrite content and they are very high. Some of them have 10%, 15% or 20% weight of pyrite in them. If the RH control is lost, we stand a good chance of losing those timbers. Is that what you meant?

**Michael Cornfield:** Are you going to have to do a lot of refinements with your air-conditioning system?

**Ian MacLeod:** Yes, we are in the process of doing that.