SNO-STR-92-13

Stress in Acrylic due to Water absorption/desorption [1]

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Abstract

The stresses that occur when water is absorbed or desorbed by acrylic have been studied.To be conservative it is recommended that the vessel be maintained in a saturated vapor atmosphere whenever the water level is lowered in the SNO cavity.

1 Introduction

Acrylic absorbs both H_2O and D_2O at approximately equal rates (UCI-Neutrino-89-10) and in doing so swells. Maximum saturation occurs at approximately 2.1% by weight, and until this situation is approached the density distribution of absorbed water decreases approximately exponentially from the surface in contact with the water. Therefore, as the acrylic absorbs water

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and swells, the outermost volume experiences a compressive stress while the inner volume experience a tensile stress as it tries to resist the swelling of the outer layers.

When the acrylic is removed from the water it dries preferentially from the outer surface resulting in the outer layer shrinking at a rate which is greater than the inner volume. Thus the outer volume experiences an increase in tensile stress, while the inner volume experiences a compressive stress. This is illustrated in schematically in figure 10. The exact magnitude of the stress has not been measured, however, a rough estimate can be calculated from the dimensional change as a function of the water absorbed, (information obtained in this manner has been provided to us by Rohm see discussion section).

This source of stress first came to our attention when crazing was observed in acrylic which had been saturated in water and subsequently exposed to solvents during the application of strain gauges. Acrylic which had not been saturated with water did not craze when the strain gauges were applied. Since the SNO acrylic vessel will become saturated with water and the level of the water will be lowered and raised possibly several times, it is necessary to obtain a quantitative value of the stress associated with absorption and desorption.

2 Experimental Technique:

The stress in the acrylic was measured by embedding strain gauges at different depths in the acrylic. This technique appeared to give reliable results when used to measure the locked in bond stress described in SNO-STR-91-59.

2.1 Sample Preparation:

Three, 4 inch diameter by 1.5 inch thick acrylic discs were cast with strain gauges embedded approximately 1/16 inch below each surface and one at the center of the disc. Teflon coated wires led from the strain gauge to the outside of the acrylic disc. These details can be seen in Figure 1.

The first attempt to encapsulate the gauges was a failure since gas bubbles developed around the gauges during polymerization of the acrylic. A second

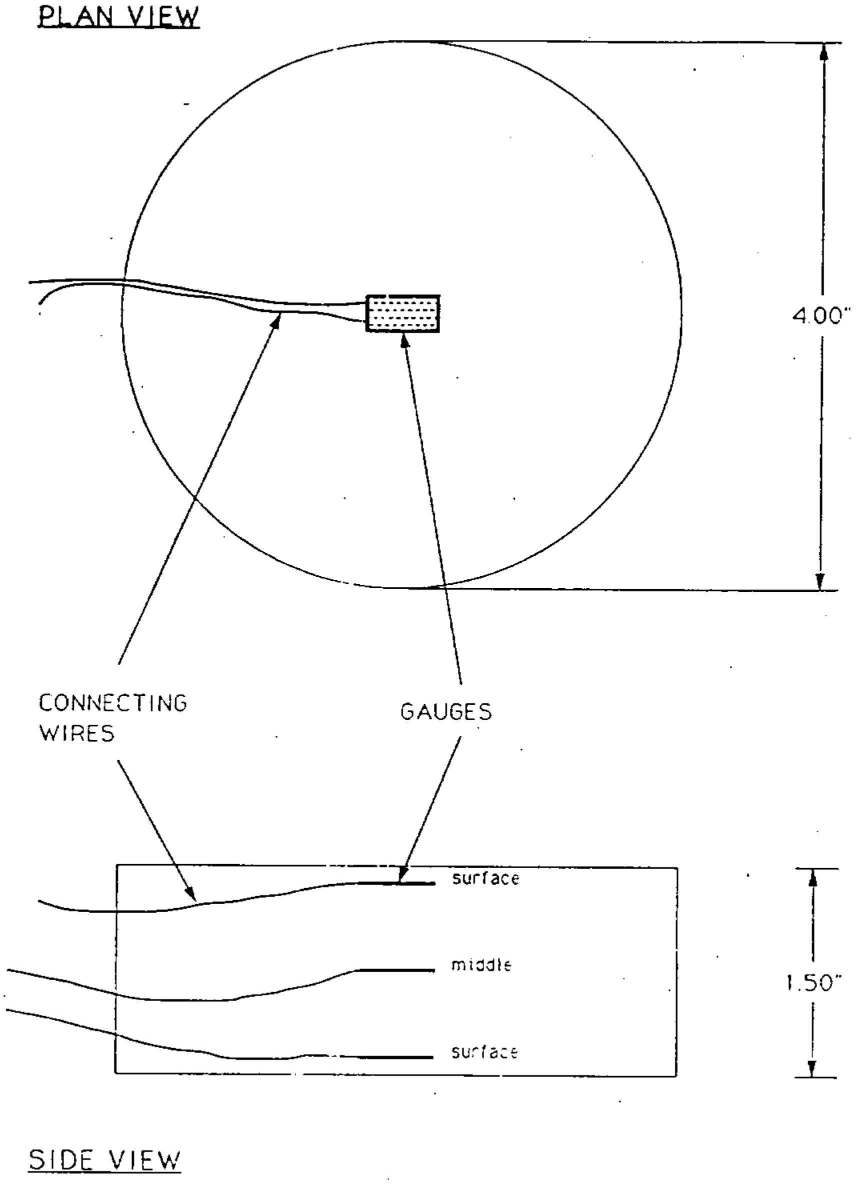

Figure 1: Location of strain gauges in acrylic test samples

attempt resulted in a 50% success rate which was deemed satisfactory for the purposes of the experiment.

2.2 Sample Conditioning:

The test specimens were then subject to accelerated water loading by immersing in 6MΩ water at 60°C for 20 days in a stainless steel, closed, constant temperature bath. Note that the resistance of the water rapidly degraded, presumably due to the leaching of ionic material from the acrylic. Immersion of the samples in water at an elevated temperature increases the rate of water absorption due to an increase in the diffusion coefficient (UCI-Neutrino-89-10). 20 days in water at 60°C is roughly equivalent to 5 years immersion in water at 10°C.

Due to the length of wire extending from each sample it was not possible to accurately measure the weight of the test samples before and after immersion. This is unfortunate since the total water absorbed is of great interest. However, data exists from earlier experiments (UCI-Neutrino-89-10) which give an approximate value of the water absorbed.

The resistance of the strain gauges were recorded before and after encapsulation and throughout the immersion in water.

2.3 Data Taking:

Once the samples were loaded with water they were allowed to return to ambient temperature (23° ± 1°C). One sample was left in the water as a reference, the second sample was placed in the saturated vapor above the water, but still within the enclosure of the constant temperature bath, the third sample was exposed to the atmosphere of the laboratory. This arrangement is shown in figure 2.

The temperature of the bath, and the temperature and humidity of the vapor above the bath and the air in the laboratory were recorded at regular intervals along with the resistance of the strain gauges.

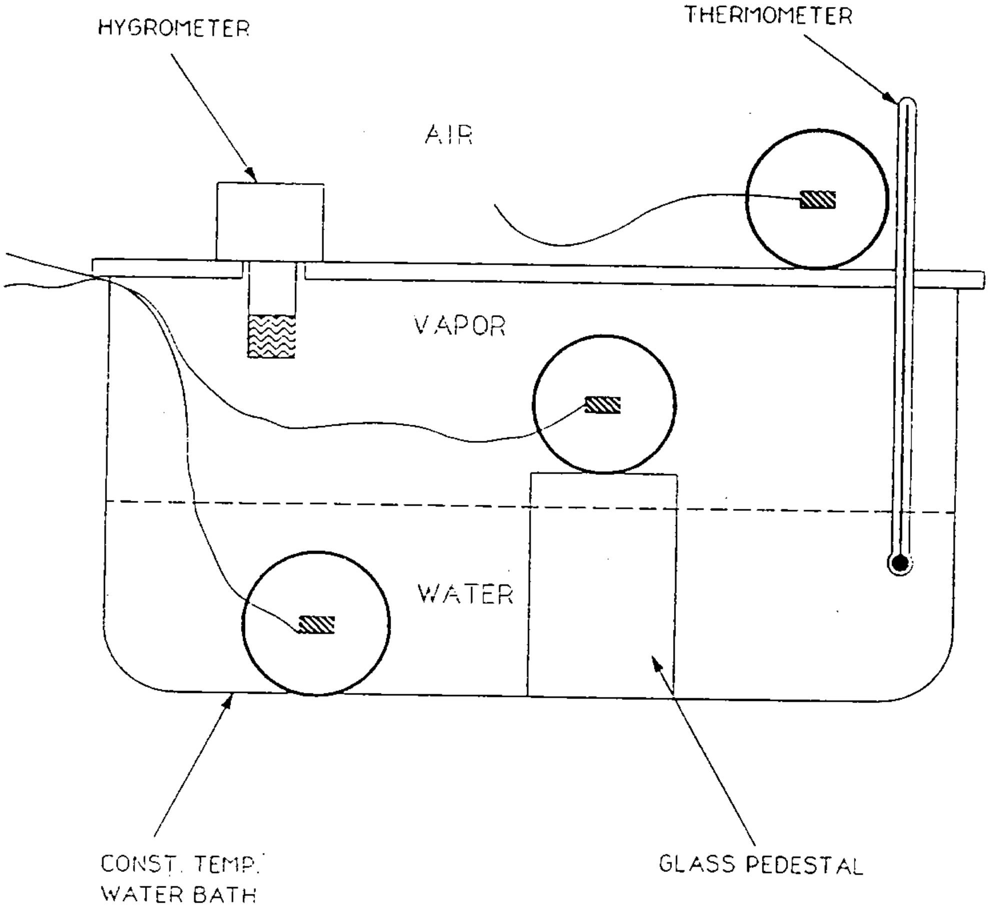

Figure 2: Arrangement of samples in bath and air

3 Results:

3.1 Encapsulation:

The resistance of Strain Gauges before and after encapsulation is given below. Those gauges noted as having failed during encapsulation were all found to be open circuit. Visual examination of these gauges gave no physical indication of why they failed.

Gauge ID	Location	Resistance (K Ohms)	
		Before	After
1A	Surface	0.350103	0.348063
1B	Middle	0.350243	0.349292
1C	Surface	0.350526	Failed
2A	Surface	0.350422	0.347929
2B	Middle	0.350390	0.349031
2C	Surface	0.350561	Failed
3A	Surface	0.350392	Failed
3B	Middle	0.350490	Failed
3C	Surface	0.350533	0.348287

It should be noted that the resistance of all gauges decreased by on average 0.5% after encapsulation. This is to be expected since the acrylic contracts by as much as 12% by volume during polymerization. The value of the resistance after encapsulation was considered to be the reference or starting value to which all subsequent measurements are to be compared.

3.2 Water loading:

In figure 3 is shown the stress recorded in sample 3C as it was loaded with water at 60°C (the other samples behaved similarly). Note that the rapid increase in tensile stress at the beginning and rapid decrease at approximately 480 hours is due to expansion of the sample during heating to 60°C and contraction during the subsequent cooling.

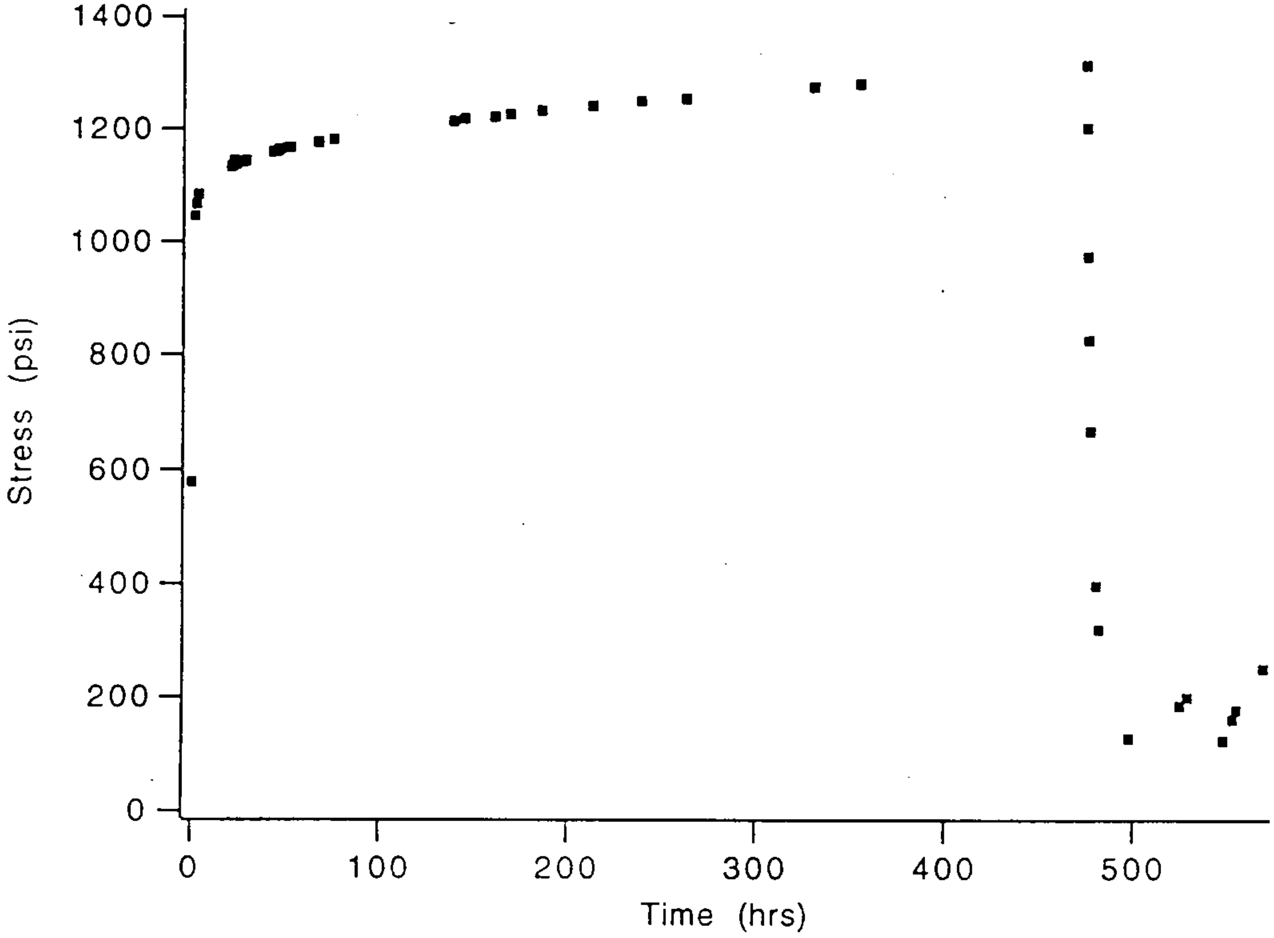

Figure 3: Surface stress as sample is loaded with water

The stress was calculated in the following manner:

$$\text{Strain} = \varepsilon = \Delta \text{ L/L} = (\Delta \text{ R/R})/\text{G.F.}$$
$$\text{where G.F.} = \text{Gauge Factor}=2.115$$
$$\text{Stress} = \sigma = \text{E}.\varepsilon = \text{E}.(\Delta \text{ R/R})/\text{G.F.}$$

The rapid increase in tensile stress (negative stress values) in the first few hours, due to the expansion of the acrylic as it changes from 23°C to 60^{0}C, gives a useful opportunity to cross check the operation of the strain gauges. Since:

$$\Delta \text{ L/L} = (\Delta \text{ R/R})/\text{G.F.} = 0.001$$

This gives a value of $2.5\text{x}10^{-5}$ as the coefficient of thermal expansion for acrylic - in good agreement with reported values and evidence that the strain gauge is working correctly.
After about two hours when the tensile stress has reached approximately 1,100psi, it continues to increase with a much smaller time constant. It is believed that this represents the stage when the test specimen is in thermal equilibrium with the bath and further increases in the tensile stress is due to the swelling of the acrylic stretching the strain gauge embedded in it. This continues until after 475 hours the tensile stress reaches a value of 1300psi, at which stage the bath is allowed to return to ambient temperature (23°C) and the tensile stress is seen to fall to between 100 and 200psi.

3.3 Atmospheric exposure:

Figures 4,5 and 6 show the effect of subsequently exposing the samples to water at 23^{0}C, saturated vapor at 23^{0}C and the arid atmosphere at Los Alamos where the average relative humidity was 27% and the temperature between 21 to 23°C during data taking. All these results come from the gauges located close to the surface of the test specimens.

An interesting result can be seen by comparing the sample in water with the sample in saturated vapor. Their behavior is almost identical, showing

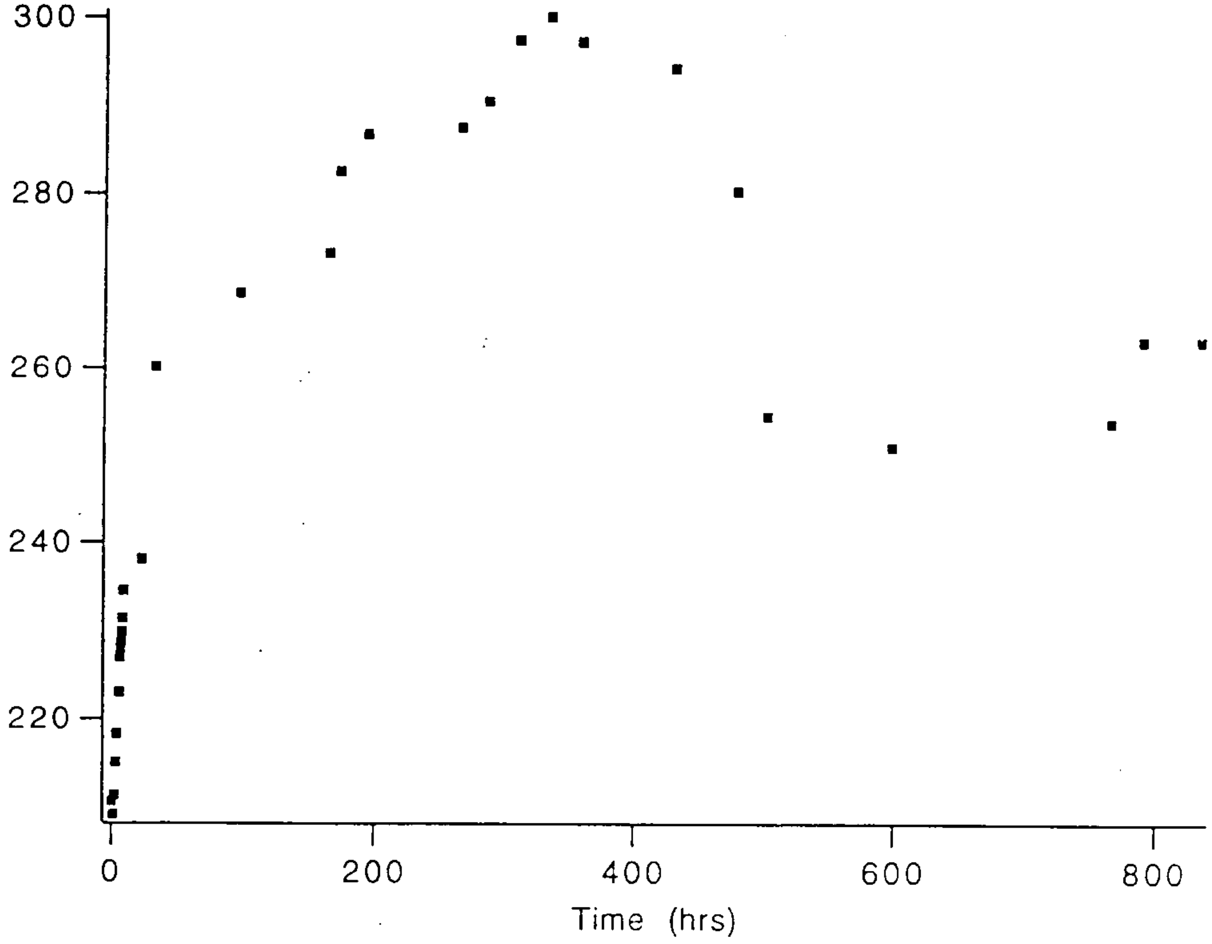

Figure 4: Stress near surface exposed to water

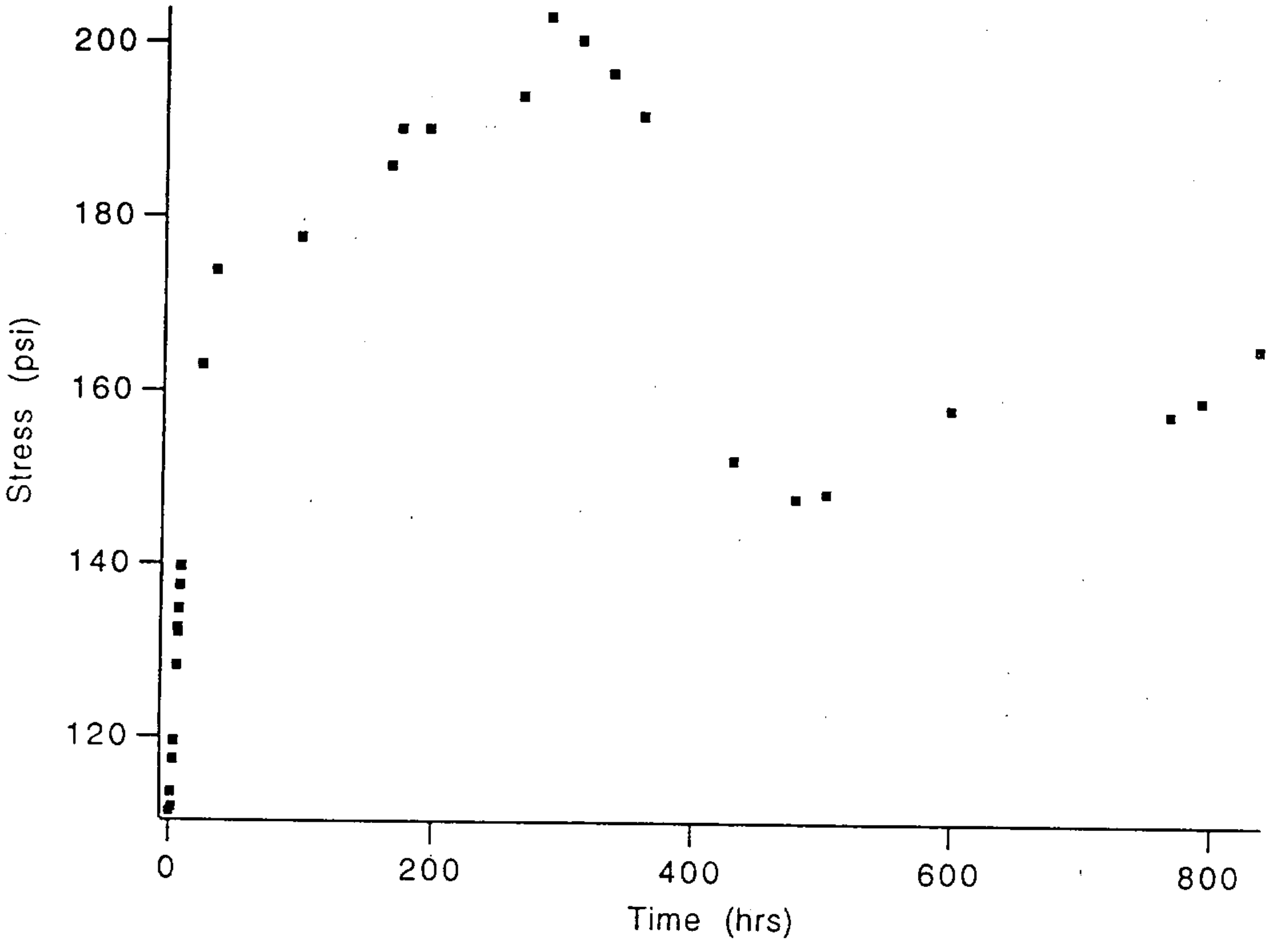

Figure 5: Stress near surface exposed to vapor

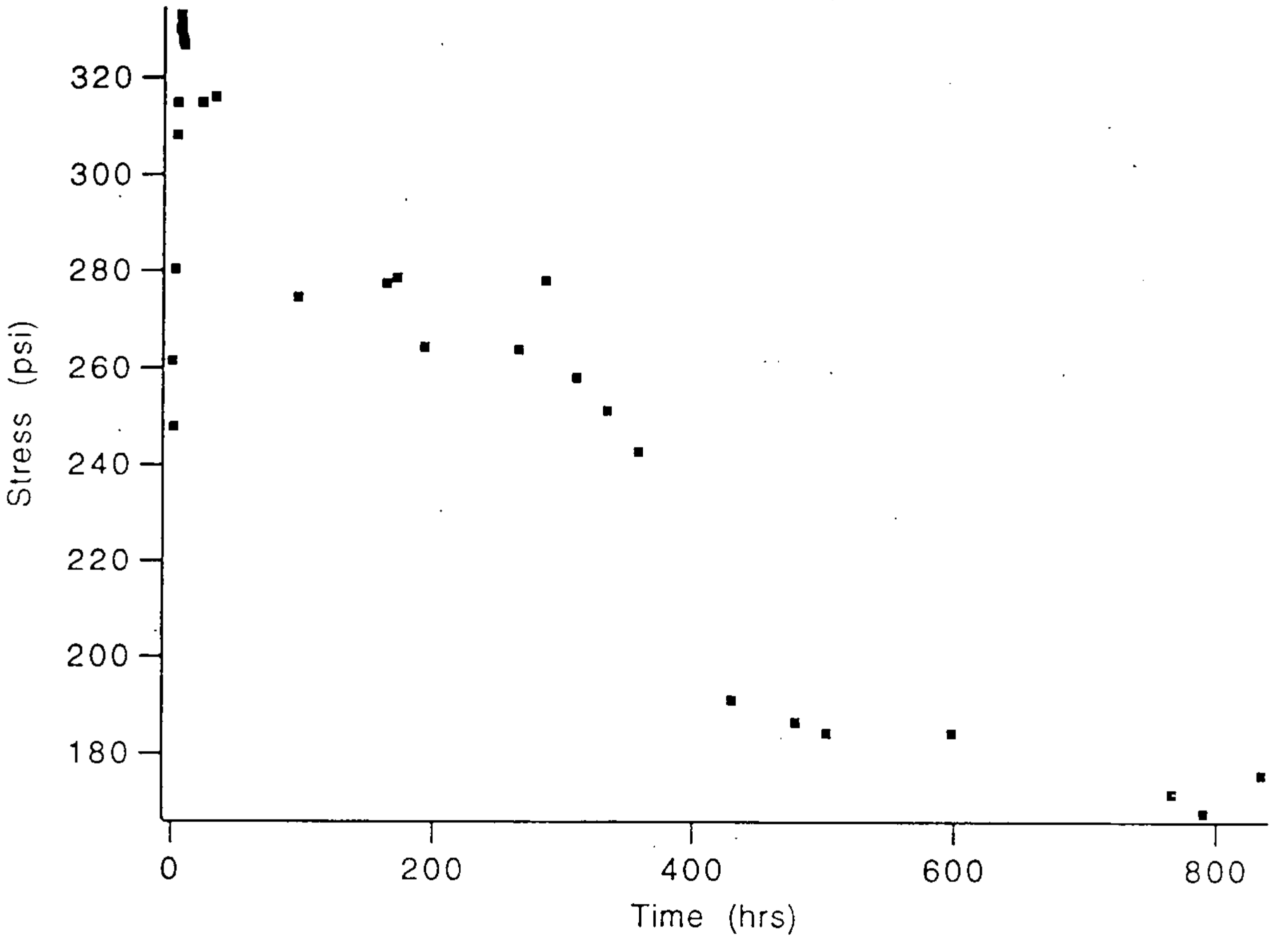

Figure 6: Stress near surface exposed to dry air

the same rate of change of stress and reaching peak stress values after the same length of time (310 hours in water, 286 hours in vapor), after which the stress is seen to decrease in both samples. The only difference is the absolute value of the stress, (300psi in water 203psi in vapor), which may possibly be attributed to the difference in depth of the gauges beneath the surface of the acrylic.
The behavior of the test specimen exposed to air is very different. The stress continues to increase rapidly, reaching a maximum value of 330psi after 5.5 hours, then decreasing until after approximately 500 hours it appears to become roughly constant at 170psi.

Figures 7 and 8 show data from the strain gauges located near the center of the samples exposed to vapor and dry air respectively.

Comparing these with the results from the gauges mounted near the surface it can be seen that the stress values are identical to within 2% - an unexpected result since the water density in the region of the gauges should be very different (the samples were not saturated). Only when the sample is in saturated equilibrium with the water and therefore uniformly swollen throughout it's volume would one expect the gauges to read the same, while other situations are depicted by the schematic in figure 10. However, as discussed below, these results are reasonable and exactly as expected.

4 Discussion:

A physical interpretation of these results is non-trivial and may be further complicated by such questions as what the density distribution of absorbed water was at the time at which the data was taken or whether the presence of the strain gauge, which is mounted on a carrier of polyimide film with dimensions of 3mm x 5mm, significantly disturbs the smooth penetration and hence density distribution of water in the region of the strain gauge? However *the almost identical behavior of the specimens in water and saturated vapor bodes well for the SNO acrylic vessel, since even in the absence of an accurate interpretation it can still be said that keeping the vessel in a saturated vapor is equivalent to keeping it immersed in water at the same*

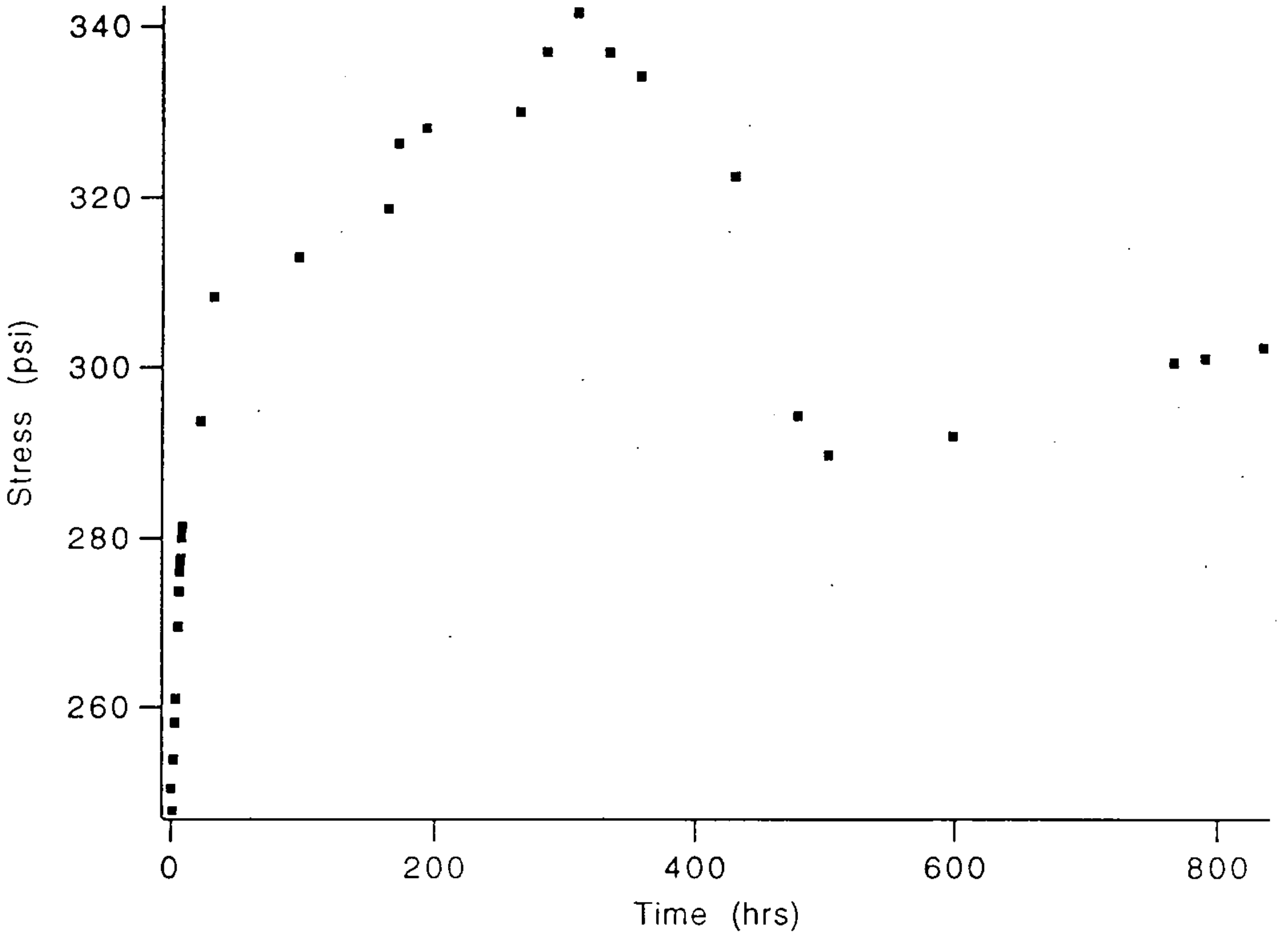

Figure 7: Stress near center of sample exposed to vapor

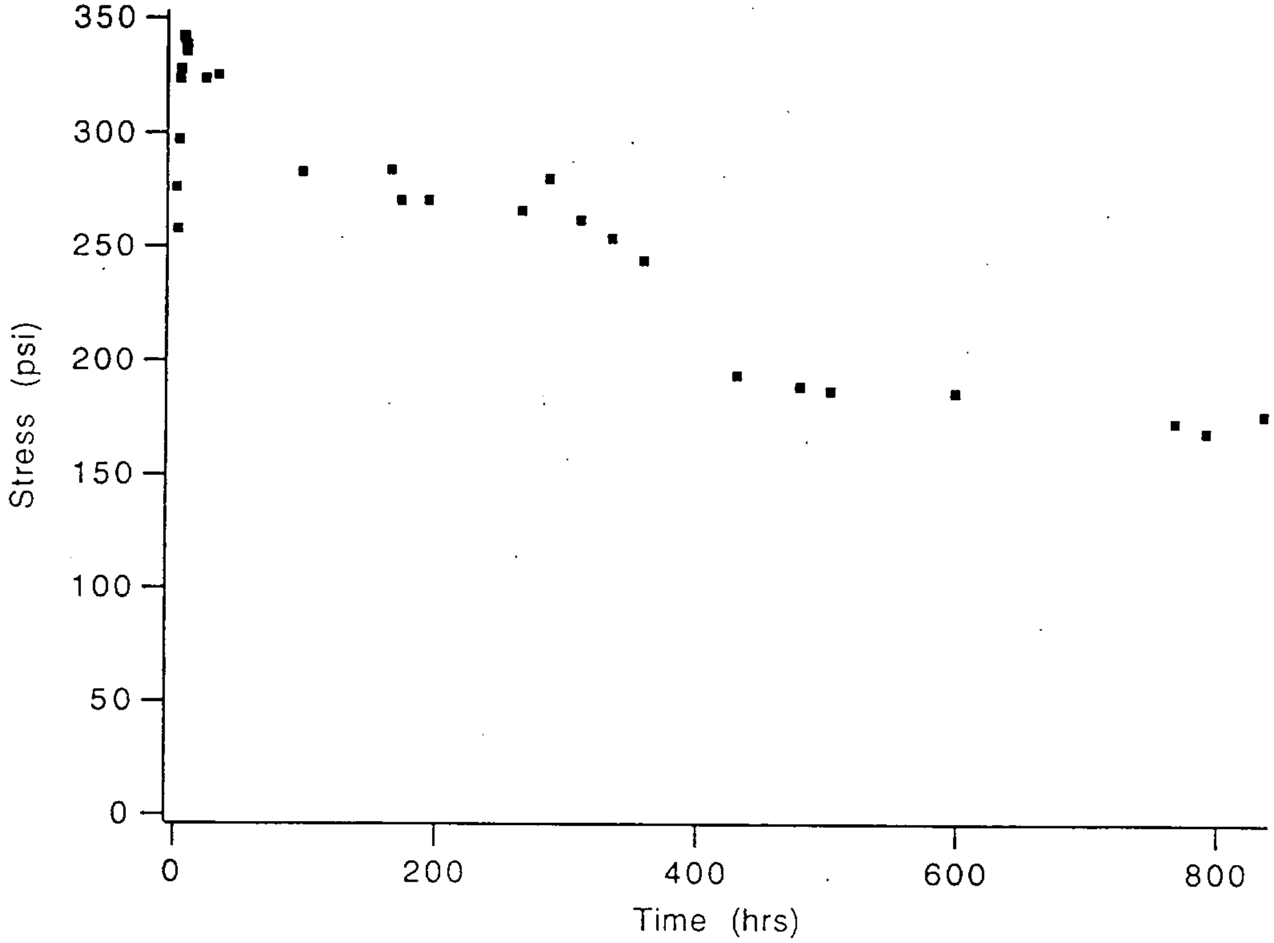

Figure 8: Stress near center of sample exposed to dry air

temperature.

Figure 9 shows the calculated tensile stresses developed during absorption and desorption as a function of the dimensionless quantity $D.\pi^2.t/d^2$, as culculated by Rohm. It can be seen that the calculated curves and the data share the same features, namely a rapid rise in tensile stress for desorption compared to a slower rise for absorption. For the appropriate values of D and d the maximum stress due to absorption from the Rohm curve occurs at 60 hours, whereas the maximum stress in the data occurs at approximately 250 hours. Given the uncertainties of the experimental set up and the idealism of the calculated values, it is probably meaningless to draw further comparisons.

At first glance, the most troublesome feature of the data is the remarkable similarity between the response as a function of time of the middle and surface gauges, naively one would expect them to read equal values but opposite signs of stress, however, this is not so. When the outer volume of the acrylic absorbs water and expands it is under a compressive stress since it is being restrained by the inner volume (which has not expanded as much). However, since the outer gauge is embedded in the acrylic, when the acrylic expanded the gauge is stretched and registers *tensile stress.* Meanwhile the inner volume of acrylic, along with the embedded gauge is trying to resist the expansion of the outer volume, is stretched and therefore registers *Tensile stress* also.

5 Conclusions and Recommendations:

The measurement of stress due to water absorption is not as trivial as it first appears. Although there are many unexplained features of the present data, it is felt that the almost identical response of the samples in water and saturated vapor, compared to the very different behavior of the sample in 25% humidity indicate that the water and vapor samples are behaving the same and not seeing the rapid stress build-up experience by the sample exposed to an arid atmosphere. Therefore it is recommended that whenever the water levels in the SNO cavity are lowered the atmosphere should remain saturated.

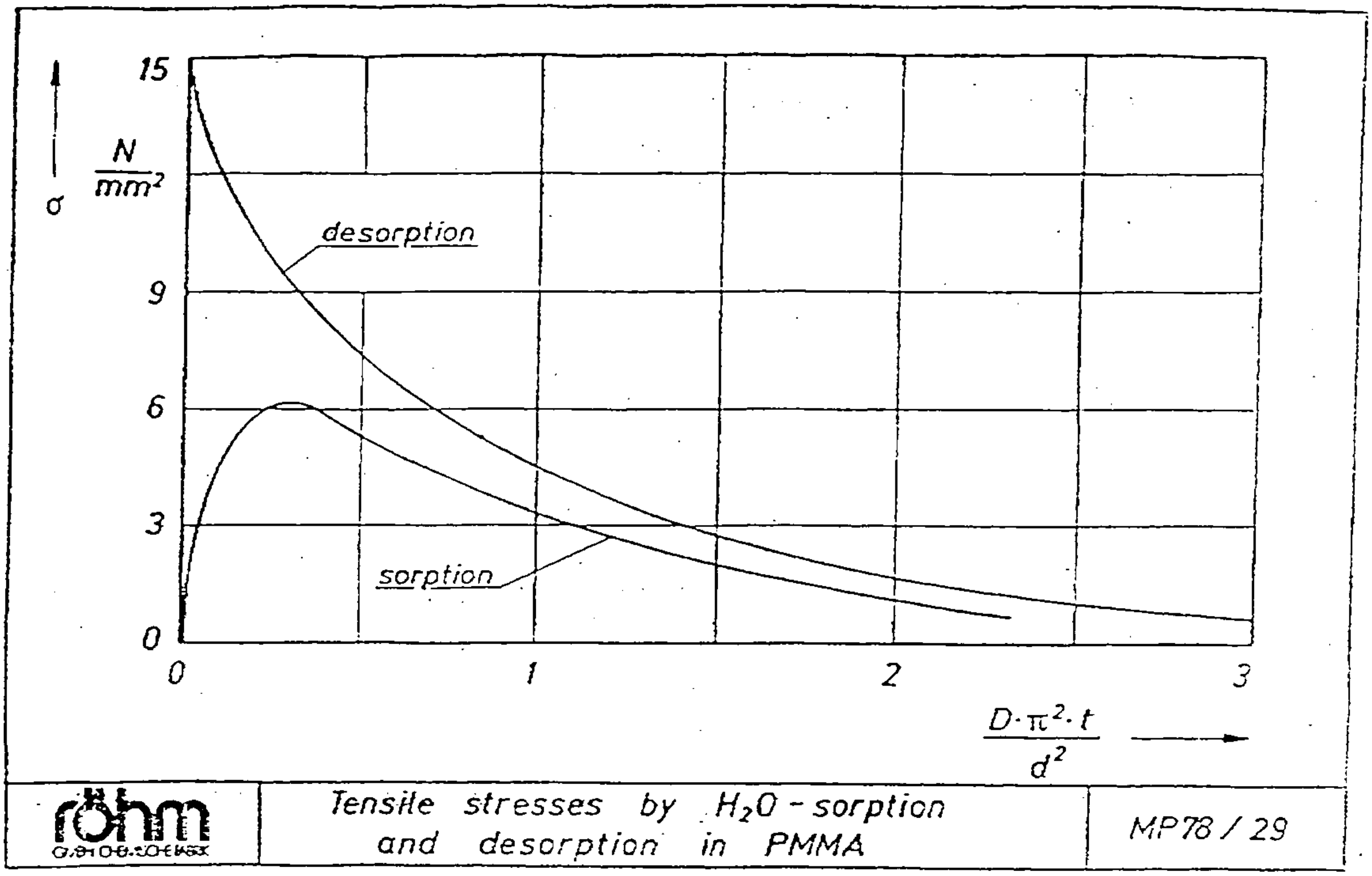

Figure 9: Tensile stress due to absorption/desorption of water in acrylic

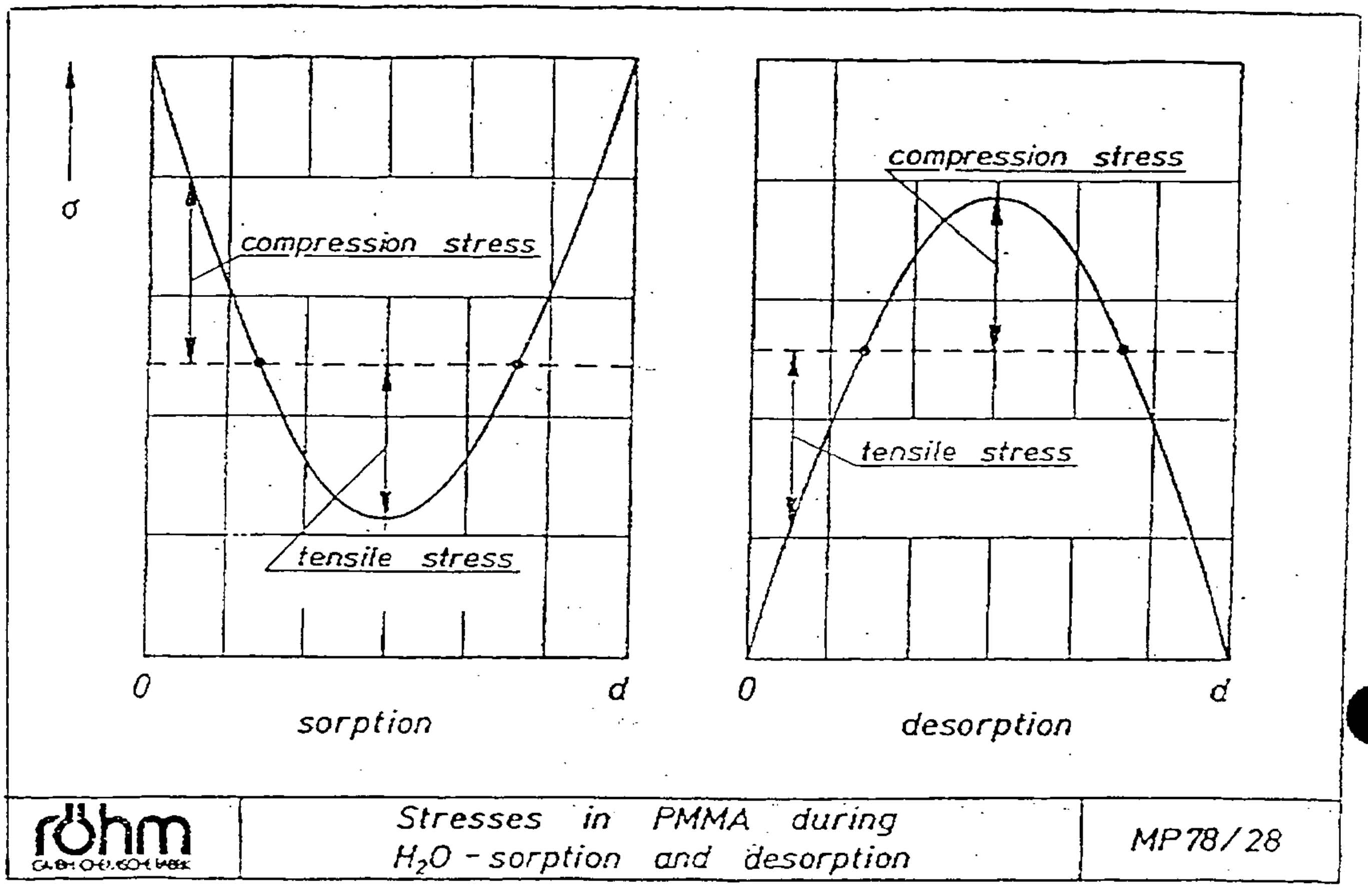

Figure 10: Tensile stress due to absorption/desorption of water in acrylic