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LIGHT SCATTERING IN CRAZED ACRYLIC

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Abstract

Measurements of the fractional undeflected intensity of a HeNe laser beam (632.8 nm) incident upon crazed acrylic at varying angles provide an indication of how an aging acrylic D_2O vessel at the Sudbury Neutrino Observatory might scatter Čerenkov radiation produced within the vessel. It is found that while the degradation in transmission varies strongly with the degree of crazing, the variance of degradation as a function of incident angle is universal in form. Transmission is maximal for normal incidence, dropping sharply to a minimum within $\approx 20^o$, then rising steadily to full transmission at $\approx 50^o$.

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1 INTRODUCTION

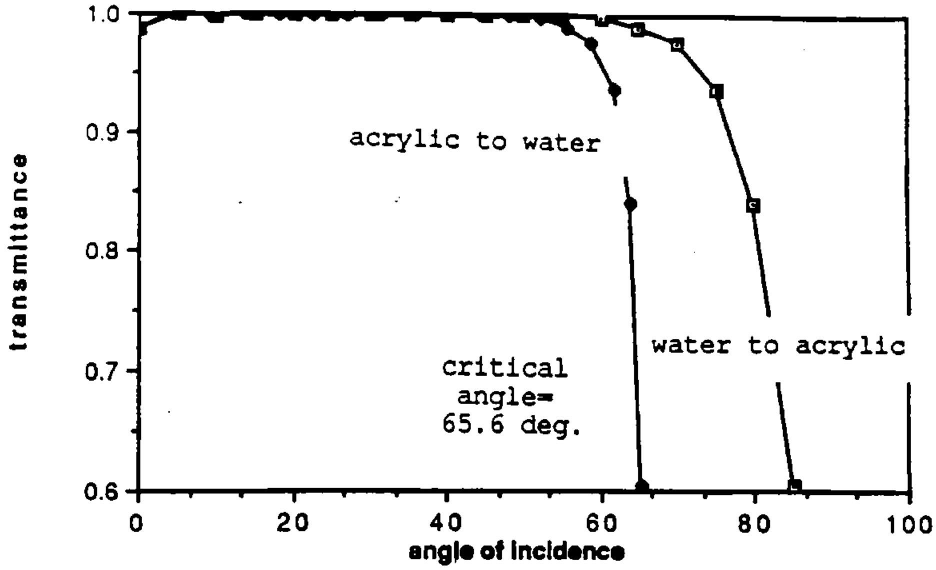
The Sudbury Neutrino Observatory (SNO) [1], scheduled to begin operation in 1995, will employ D_2O as the primary medium with which solar and other extraterrestrial neutrinos will interact. From the Čerenkov radiation produced by the secondary particles, the kinetic energy, direction of approach, and type of incident neutrino can be ascertained. The spherical vessel designed to contain the heavy water will be contructed using thermoformed acrylic, chosen for its strength, transparency, and radioactive purity. Čerenkov photons produced in the D_2O must pass through the transparent tank to be detected in photomultipliers suspended outside the vessel.

When acrylic is placed under tensile stress, cracking, or a condition refered to as "crazing" develops. Crazing is characterized by parallel crack-like damage zones running transversely to the direction of the applied stress [4]. The damage zone consists of voids (40-50%) and material which has a lower density than the bulk acrylic. With the continued application of stress to the acrylic, the crazing develops into easily visible cracks and seriously weakens the acrylic [2]. Because of the difficulty in distinguishing between the two, we use the terms "cracking" and "crazing" interchangeably throughout the report.

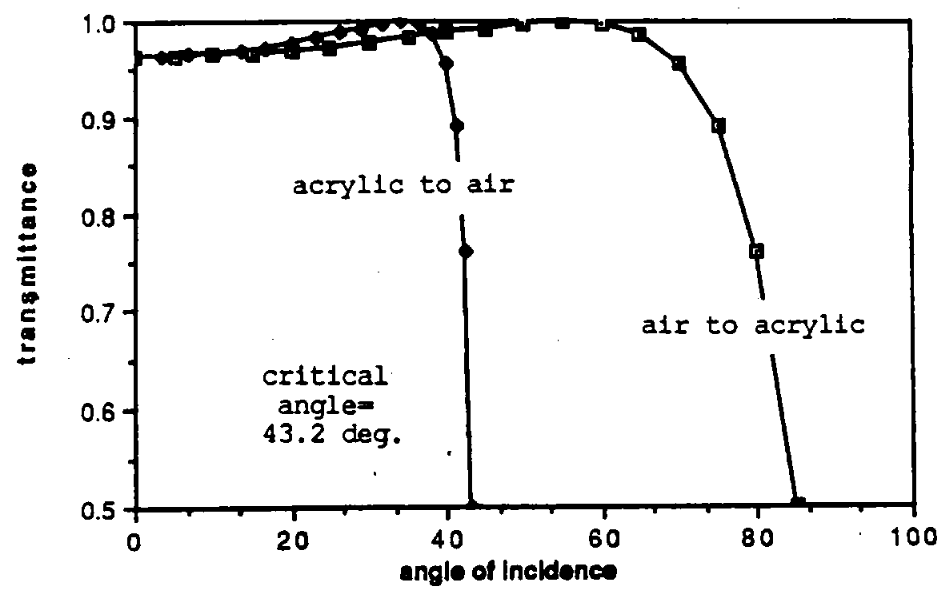
Since cracking and crazing are visible to the unaided eye, it is clear that light transmission in crazed acrylic differs from that in unaffected acrylic and that this may have serious consequences on the reconstruction of events in SNO. The goal of our observations is to develop an understanding of the effects that cracked and crazed acrylic has on incident light.

2 THEORY

Assuming that crazing is a macroscopic effect, that is, that the effects of crazing on transmission due to point scattering are negligible, then a basic electromagnetic treatment involving reflectance and transmittance of light in acrylic and incident upon the planar crazing should suffice to explain the observed effects (an extended discussion of the observed crazing is given in appendix 2). Graphs of transmittance vs. angle of incidence to and from acrylic surrounded by both air and water are shown below in Figure 1.



transmittance between water and acrylic as
calculated using Fresnel's equations, TM mode



transmittance between air and acrylic, TM mode

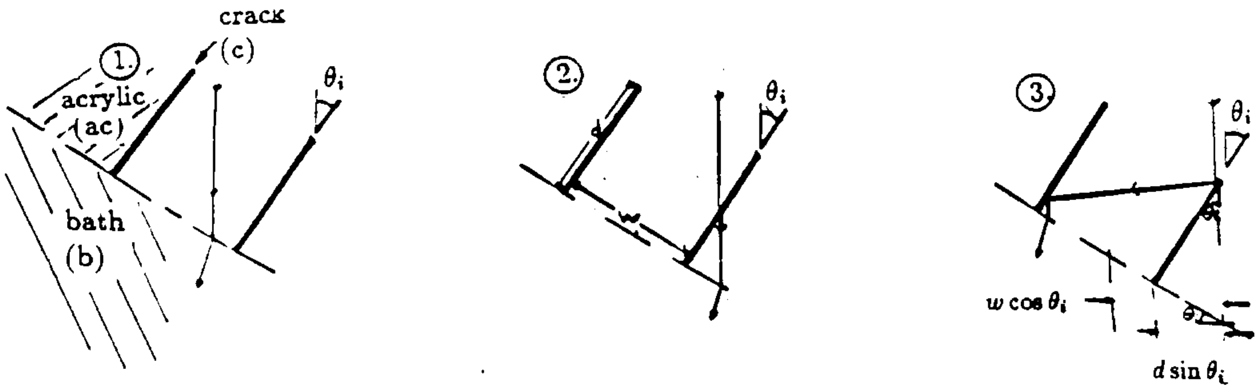
Figure 1: Transmittance to and from acrylic in water, air.

Data for the graphs was calculated using the Fresnel equations for incidence on a dielectric material of polarized light in transverse magnetic (TM) mode [5]. [1] In our simplified analysis of transmission through crazed acrylic, let us assume that light may be transmitted without net angular deflection in 3 ways:

1. transmission through the acrylic without striking any cracks or crazing.
2. transmission directly through any cracks or crazing.
3. reflection from one crack to a second crack, and reflection from the second back into the same direction as the incident beam, like an image through a periscope.

Figure 2 below illustrates the three modes of transmission. Assume cracks of uniform depth **d**, all perpendicular to the surface of the acrylic, and uniform width between cracks **w**. Transmittance by (1) is given by the product of the fraction of light passing without striking crazing and the transmittance into and out of the acrylic (which are identical by the Fresnel equations). Transmittance by (2) is given by the product of the fraction of light striking the crazing, transmittance into and out of acrylic, and transmittance through a crack. Transmittance by (3) is given by the product of the fraction of light striking the crazing, the transmittance through the acrylic, the reflectance (R= 1-T) between two cracks, and the fraction of light that is directed back in line with the incident beam. At angles of incidence for which the tangent exceeds 3w/d, the reflectance factor would be raised (from the second) to the fourth power in the analysis. This final means of transmittance assumes a lower bound as light passing through the second crack and reflecting back into line from the third (or fourth, etc.) crack is unaccounted for.
To obtain the total transmittance as a function of incident angle, we need to know the ratio of crack depth to distance between cracks, the refractive index of the medium in which the acrylic is tested, and the refractive index

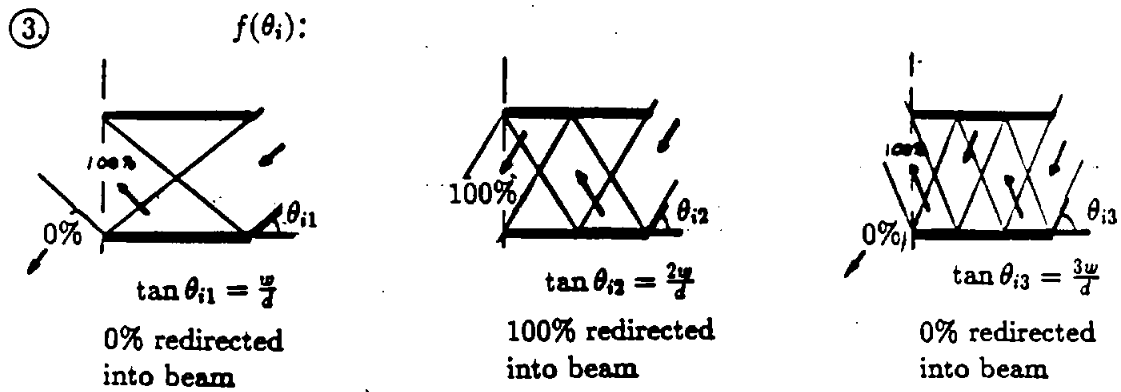
[1] Transmittance in TM mode was graphed because it was discovered, late in the experiment, that the laser was polarized $\approx 20°$ from TM, meaning that $> 88\%$ of the incident radiated energy was TM. In order to simplify the calculations of transmittance while remaining as consistent as possible, the polarization was set to $0°$ from TM (pure TM) for the remainder of the experiment in which the final series of four plates was tested.



$$\text{(1)}\ T = \left(\frac{w\cos\theta_i - d\sin\theta_i}{w\cos\theta_i}\right)(T_{b\to ac})(T_{ac\to b}) = \left(1-\frac{d}{W}\tan\theta_i\right)(T_{b\to ac})^2$$

$$\text{(2)}\ T = \left(\frac{d\sin\theta_i}{w\cos\theta_i}\right)(T_{b\to ac})(T_{ac\to c})(T_{c\to ac})(T_{ac\to b}) = \left(\frac{d}{W}\tan\theta_i\right)(T_{b\to ac})^2(T_{ac\to c})^2$$

$$\text{(3)}\ T = \left(\frac{d\sin\theta_i}{w\cos\theta_i}\right)(T_{b\to ac})(1-T_{ac\to c})(1-T_{c\to ac})(T_{ac\to b})(f(\theta_i)) =$$
$$\left(\frac{d}{w}\tan\theta_i\right)(T_{b\to ac})^2(1-T_{c\to ac})^2(f(\theta_i))$$



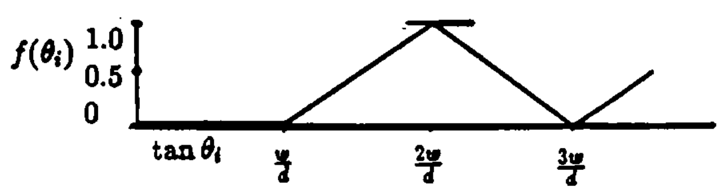


Figure 2: Principal modes of transmission.

within the cracks. This simple model will be applied to crazed samples and compared to the observed transmittance.

3 APPARATUS and PROCEDURE

A schematic of the experimental setup[2] is shown below in figure 3. A HeNe laser was employed as the light source. While the laser emits light at 632.8nm and 1150nm, the silicon photodiode detector, used to measure the intensity of the transmitted beam, is sensitive between 350nm and 1100nm, and therefore sees only the peak of shorter wavelength. The detector is also sensitive to ambient light, which was determined to contribute between 0.5% and 2% of the total irradiance received by the detector. To conserve work space, the beam was folded back on itself by two 1" diameter pyrex first-surface mirrors. A variable aperture shutter was used to define the beam diameter before it passed through the acrylic sample under test and into the photodetector. To measure the transmission through the sample while immersed in water, a square, transparent container was positioned around the sample and filled with water.

By measuring the laser diameter at the shutter and the photodetector nearly 500mm downstream as shown in figure 3, the angular spread of the laser in the region of incidence with the acrylic was calculated to be between 0.2° and 0.3°. The shutter size was set such that the transmitted spot would be as large as possible while entirely contained by the sensitive area of the photodetector. A large beam diameter was desirable in order to integrate over a statistically large sample of crazing. To allow for refractive displacement of the beam, the photodetector was fixed to an X-Y micrometer so that the beam could be centered on the detector for all angles of incidence.

Fitting 6.4x50x50mm or 6.4x50x100mm acrylic plates into a square lense holder attached to an angular dial, transmission through each sample was measured before and after crazing. Since the lens holder rotated only about a vertical axis, in order to test transmission for any angle of incidence the crazed plates were tested with the direction of the crazing parallel to and perpendicular to the axis of rotation. Since cracks are parallel to one an-

[2]Special thanks to Dr. Peggy Dyer and Judy Gursky for use of Laboratory Facilities.

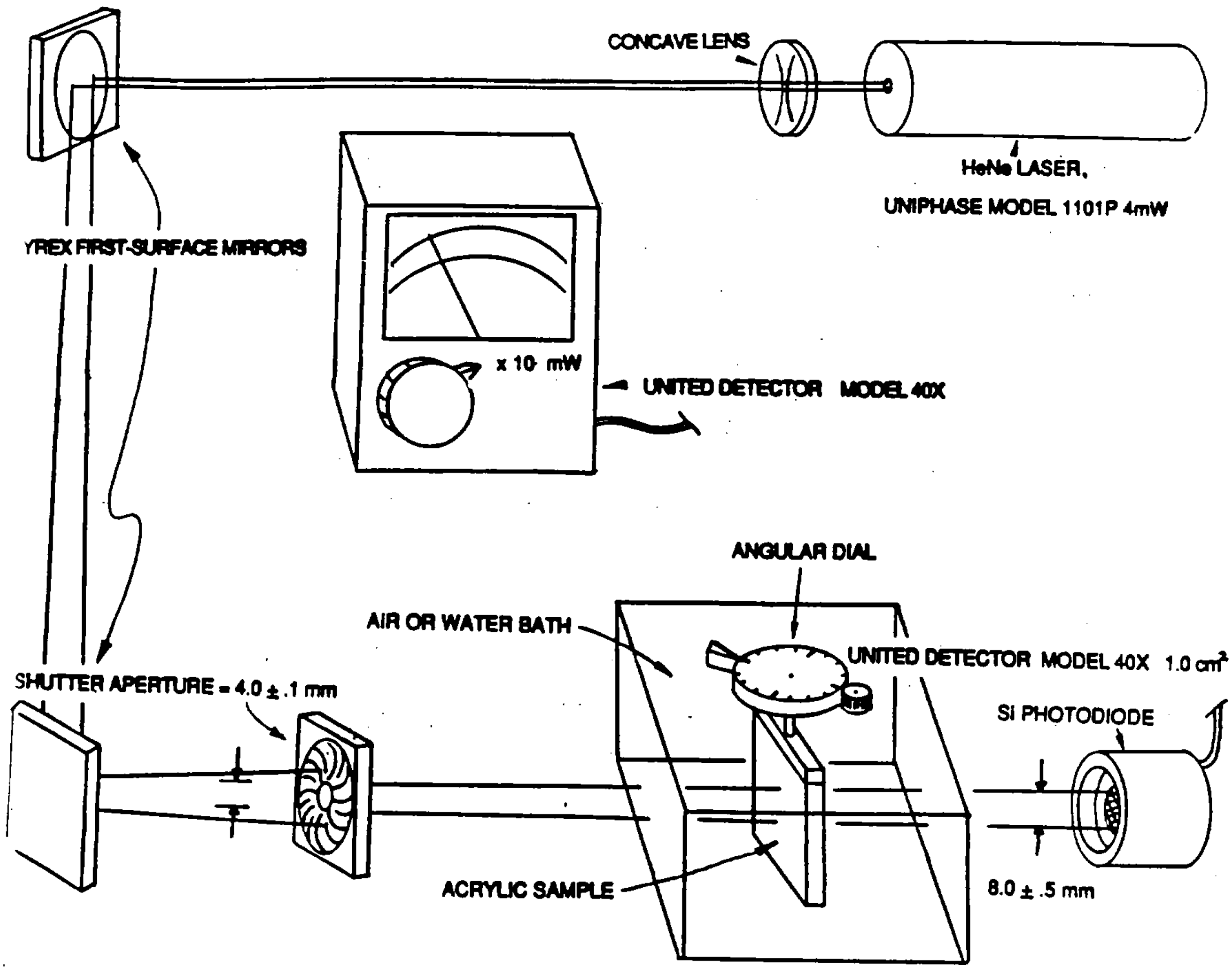


Figure 3: Schematic of experimental setup.

other, angle of incidence to a crazed region is determined by not only the angle of incidence of the beam to the acrylic surface but also the angle between the direction of the cracks and the projection of the incident beam onto the plane of the acrylic surface. Thus, transmittance for any angle of incidence is the product of transmittance at some angle with crazing vertical and transmittance for another angle with crazing horizontal, the square of the cosines of the two angles equalling 1.

The plates were crazed in air or while immersed in tap water or a solution of ethanol (a detailed description of crazing process is provided in appendix 1). The transmission as a function of angle was then recorded where the crazed side of the acrylic was the further side from the light source. Tests in which the samples were crazed and tested while immersed in water were aimed at simulating the possibility of crazing at Sudbury in which the vessel would be filled and surrounded by liquid of refractive index = 1.33. Tests of transmission through dried samples were performed in the interest of comparing these results to those of tests in water. Angles of incidence of the light to the acrylic varied from roughly -70^{o} to 70^{o}, depending on how great an angle the plate could be turned while keeping the beam passing through the crazed region.

Acrylic plates were cut, prepared, and tested in groups of 4 to 12, with new groups added as new questions arose. The first group, consisting of 6.4x50x50mm plates, was named series 'A'. Each plate had inscribed on it an 'A' followed by a number to uniquely identify it. Data was collected on plates A1,A2,A4,A6, and A7, (samples A3 and A5 snapped during crazing). Following the 'A' series was the 'W' series, so named since following sereies 'A' it was decided to cut longer plates (6.4x50x100mm) to achieve a wider region of crazing (see appendix 1). Following 'W' were series 'I-VI' (1-6),'2min-27hrs', and finally, series 'F'.

4 RESULTS

In figure 4, a typical view of the transmitted beam and the scattered portion is drawn. Careful examinations were made of the transmitted, reflected, and scattered parts of the incident beam on crazed samples of series 'A'. Some

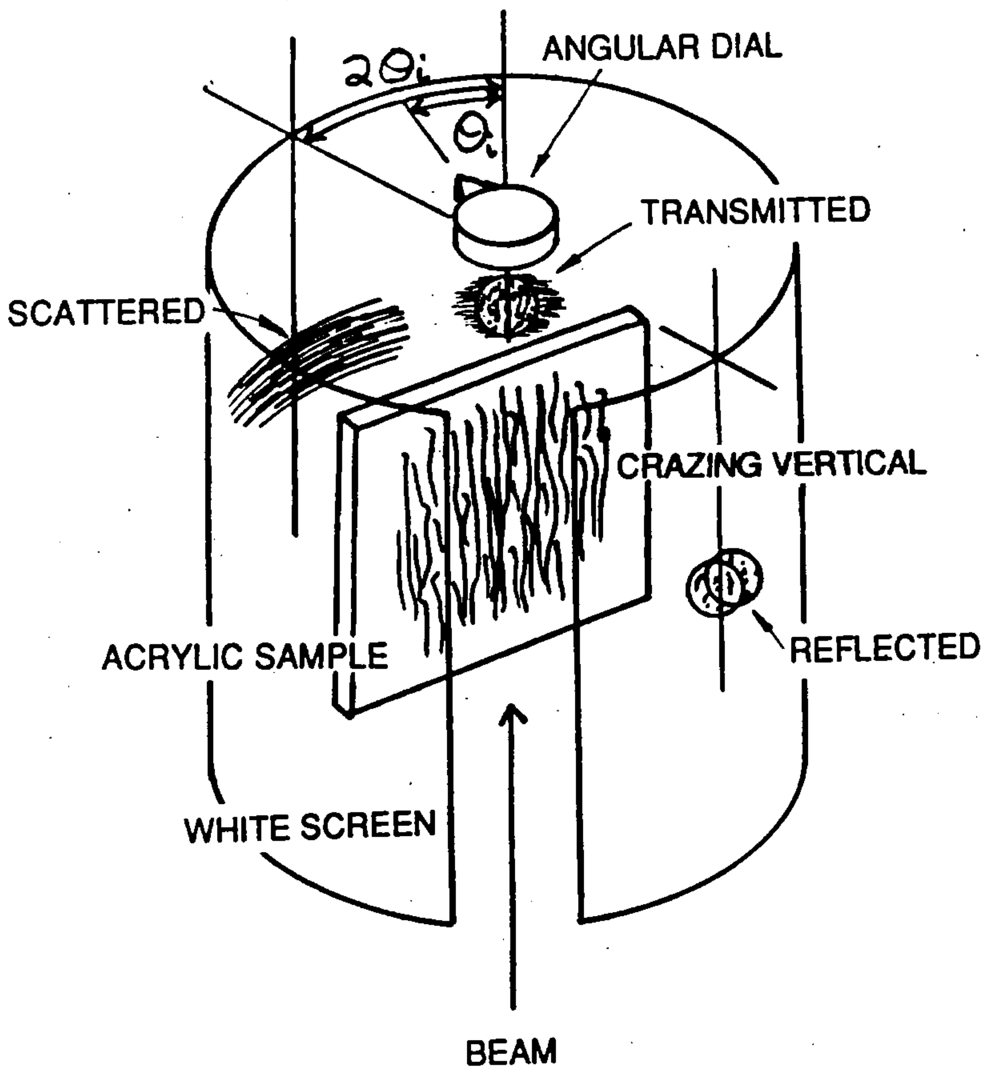


Figure 4: Effect of crazing on incident light beam.

characteristics were:

- The transmitted spot remained circular with roughly the same diameter as the incident beam. Superimposed on this spot was a red smear, varying in size and intensity. Nearly as bright as the central spot as in the case of (A7) or barely visible as in the case of (A6), the band-like smear extended equally to both sides of the central spot, similar to an outward smear of ink to opposite sides of a nearly dried circular blotch. The smear was vertical for crazing directed horizontally and visa-versa for vertically-oriented crazing as depicted in figure 4.

- In the case of vertical crazing, a second red smear traced, as the acrylic sample was turned 360°, a circle on the white screen surrounding the sample. The axis of rotation of the angular dial was normal to the plane of this circular path. The center of the smear was located at twice the angular displacement from the transmitted spot as the normal to the surface of the acrylic sample, as depicted in figure 4. Spread wider than the smear remaining in the beam line, the scattered band would range typically $10^o \rightarrow 20^o$ in width, varying for each sample. The smears of samples A4 and A7 were only a few degrees wide and were faint while those of A2 and A6 were wide and intense. The smears of series 'F' grew wider as the severity of the crazing increased. In the case of horizontal crazing, the red band remained at 0^o for all angles of incidence, rendering the transmitted smear and the scattered smear indistinguishable, a single, vertical red smear on top of the transmitted spot.

- Two reflected beams could be seen, each a partial reflection from the two faces of the acrylic, as shown in figure 4. In most cases both spots were circular, the distance between their centers growing with increasing incident angle of the laser. In the case of crazing directed horizontally, the spot from the second surface assumed a band-like shape.

Graphs of transmittance over angles ranging generally from -70^o to 70^o are shown in figures 5 to 12. The intensity is measured in mW. In some cases transmittance previous to crazing is graphed in addition to transmittance where the crazing is directed along the axis of the angular dial (vertical crazing) and/or where the crazing lies perpendicular to the axis (horizontal crazing). In a few cases, small angle detail was examined and graphed as well. It should be noted that although the width between line crazings in samples A2 and A7 was measured as the same, in later examination it was observed that line crazing in sample A2 was less dense than that of A7, and that the density of line crazing was similarly high in samples A4 and A7 and likewise lower in A2 and A6.

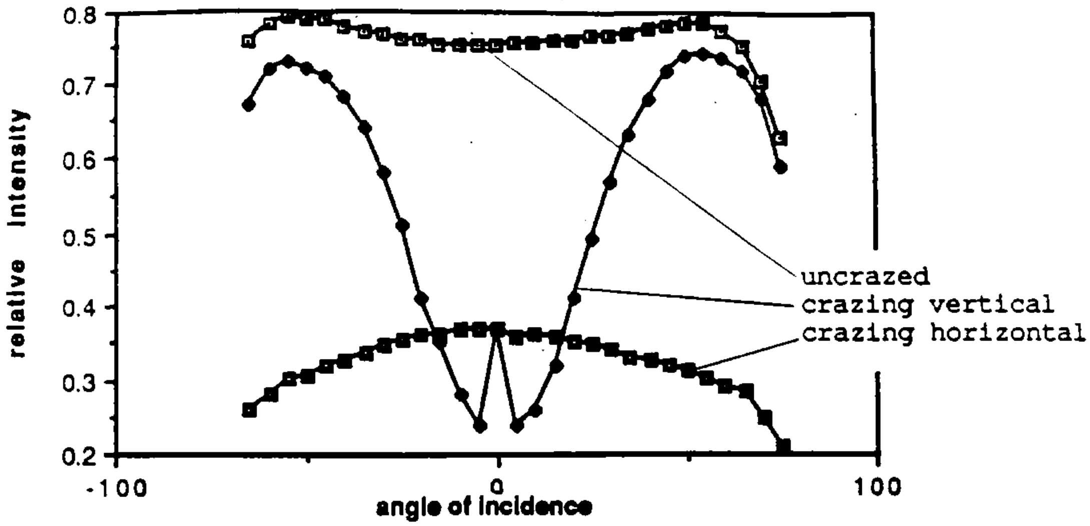
For the sake of clarity, error bars have been omitted from the figures. Sources of errors include fluctuation in laser intensity ($\approx \pm .01$mW) and systematic errors associated with reading the analog meter ($\pm .01$mW), setting the angular dial ($\pm 1^o$), and centering the transmitted beam on the photodetector ($\pm .005$ mW).

5 DISCUSSION

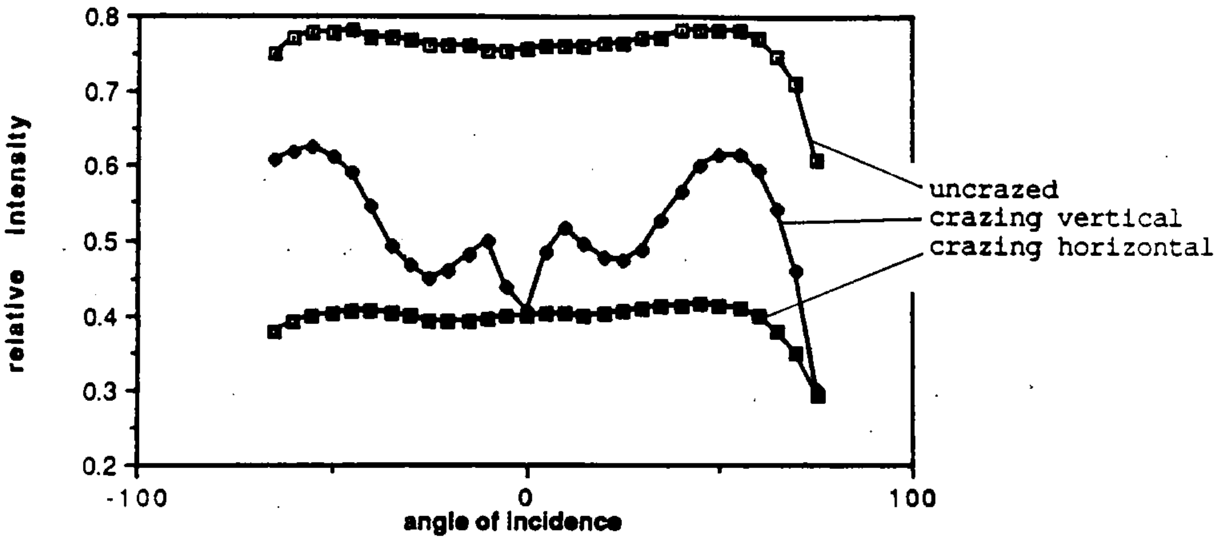
It can be seen from figures 5 to 12 that the angular dependence of transmittance is uniform within each of three testing categories; transmittance (1) previous to crazing, (2) with crazing set vertically, and (3) with crazing set horizontally. Each of these categories can be further divided into two more; testing in (1) air and (2) water.

Transmittance in uncrazed acrylic is consistent with transmittance calculated using the Fresnel Equations. Graphs of transmittance through uncrazed acrylic in air and water as calculated by Fresnel's Equations for light incident in TM mode are shown in Figure 13. With the exception of series 'F' which was polarized TM $\pm 5^o$), the polarization was $21^o \pm 5^o$ from pure TM. The similarity between Figure 13 and the experimental transmittance in uncrazed acrylic is evident, even though in all cases except series 'F', only 88% of the incident energy was TM radiation.

Transmittance through acrylic with crazing oriented horizontally decreases at an increasing rate as angle of incidence increases. The transmittance at $\theta_i = 0^o$ is roughly the same as that of vertical crazing at normal incidence, which is no surprise (at $\theta_i = 0^o$, horizontal crazing= vertical crazing). As-

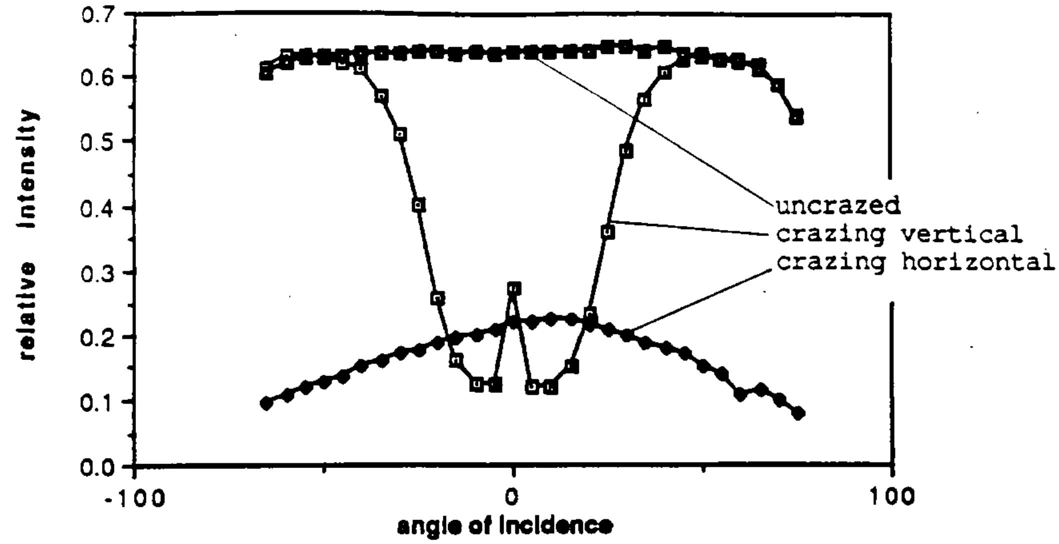


A2 10% ethanol, 5.5min.
radius of curvature= 89mm
flat crazing; w=.25mm d=immeasureable
line crazing; w=.04mm d<<.02mm
(line, d < measureable)
tested in air

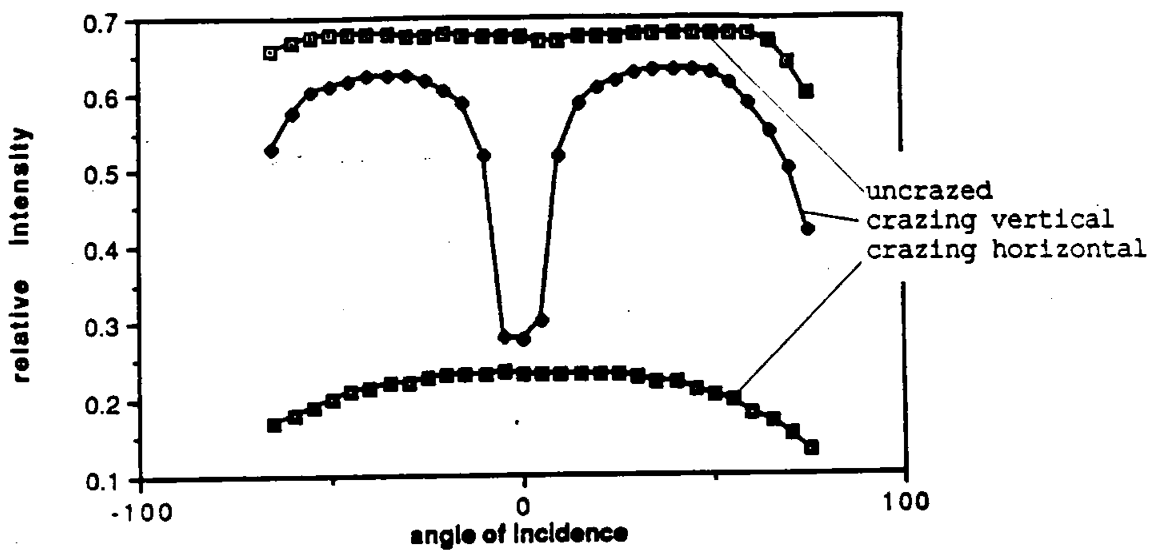


A4 100% ethanol, 10min.
r of c= 89mm
flat; w=.08mm d=.07mm
line; w=immeasureable d<<.02mm
tested in air

Figure 5: Transmission as a function of angle - Series A.

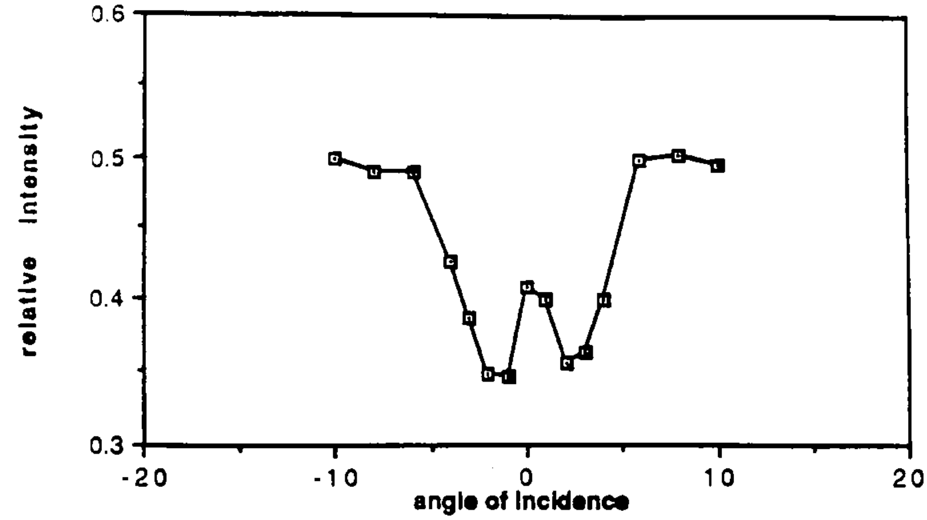


A6 10% ethanol, 11min.
r of c= 89mm
flat; w=.25mm d=immeasurable
line; w=.04mm d<<.02mm
tested in water

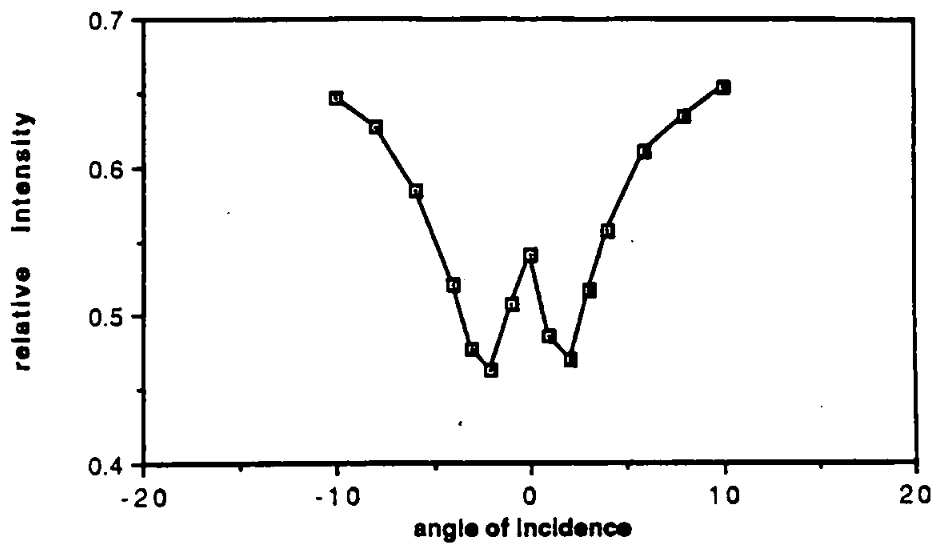


A7 100% ethanol, 5.5min.
r of c= 89mm
flat; w=.13mm d=.08mm
line; w=.04mm d<<.02mm
tested in water

Figure 6: Transmission as a function of angle - Series A.

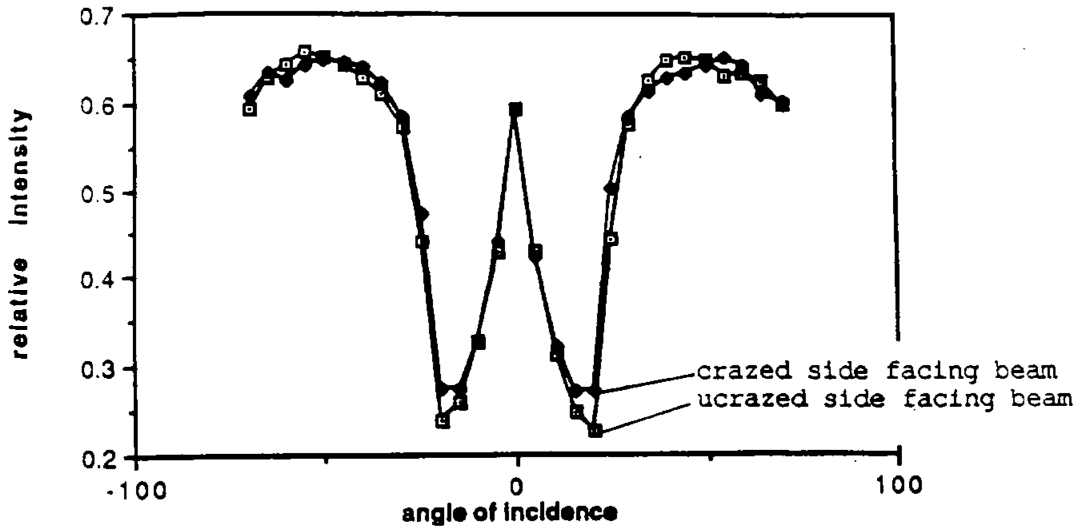


A4, small angle, demontrates
spike at 0 degrees not apparent
on other graph

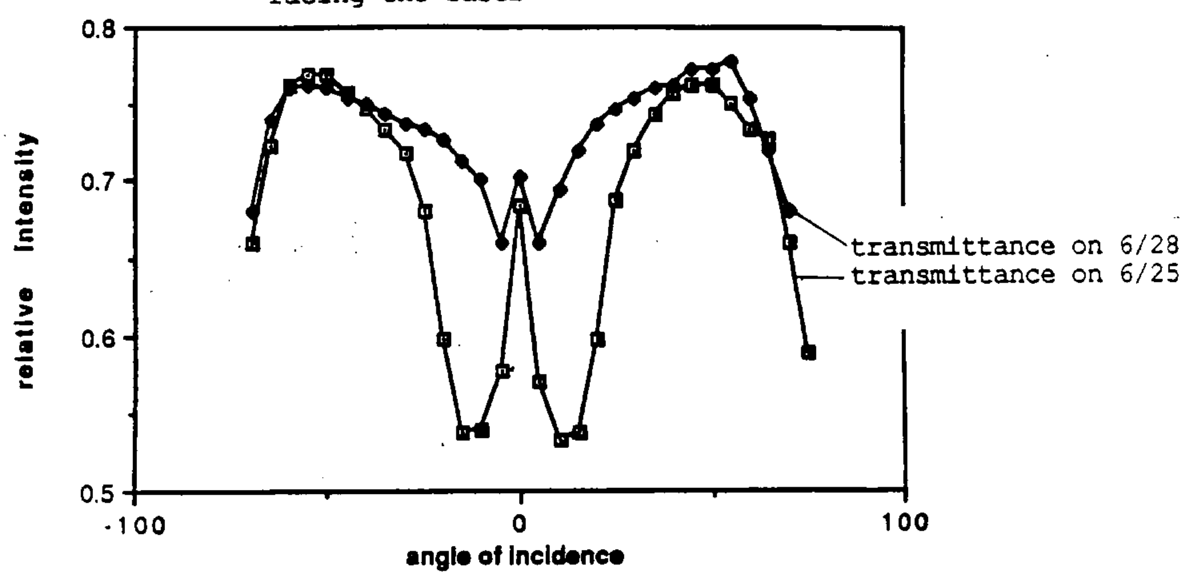


A7, with central maximum not
visible on other graph

Figure 7: Central maxima of A4 and A7 with higher resolution.

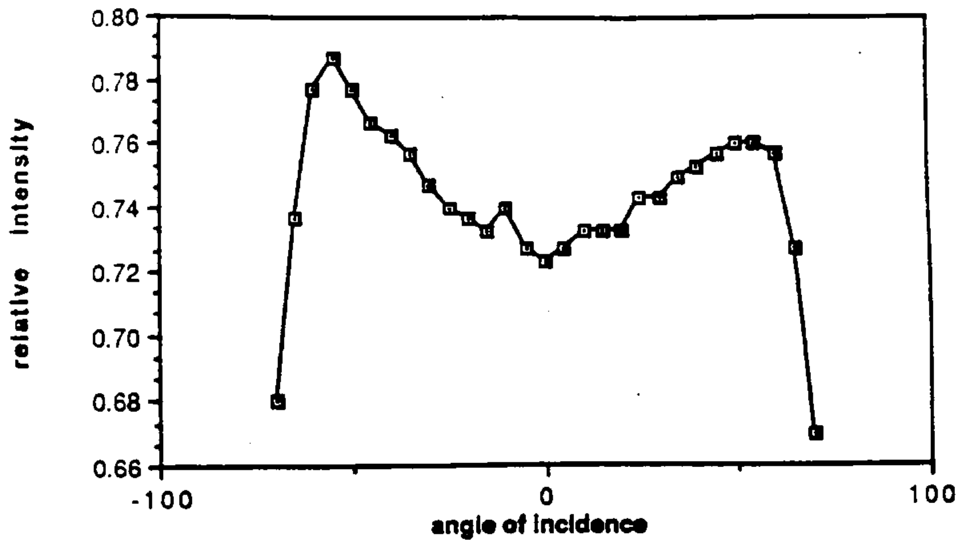


W1 crazed in water, 15.5 hrs
r of c= 127mm
flat; w= .23mm d= .06mm
line; w= .04mm d<<.02mm
transmittance identical for
either side of the sample
facing the laser

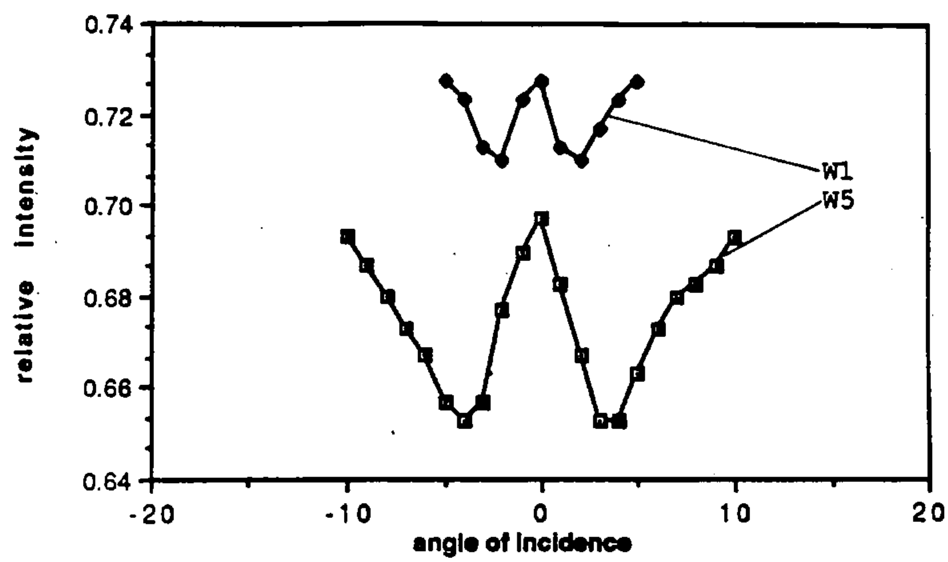


W1 retested three days later
demonstrates the effect of allowing
a curved sample to straighten

Figure 8: Transmission as a function of angle - Series W.

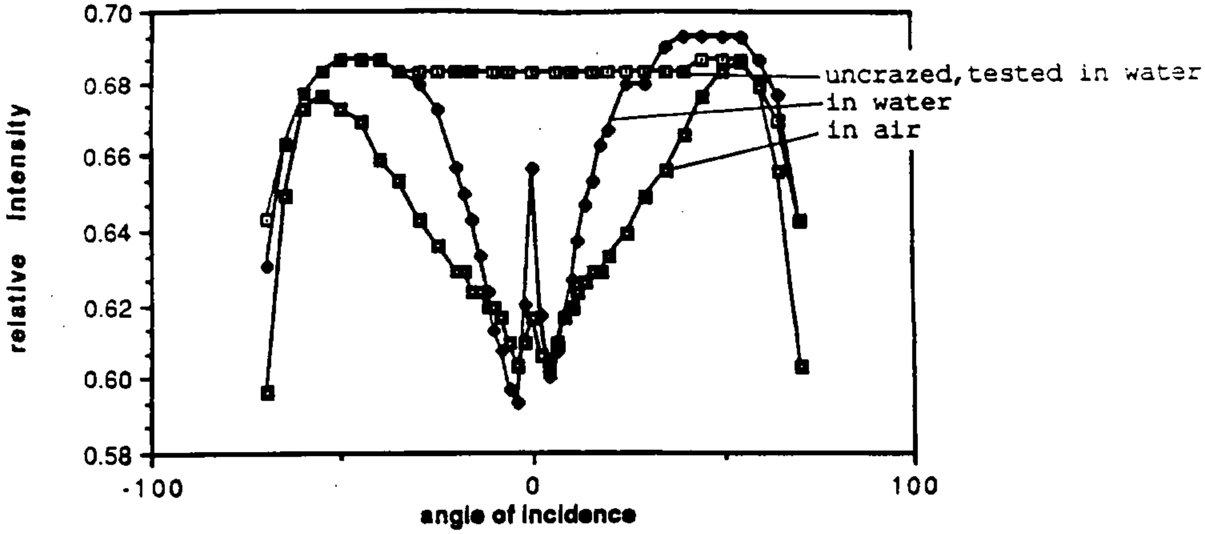


W5 crazed in air, 1hr.
r of c= 127mm
flat; w= .13mm d=.05mm
line crazing appears as flat
crazing in early stages.

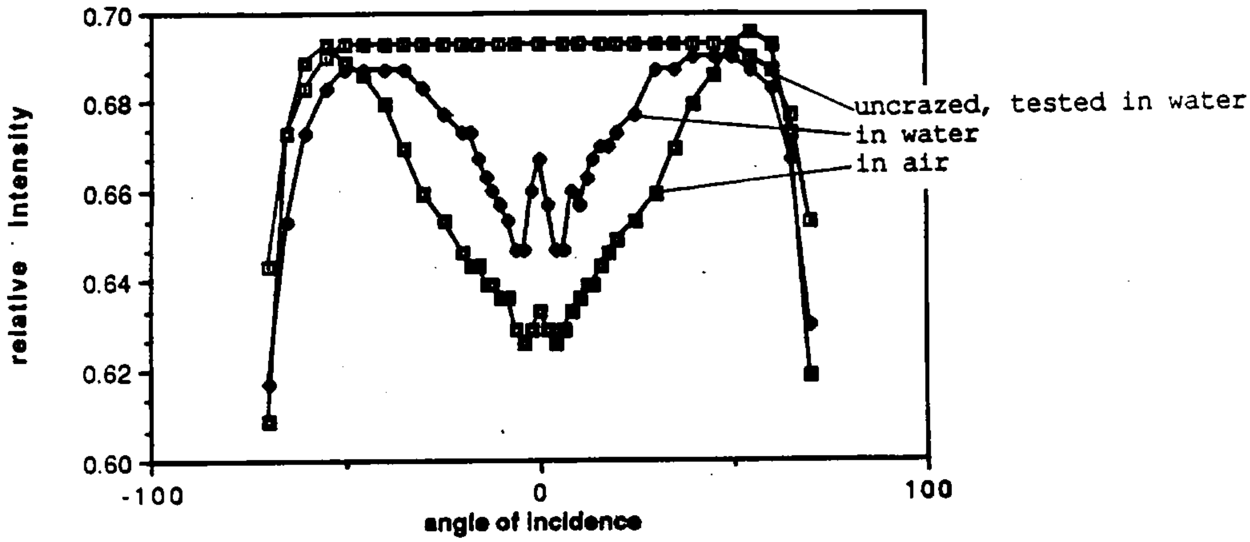


W1 and W5 at small angles
demonstrating central maxima

Figure 9: Transmission in W5 (top), and W1 and W5 with higher resolution (bottom).

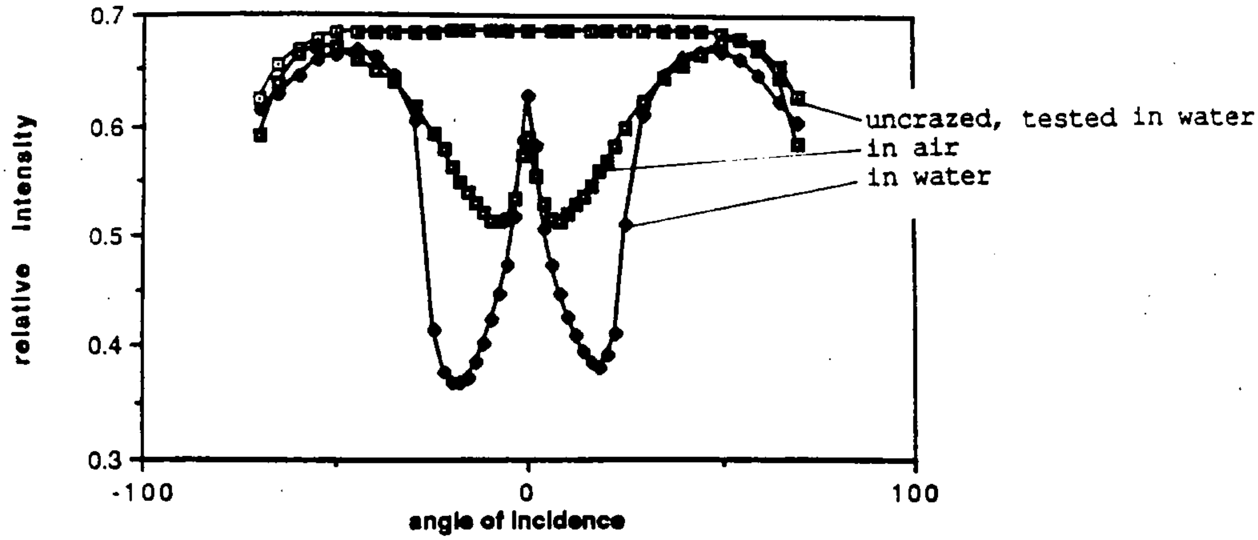


F1 crazed in water, 2min.
flat crazing; (crazing with depth)
tested in water and air
difference in unobstructed beam
intensity in water and air normalized
for comparison for F1 - F4
w= .09mm d=.025mm

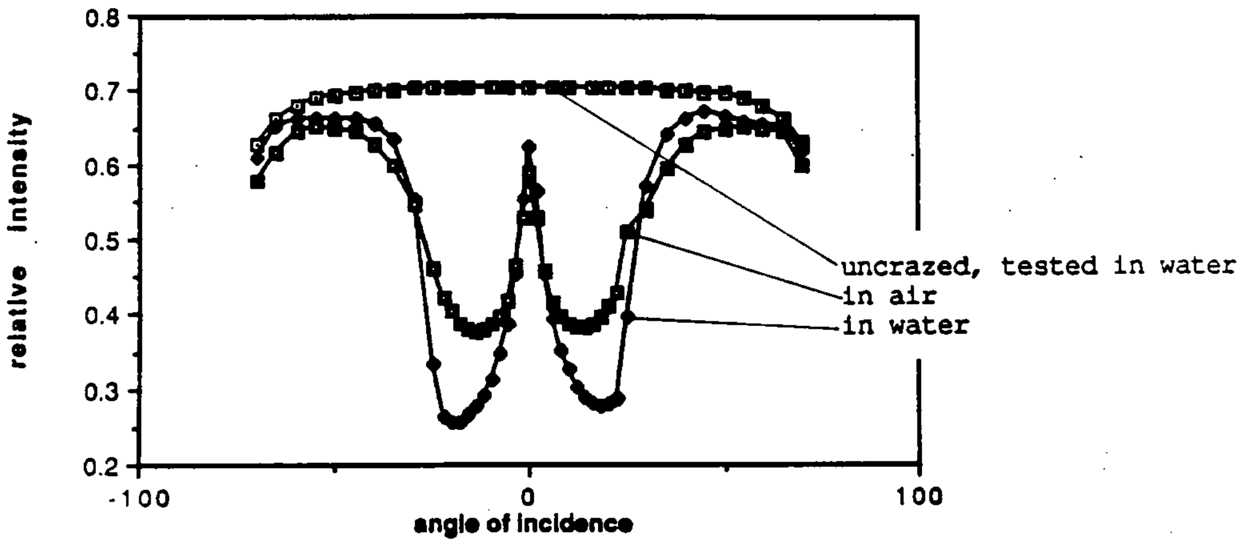


F2 crazed in water, 10min.
tested in water and air
like F1, not crazed long enough
for plate to remain bent
differences entirely due to bath
w= .20mm d= .05mm

Figure 10: Transmission as a function of angle - Series F.

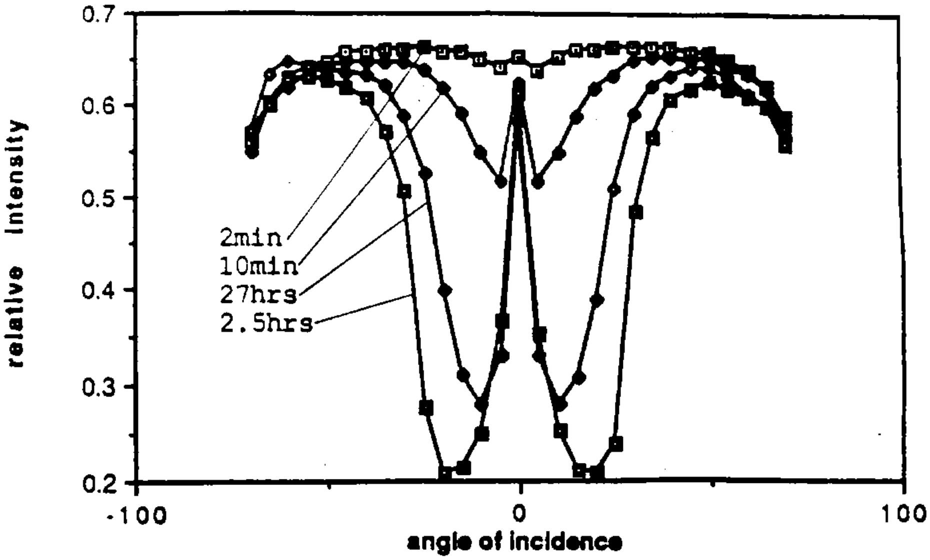


F3 crazed in water, 1hr.
tested in water and air
difference due to difference
in curvature of sample at time
of testing
w= .17mm d= .08mm

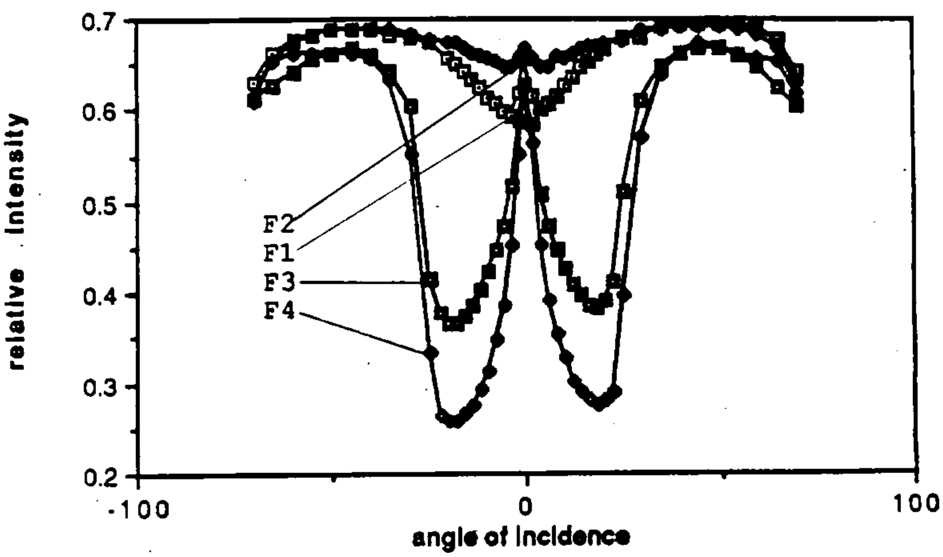


F4 crazed in water, 10.5hrs.
tested in water and air
w= .25mm d= .38mm

Figure 11: Transmission as a function of angle - Series F.

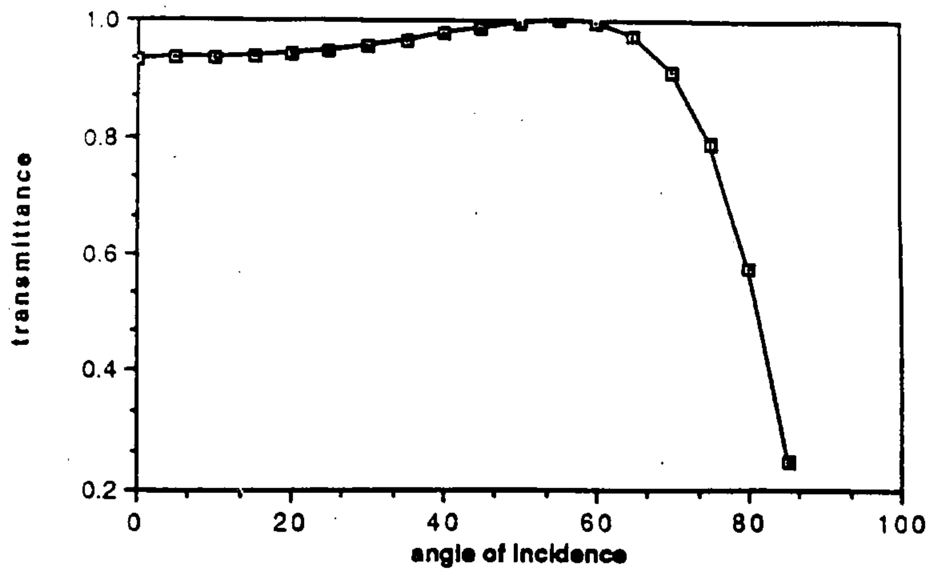


2min., 10min., 2.5hrs., 27hrs.
all crazed in water, r of c= 127mm
crazing not examined.
longer crazing means deeper trough
except for sample '27hrs.'

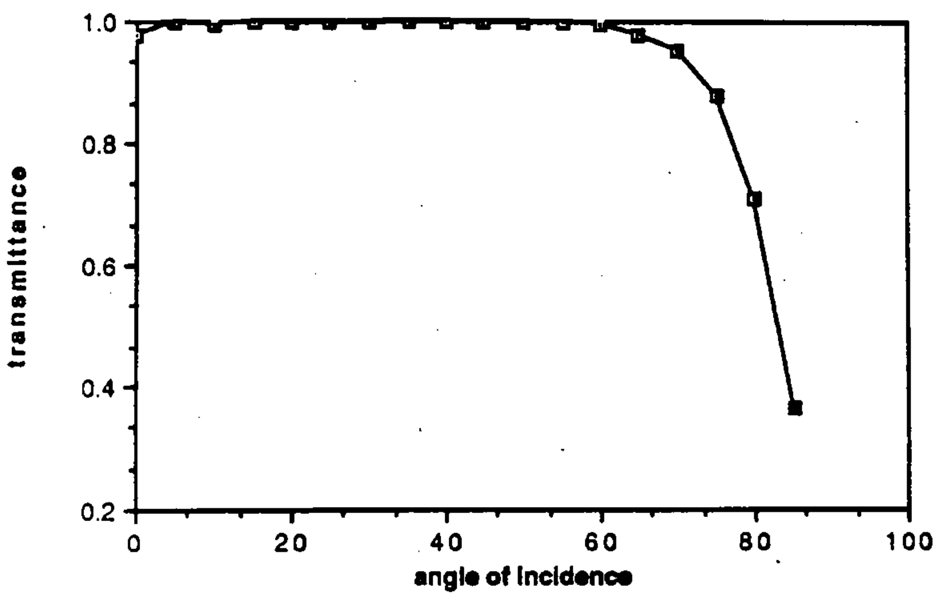


F1-F4 in water

Figure 12: Transmission as a function of angle - Series F.



transmittance in uncrazed acrylic in air



transmittance in uncrazed acrylic in water

Figure 13: Transmittance through uncrazed acrylic in air and water

suming that the cracks grow into the acrylic normally, for horizontal crazing the incident beam strikes the crazing at $\theta_i = 90°$ for all angles of incidence to the face of the acrylic sample. In this simplified view, transmittance would not be affected by the crazing depending on angle of incidence, and would behave similarly to the uncrazed case. Transmittance steadily decreased with increasing angle of incidence, unlike transmittance in uncrazed acrylic. A more severe crazing on the outside fringes of the crazed region of each sample may be the cause. The effect is most pronounced in sample A2 in which the uneven crazing, unavoidable for that crazing technique, is most pronounced. The fact that transmittance is typically 50% below transmittance in uncrazed acrylic demonstrates that, even for normal incidence, $\sim$ half of the light passing through the acrylic is interupted by crazing. Since, following series 'A', it was decided that transmittance through horizontal crazing did not yield particularly interesting results, samples were not tested in this orientation for the remainder of the experiment.

Transmission through acrylic with crazing directed along the axis of incident angle (vertical crazing) proved to be most complicated (as one might expect, considering the geometry of the crazing) and most interesting. In all cases the angular variance of transmittance began with a local maximum at 0 degrees , fall to a minimum within $\approx 20°$, increased steadily toward the uncrazed transmittance, meeting it at $\approx 55°$, and afterward descended toward zero as if no crazing were present. With two exceptions, the depth of the trough increased as crazing time increased. In the case of the first exception, sample 27 hrs, the dicrepancy can be can be attributed to the fact that this sample was left to straighten for 48 hrs after having been crazed. On occasions in which a sample was tested immediately following crazing and again one or two days later, transmittance later increases, as if the sample were tested immediately after having been bent *for a shorter time*. This tendency is depicted in Figure 8. Sample 2.5 hrs, with a deeper trough, was tested within an hour after crazing, the sample still curved from having been bent for a relatively long 150 minutes. In the case of the second exception, F1, which crazed 1/5th as long as F2, was found to have more extensive crazing. The reason for this is not understood.

A qualitative correlation between band width and width of the central maxima was observed without exception in all samples examined including series 'A' (photos of only series 'A' were taken) and series 'F'. The central maxima

present in all gathered spectra was concluded to be the result of the scattering of incident beam by the crazing into a red band perpendicular to the direction of the crazing whose angular width was seen to vary from approx. $2^o \rightarrow 20^o$. At small angles, a portion of the band would fall on the detector with the transmitted beam. In addition to the unobstructed portion of the incident beam, the detector measured the intensity along the band of scattered light from a central maximum at 0^o outward as the band faded. As a reflection from the cracks the scattered band was located at twice the angle that the acrylic was turned. That the band turned at twice the rate that the acrylic turned was checked for series 'A'. It was apparent that the band-like structure of the scattered light resulted from crazing that was not entirely perpendicular to the surface of the acrylic. Some cracks (or only portions thereof) were angled slightly to either side, the greater the twist the less frequent the case, spreading an incident beam into a band that was perpendicular to both the direction of the crazing and the beamline.
In order to explain transmittance outside the central maximum, The model described in the theory section was applied to the samples of series 'F', in which the acrylic was crazed and tested in water. The depth and distance between cracks were estimated, and it was assumed that the cracks did not fill with water, even though the samples were crazed in a water bath. Water-filled cracks would have been far less visible than air filled cracks, the difference in indices of refraction of water (1.33) and acrylic (1.46) being less than a third of difference between those of acrylic and air. Throughout the experiment no difference in visibility was noticed.
A comparison of the observed transmittance and the modeled transmittance (refer to THEORY) are displayed in Figure 14. To a first approximation, the model mimics the experiment. Between $40^o \rightarrow 50^o$ the transmittance is by mode (1), whose contribution continues to decrease for increasing angle whereupon mode (2) kicks in to boost transmittance to unity around 60^o. Mode (3) contributes only in the case of F4, in which crazing is densest, to initialize the increase in transmittance at 40^o. If crazing is not entirely perpendicular to the acrylic surface as was suggested above, the "bird's head" of the model would widen to mimic more closely the behavior of the experimental transmittance between $40^o \rightarrow 80^o$ incidence. In addition, the contribution by mode (1) would decrease, yielding lower transmittance at less than 40^o. Since time did not permit, modeling of crazed acrylic in air was omitted. In

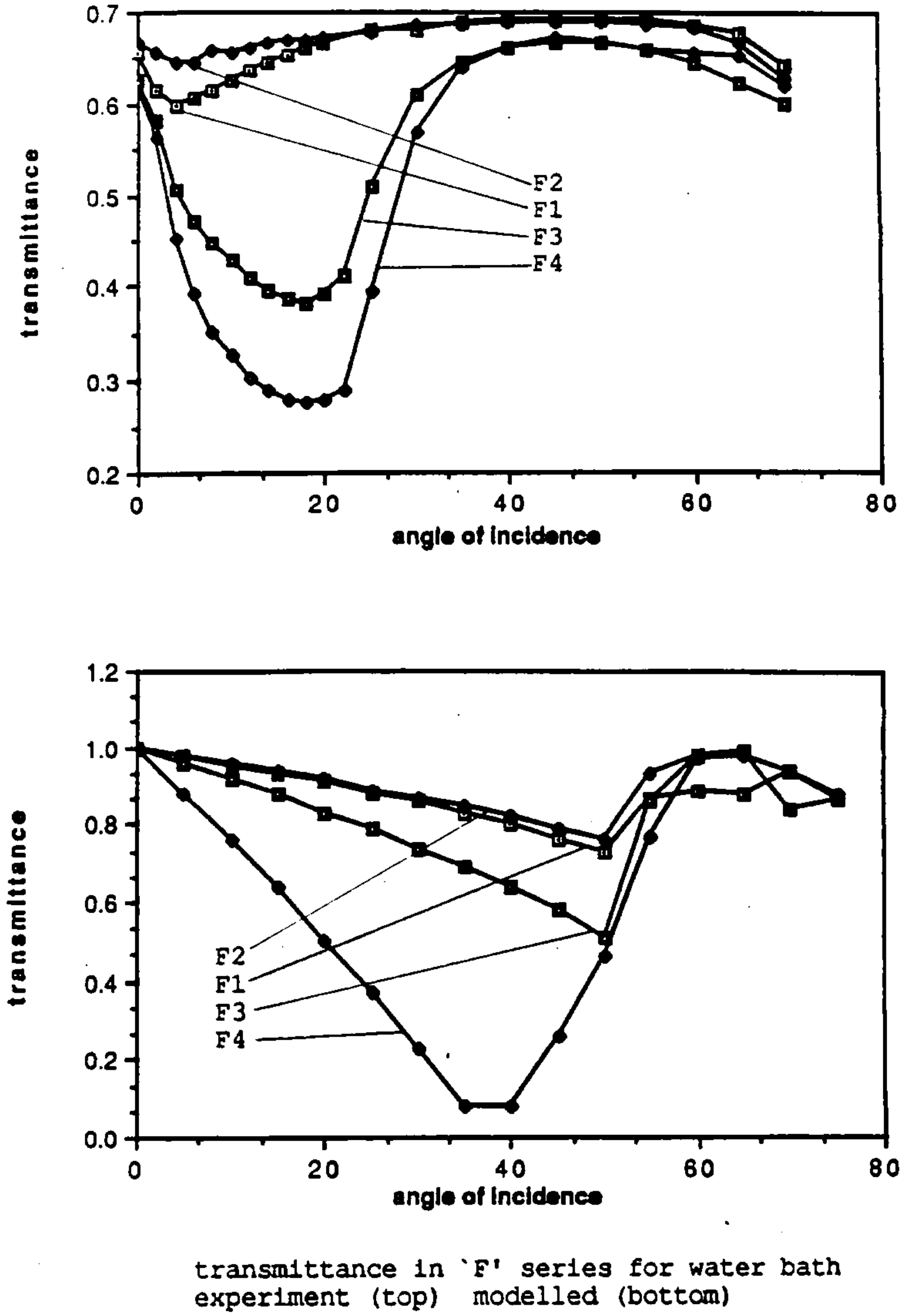


Figure 14: Comparison of observed and modeled transmission.

this case mode (2) would never have contributed since the critical angle of transmission from acrylic to air is 43.2°, and light incident on crazing would have struck only at greater than 46.8°. Mode (3) would have assumed the role that mode (2) played previously to some degree, giving what would have probably been similar results, with the effects of imperfect crazing acting similarly in this case as before.

6 SUMMARY

It has been found that crazed acrylic significantly degrades light transmission for angles of incidence $<\sim 60°$. At greater angles of incidence, transmittance decreases regardless of crazing. The method by which the light is scattered appears to be a simple effect in which the cracks in the acrylic act as mirrors to deflect incident light out of its initial path.

In this experiment, only samples of acrylic 7mm thick were examined. It may happen that cracks in thicker acrylic open wider to fill with water, in which case the degradation would not be as pronounced. In any case , a significantly crazed vessel at Sudbury would result in greater difficulty, if not impossibility, in reconstructing information on secondary charged particles by C̃erenkov radiation.

If it is anticipated that the stresses on the acrylic vessel at sudbury may be sufficient to induce crazing within the duration of the experiment, thickening the vessel walls or applying pressure to the vessel as appropriate to reduce stress might be considered.

References

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[2] J. D. Stachiw, J. L. Stachiw, "Crazing and Degradation of Flexure Strength in Acrylic Plates as a Function of Time", National Ocean Systems Center, San Diego, June 1989.

[3] J. D. Stachiw, "Acrylic Plastic Viewports", Marcel Dekker, Inc. 1982

[4] E. H. Andrews, L. Bevan, "Mechanics and Mechanism of Environmental Crazing in a Polymeric Glass", Polymer, 1972, Vol. 13, pp. 337-346.

[5] F. L. Pedrotti, L. S. Pedrotti, "Introduction to Optics", Prentice-Hall, Inc. New Jersey, 1st ed. 1987.

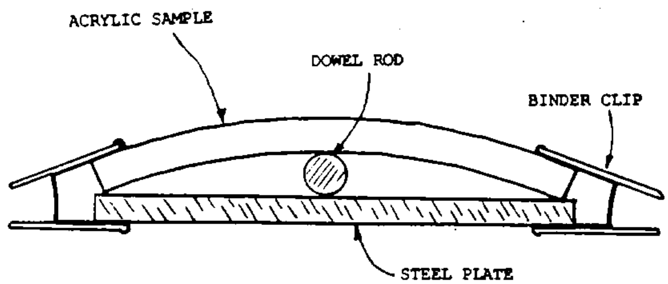

Figure 15: bending tech # 1

APPENDIX 1; CRAZING TECHNIQUES

Although crazing will eventually occur in any sample of acrylic subjected to tensile stress, the process may demand years (in the case of low stress), or can be accelerated to seconds by applying organic solvents to the stressed surface [2]. It may be noted that a fingerprint becomes etched on acrylic under high tensile stress after less than 10 minutes (although there is no apparent effect if the sample is unstressed, even after 2 hours of exposure). It was observed that finger oil acts as an agent to accelerate crazing just as ethyl alcohol does, which was employed in this experiment during the crazing of the samples of series 'A'.

Beginning with 1.6x50x50mm squares of acrylic, each piece was bent by hand over a dowel rod placed between the acrylic and a steel plate. The piece was then clamped to the plate with a 3.2mm binder clip on each side, as shown in figure 15, and squirted with pure ethanol. This bending techinique was quickly abandoned because the resulting region of crazing was too narrow for testing over a wide range of angles of incidence. In addition, the crazes and/or cracks appeared to extend to a depth comparable to the thickness of the acrylic. To minimize possible dependence of the nature of crazing on the

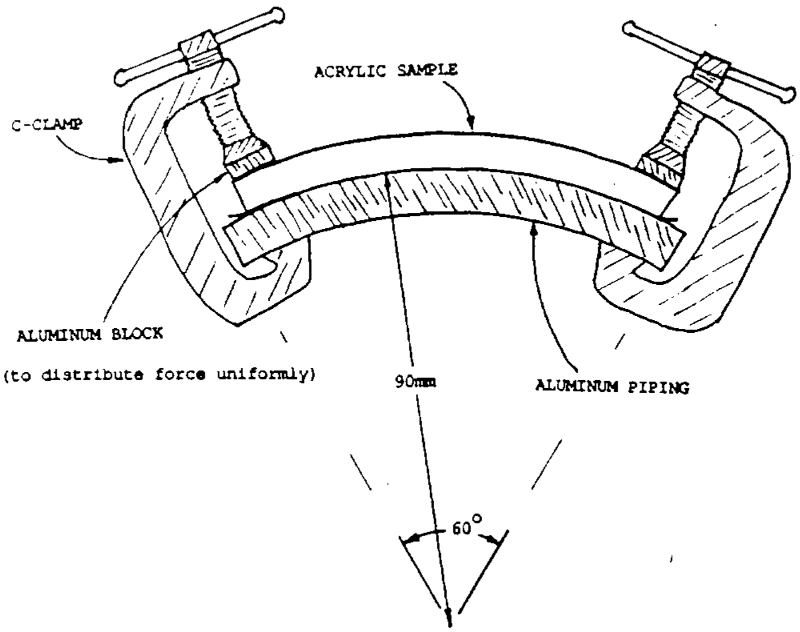

Figure 16: Bending tech. # 2

thickness of the acrylic, we turned to 6.4mm plates (the thickest available). In the interest of achieving uniform crazing over a wider region, the acrylic was clamped down to a 60° section of scrap aluminum piping 180mm in diameter (piping was chosen for a more uniform distribution of stress) using four C-clamps as shown above in Figure 16.

Roughly 7mm thick, no flattening of the aluminum to a larger radius of curvature during bending was visible, nor could any bowing of the acrylic away from the pipe between the clamped ends be seen. The modulus of tensile elacticity of acrylic is 3,400MPa [3] from which the stress at the surface of an acrylic plate 6.4mm thick is calculated to be 245MPa. In this method and the one to follow, a folded kimwipe was sandwiched between the acrylic and the aluminum to avoid scratching the sample. Plates of series 'A', 6.4X50x50mm, were bent using this procedure, which demanded roughly 40 minutes to complete. Upon bending, samples A2 and A6 were immersed in a 10% ethanol, 90% tap water solution to craze, while samples A1, A4, and A7 were immersed in baths of 100% ethanol.

Every attempt to bend 3.2mm plates in this manner resulted in a snapped plate. It was concluded that 3.2mm acrylic, while only slightly more flexible than 6.4mm, is considerably weaker. 6.4mm plates, although tougher to bend, were in most cases strong enough to resist snapping when clamped flush to the pipe.

Following series 'A', a faster and safer method of bending the acrylic was adopted. A 360 degree section of scrap aluminum piping 254mm in diameter and ≈25mm thick was used in place of the smaller section used previously. Two hose clamps held the acrylic sample in place while large C-clamps pressed the ends of the sample to the pipe, as shown in figure 17. Pressure at the surface of a 6.4mm thick sample was reduced to 173MPa. (Although the stress was reduced using this method, at least half of the plates to be tested were broken. It was interesting that each time the cloth pressed between the acrylic and the pipe was wet with water, the sample snapped, but did not if the cloth was left dry. It is apparent that evaporation from the exposed area of the cloth cooled the sample enough to increase the modulus of elacticity to where the acrylic would snap).

All samples following series 'A', 6.4x50x100mm, (cut wider to achieve an even wider region of crazing) were bent and crazed using this method, which cut assembly time to roughly 10 minutes. Since it was noticed following series 'A' that samples could be crazed in minutes without ethanol, the remainder of the crazing would take place in tap water instead of an ethanol solution, with the C-clamps removed, leaving the tightened hose clamps holding the acrylic against the pipe.

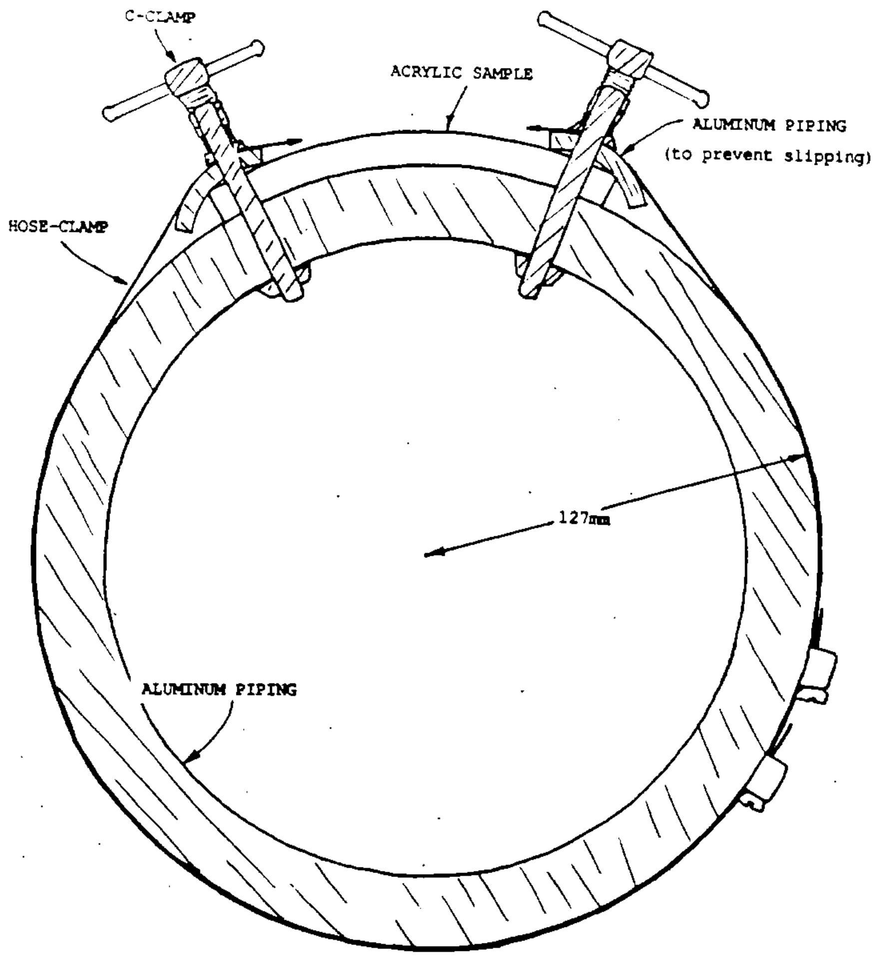

Figure 17: Bending tech. # 3

APPENDIX 2; CRACKS AND CRAZING

An American Optical model 570 microscope was employed for close examination of the samples following crazing and optical testing. Observations on the crazing of the samples of plate series 'A', 'W', and 'F' were collected. Examination of samples in series 'A' seemed to reveal two types of crazing. The larger of the two, observable to the unaided eye, was dubbed "flat" crazing, and appeared as planar fracturing perpendicular to the face of the sample and located ≈.25mm beneath the acrylic surface, extending another ≈.08mm into the acrylic. Always aligned perpendicular to the direction of the tensile stress on the acrylic, the cracks averaged roughly .64mm in length, with a frequency of between 4 to 10 per mm. The smaller crazing, only seen when viewed through a microscope, was dubbed "line" crazing, and appeared as short aligned scratches on the surface, having no depth. "Line" crazing, lying parallel to flat crazing averaged roughly .25mm in length with a frequency of about 30 "lines" per mm.

That "flat" crazing did not begin at the surface of the acrylic was a curious result, and was checked and rechecked in samples A2, A4, A6, and A7. When it was found that ethanol plasticizes acrylic [4], this mystery as well as that of the apparent dichotomy in craze effects was explained. Ethanol penetrated the acrylic resulting in a flexible surface layer atop relatively brittle pure acrylic. The cracking, expected to begin on the surface of the stressed acrylic, begins without the aid of ethanol on the upper 'surface' of the region of unelasticized acrylic, the tensile stress high enough to initiate the process in minutes. Crazing began on the upper layer as tiny stretchings, some as small as can be discerned with the microscope (about .025mm in length) and roughly 5 to 10 times as many per unit area as the cracking below. It is possible that "line" crazing is truely crazing while the "flat" crazing is actually cracking, although discerning between cracking and crazing was never possible. Using the terms loosely, two types of crazing were observed essentially because each took place in one of two different materials.

In the interest of achieving crazing that would best simulate what could occur in the Sudbury vessel, attempts were made at crazing samples in water. It was found that, with stresses on the acrylic as high as we applied, crazing could be achieved in a matter of minutes (as opposed to only seconds in ethanol solution), so ethanol was abandoned. Beginning with series 'W' it was observed that while "line" and "flat" crazing were both present, the "flat" crazing originated at the surface of the sample, and there was no distinguishing between the two types. Lengths of the crazings at the surface varied continuously from as small as could be discerned ($\leq$ .025mm) to about 8mm. The cracks did not extend in depth proportionally to their lengths. While larger cracks appeared geometrically similar, it is clear that when crazing begins most growth is along the surface, as cracks up to about .25mm in length had no apparent depth.

SNO-STR-90-87

LIGHT SCATTERING IN CRAZED ACRYLIC

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20 July 1990

Abstract

Measurements of the fractional undeflected intensity of a HeNe laser beam (632.8 nm) incident upon crazed acrylic at varying angles provide an indication of how an aging acrylic D_2O vessel at the Sudbury Neutrino Observatory might scatter Čerenkov radiation produced within the vessel. It is found that while the degradation in transmission varies strongly with the degree of crazing, the variance of degradation as a function of incident angle is universal in form. Transmission is maximal for normal incidence, dropping sharply to a minimum within $\approx 20°$, then rising steadily to full transmission at $\approx 50°$.

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1 INTRODUCTION

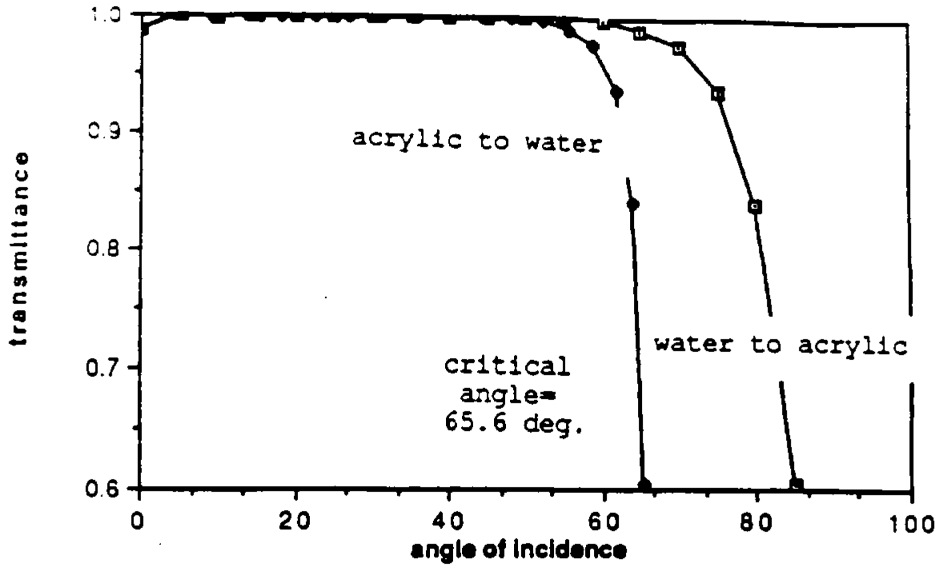
The Sudbury Neutrino Observatory (SNO) [1], scheduled to begin operation in 1995, will employ D_2O as the primary medium with which solar and other extraterrestrial neutrinos will interact. From the Čerenkov radiation produced by the secondary particles, the kinetic energy, direction of approach, and type of incident neutrino can be ascertained. The spherical vessel designed to contain the heavy water will be contructed using thermoformed acrylic, chosen for its strength, transparency, and radioactive purity. Čerenkov photons produced in the D_2O must pass through the transparent tank to be detected in photomultipliers suspended outside the vessel.

When acrylic is placed under tensile stress, cracking, or a condition refered to as "crazing" develops. Crazing is characterized by parallel crack-like damage zones running transversely to the direction of the applied stress [4]. The damage zone consists of voids (40-50%) and material which has a lower density than the bulk acrylic. With the continued application of stress to the acrylic, the crazing develops into easily visible cracks and seriously weakens the acrylic [2]. Because of the difficulty in distinguishing between the two, we use the terms "cracking" and "crazing" interchangeably throughout the report.

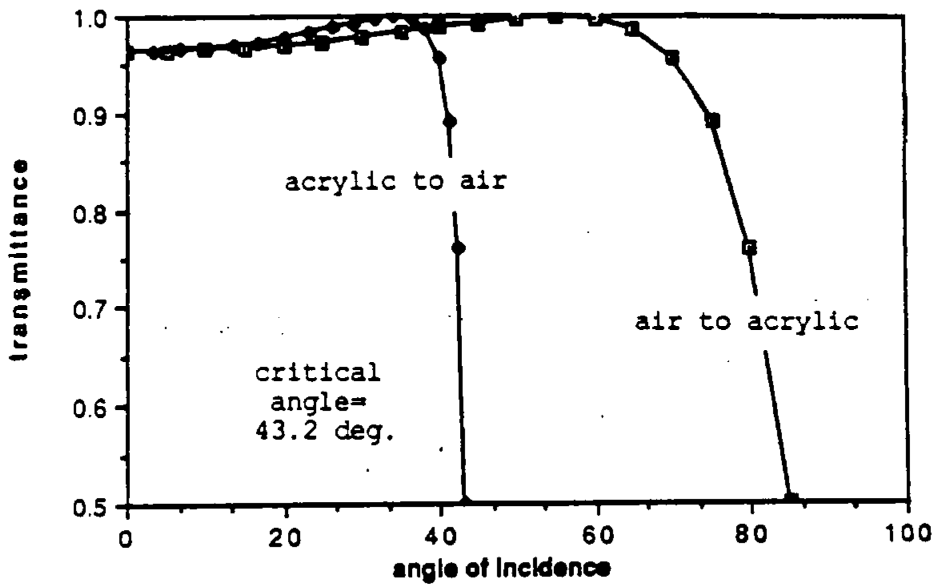
Since cracking and crazing are visible to the unaided eye, it is clear that light transmission in crazed acrylic differs from that in unaffected acrylic and that this may have serious consequences on the reconstruction of events in SNO. The goal of our observations is to develop an understanding of the effects that cracked and crazed acrylic has on incident light.

2 THEORY

Assuming that crazing is a macroscopic effect, that is, that the effects of crazing on transmission due to point scattering are negligible, then a basic electromagnetic treatment involving reflectance and transmittance of light in acrylic and incident upon the planar crazing should suffice to explain the observed effects (an extended discussion of the observed crazing is given in appendix 2). Graphs of transmittance vs. angle of incidence to and from acrylic surrounded by both air and water are shown below in Figure 1.



transmittance between water and acrylic as
calculated using Fresnel's equations, TM mode



transmittance between air and acrylic, TM mode

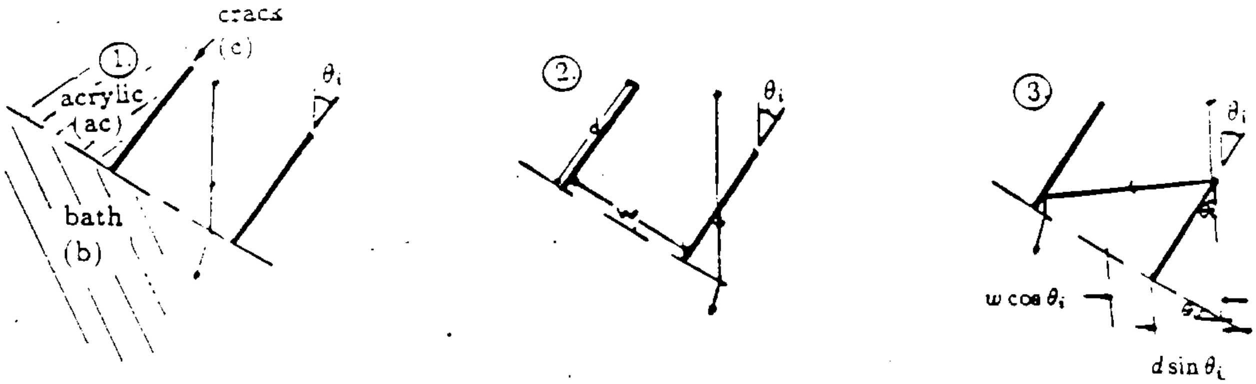
Figure 1: Transmittance to and from acrylic in water, air.

Data for the graphs was calculated using the Fresnel equations for incidence on a dielectric material of polarized light in transverse magnetic (TM) mode [5]. [1] In our simplified analysis of transmission through crazed acrylic, let us assume that light may be transmitted without net angular deflection in 3 ways:

1. transmission through the acrylic without striking any cracks or crazing.
2. transmission directly through any cracks or crazing.
3. reflection from one crack to a second crack, and reflection from the second back into the same direction as the incident beam, like an image through a periscope.

Figure 2 below illustrates the three modes of transmission. Assume cracks of uniform depth d, all perpendicular to the surface of the acrylic, and uniform width between cracks **w**. Transmittance by (1) is given by the product of the fraction of light passing without striking crazing and the transmittance into and out of the acrylic (which are identical by the Fresnel equations). Transmittance by (2) is given by the product of the fraction of light striking the crazing, transmittance into and out of acrylic, and transmittance through a crack. Transmittance by (3) is given by the product of the fraction of light striking the crazing, the transmittance through the acrylic, the reflectance (R= 1-T) between two cracks, and the fraction of light that is directed back in line with the incident beam. At angles of incidence for which the tangent exceeds 3w/d, the reflectance factor would be raised (from the second) to the fourth power in the analysis. This final means of transmittance assumes a lower bound as light passing through the second crack and reflecting back into line from the third (or fourth, etc.) crack is unaccounted for.
To obtain the total transmittance as a function of incident angle, we need to know the ratio of crack depth to distance between cracks, the refractive index of the medium in which the acrylic is tested, and the refractive index

[1] Transmittance in TM mode was graphed because it was discovered, late in the experiment, that the laser was polarized $\approx 20^{\circ}$ from TM, meaning that $> 88\%$ of the incident radiated energy was TM. In order to simplify the calculations of transmittance while remaining as consistent as possible, the polarization was set to 0° from TM (pure TM) for the remainder of the experiment in which the final series of four plates was tested.

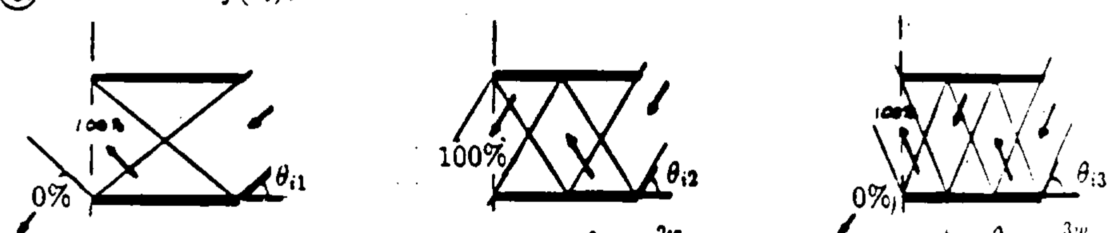


(1) $T = \left(\frac{w \cos \theta_i - d \sin \theta_i}{w \cos \theta_i}\right)(T_{b \to ac})(T_{ac \to b}) = (1 - \frac{d}{W} \tan \theta_i)(T_{b \to ac})^2$

(2) $T = \left(\frac{d \sin \theta_i}{w \cos \theta_i}\right)(T_{b \to ac})(T_{ac \to c})(T_{c \to ac})(T_{ac \to b}) = (\frac{d}{W} \tan \theta_i)(T_{b \to ac})^2 (T_{ac \to c})^2$

(3) $T = \left(\frac{d \sin \theta_i}{w \cos \theta_i}\right)(T_{b \to ac})(1 - T_{ac \to c})(1 - T_{c \to ac})(T_{ac \to b})(f(\theta_i)) =$
$(\frac{d}{w} \tan \theta_i)(T_{b \to ac})^2 (1 - T_{c \to ac})^2 (f(\theta_i))$

(3) $f(\theta_i)$:



$\tan \theta_{i1} = \frac{w}{d}$
0% redirected into beam

$\tan \theta_{i2} = \frac{2w}{d}$
100% redirected into beam

$\tan \theta_{i3} = \frac{3w}{d}$
0% redirected into beam

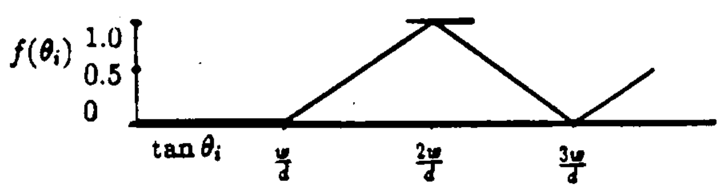


Figure 2: Principal modes of transmission.

within the cracks. This simple model will be applied to crazed samples and compared to the observed transmittance.

3 APPARATUS and PROCEDURE

A schematic of the experimental setup[2] is shown below in figure 3. A HeNe laser was employed as the light source. While the laser emits light at 632.8nm and 1150nm, the silicon photodiode detector, used to measure the intensity of the transmitted beam, is sensitive between 350nm and 1100nm, and therefore sees only the peak of shorter wavelength. The detector is also sensitive to ambient light, which was determined to contribute between 0.5% and 2% of the total irradiance received by the detector. To conserve work space, the beam was folded back on itself by two 1" diameter pyrex first-surface mirrors. A variable aperture shutter was used to define the beam diameter before it passed through the acrylic sample under test and into the photodetector. To measure the transmission through the sample while immersed in water, a square, transparent container was positioned around the sample and filled with water.

By measuring the laser diameter at the shutter and the photodetector nearly 500mm downstream as shown in figure 3, the angular spread of the laser in the region of incidence with the acrylic was calculated to be between 0.2° and 0.3°. The shutter size was set such that the transmitted spot would be as large as possible while entirely contained by the sensitive area of the photodetector. A large beam diameter was desirable in order to integrate over a statistically large sample of crazing. To allow for refractive displacement of the beam, the photodetector was fixed to an X-Y micrometer so that the beam could be centered on the detector for all angles of incidence.

Fitting 6.4x50x50mm or 6.4x50x100mm acrylic plates into a square lense holder attached to an angular dial, transmission through each sample was measured before and after crazing. Since the lens holder rotated only about a vertical axis, in order to test transmission for any angle of incidence the crazed plates were tested with the direction of the crazing parallel to and perpendicular to the axis of rotation. Since cracks are parallel to one an-

[2]Special thanks to Dr. Peggy Dyer and Judy Gursky for use of Laboratory Facilities.

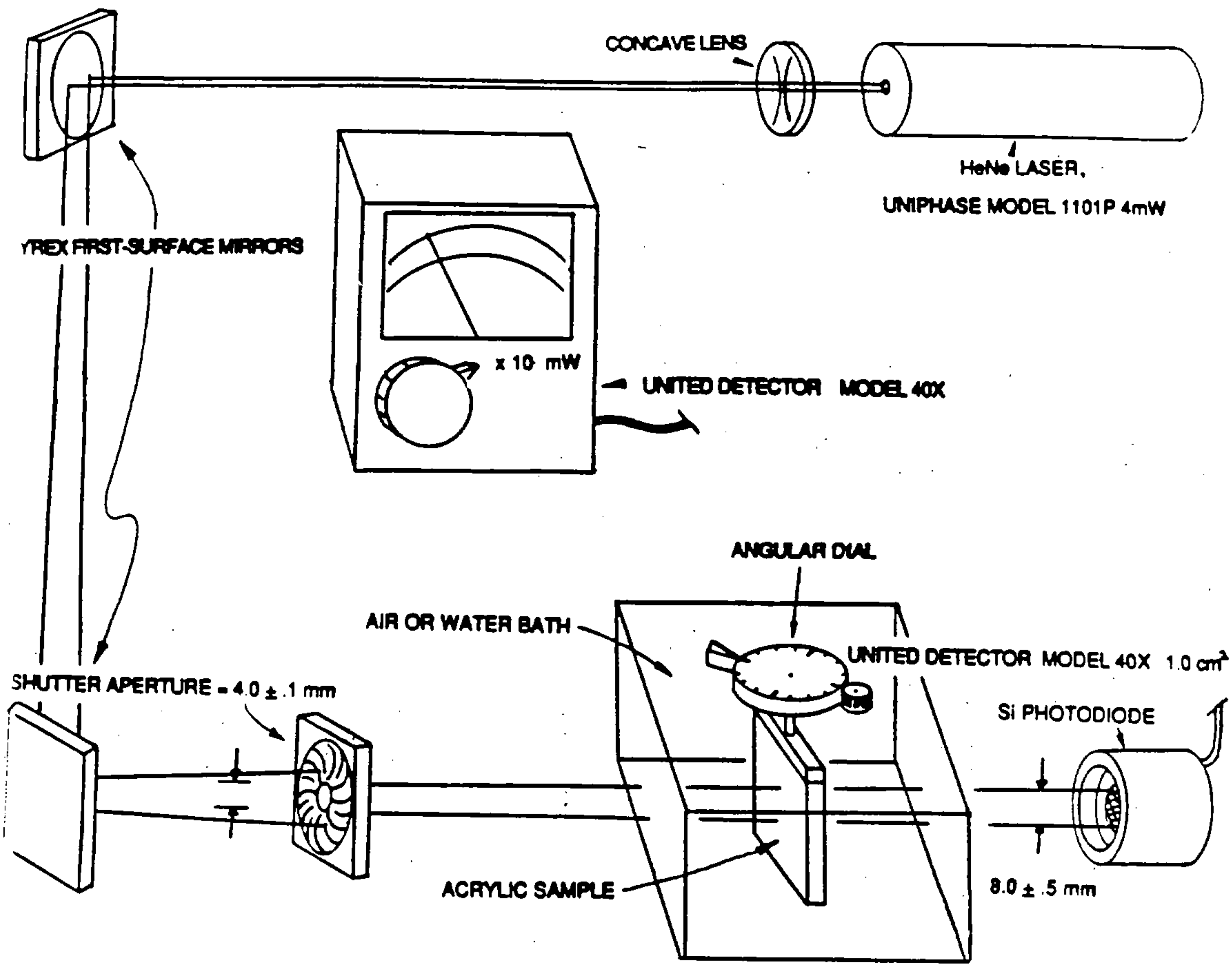


Figure 3: Schematic of experimental setup.

other, angle of inciden : to a crazed region is determined by not only the angle of incidence of t! beam to the acrylic surface but also the angle between the direction of ıe cracks and the projection of the incident beam onto the plane of the acrylic surface. Thus, transmittance for any angle of incidence is the product of transmittance at some angle with crazing vertical and transmittance for another angle with crazing horizontal, the square of the cosines of the two angles equalling 1.

The plates were crazed in air or while immersed in tap water or a solution of ethanol (a detailed description of crazing process is provided in appendix 1). The transmission as a function of angle was then recorded where the crazed side of the acrylic was the further side from the light source. Tests in which the samples were crazed and tested while immersed in water were aimed at simulating the possibility of crazing at Sudbury in which the vessel would be filled and surrounded by liquid of refractive index = 1.33. Tests of transmission through dried samples were performed in the interest of comparing these results to those of tests in water. Angles of incidence of the light to the acrylic varied from roughly -70° to 70°, depending on how great an angle the plate could be turned while keeping the beam passing through the crazed region.

Acrylic plates were cut, prepared, and tested in groups of 4 to 12, with new groups added as new questions arose. The first group, consisting of 6.4x50x50mm plates, was named series 'A'. Each plate had inscribed on it an 'A' followed by a number to uniquely identify it. Data was collected on plates A1,A2,A4,A6, and A7, (samples A3 and A5 snapped during crazing). Following the 'A' series was the 'W' series, so named since following sereies 'A' it was decided to cut longer plates (6.4x50x100mm) to achieve a wider region of crazing (see appendix 1). Following 'W' were series 'I-VI' (1-6).'2min-27hrs', and finally, series 'F'.

4 RESULTS

In figure 4, a typical view of the transmitted beam and the scattered portion is drawn. Careful examinations were made of the transmitted, reflected, and scattered parts of the incident beam on crazed samples of series 'A'. Some

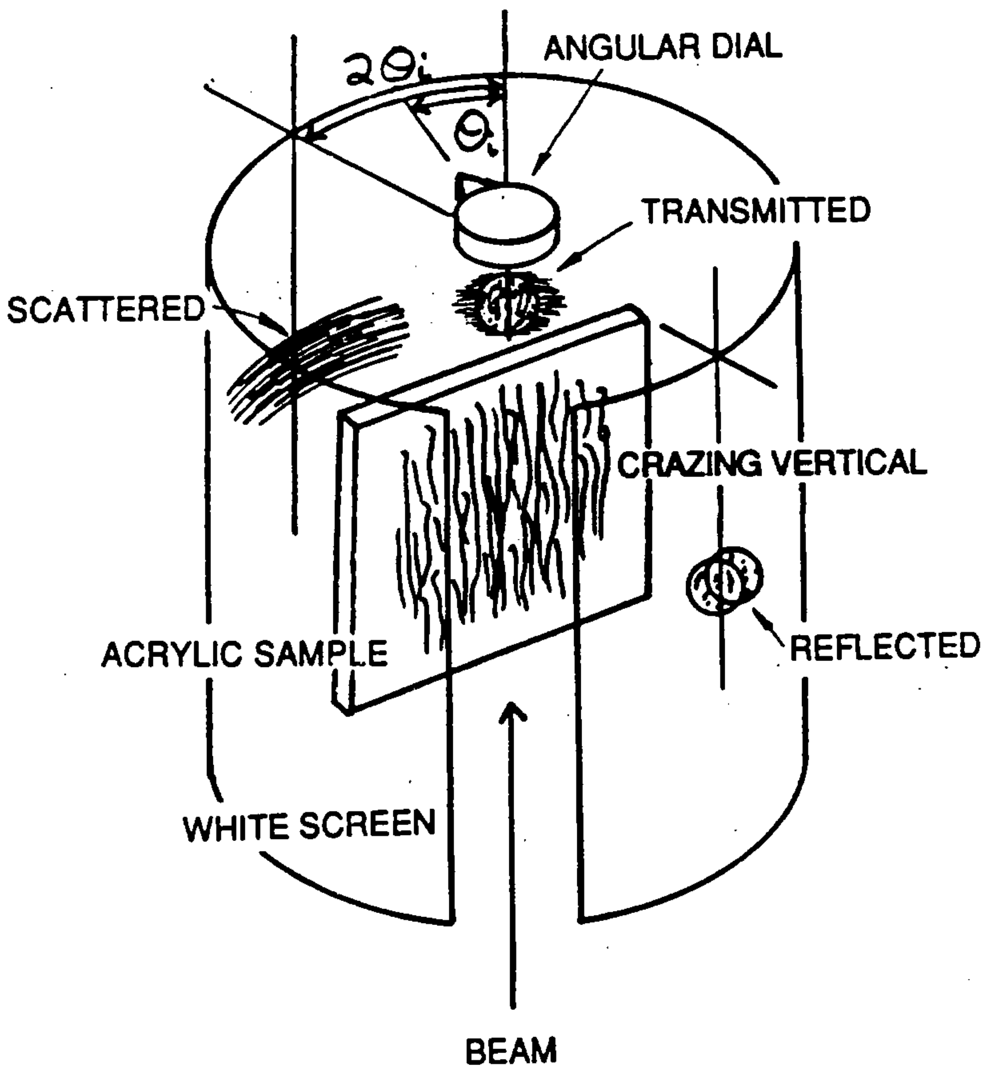


Figure 4: Effect of crazing on incident light beam.

characteristics were:

- The transmitted spot remained circular with roughly the same diameter as the incident beam. Superimposed on this spot was a red smear, varying in size and intensity. Nearly as bright as the central spot as in the case of (A7) or barely visible as in the case of (A6), the band-like smear extended equally to both sides of the central spot, similar to an outward smear of ink to opposite sides of a nearly dried circular blotch. The smear was vertical for crazing directed horizontally and visa-versa for vertically-oriented crazing as depicted in figure 4.

- In the case of vertical crazing, a second red smear traced, as the acrylic sample was turned 360°, a circle on the white screen surrounding the sample. The axis of rotation of the angular dial was normal to the plane of this circular path. The center of the smear was located at twice the angular displacement from the transmitted spot as the normal to the surface of the acrylic sample, as depicted in figure 4. Spread wider than the smear remaining in the beam line, the scattered band would range typically 10° → 20° in width, varying for each sample. The smears of samples A4 and A7 were only a few degrees wide and were faint while those of A2 and A6 were wide and intense. The smears of series 'F' grew wider as the severity of the crazing increased. In the case of horizontal crazing, the red band remained at 0° for all angles of incidence, rendering the transmitted smear and the scattered smear indistinguishable, a single, vertical red smear on top of the transmitted spot.

- Two reflected beams could be seen, each a partial reflection from the two faces of the acrylic, as shown in figure 4. In most cases both spots were circular, the distance between their centers growing with increasing incident angle of the laser. In the case of crazing directed horizontally, the spot from the second surface assumed a band-like shape.

Graphs of transmittance over angles ranging generally from −70° to 70° are shown in figures 5 to 12. The intensity is measured in mW. In some cases transmittance previous to crazing is graphed in addition to transmittance where the crazing is directed along the axis of the angular dial (vertical crazing) and/or where the crazing lies perpendicular to the axis (horizontal crazing). In a few cases, small angle detail was examined and graphed as well. It should be noted that although the width between line crazings in samples A2 and A7 was measured as the same, in later examination it was observed that line crazing in sample A2 was less dense than that of A7, and that the density of line crazing was similarly high in samples A4 and A7 and likewise lower in A2 and A6.

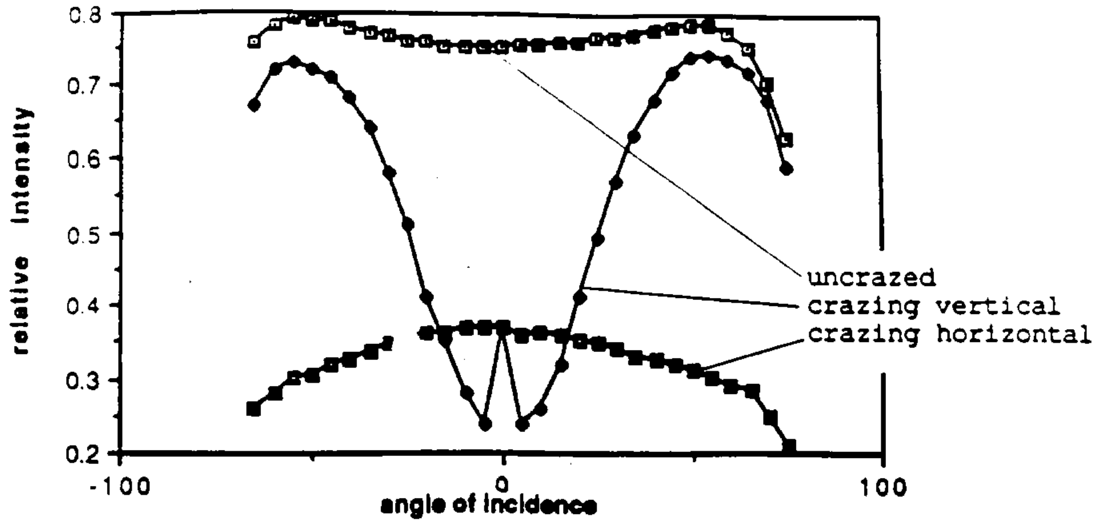
For the sake of clarity, error bars have been omitted from the figures. Sources of errors include fluctuation in laser intensity ($\approx \pm.01$mW) and systematic errors associated with reading the analog meter ($\pm.01$mW), setting the angular dial ($\pm 1^\circ$), and centering the transmitted beam on the photodetector ($\pm.005$ mW).

5 DISCUSSION

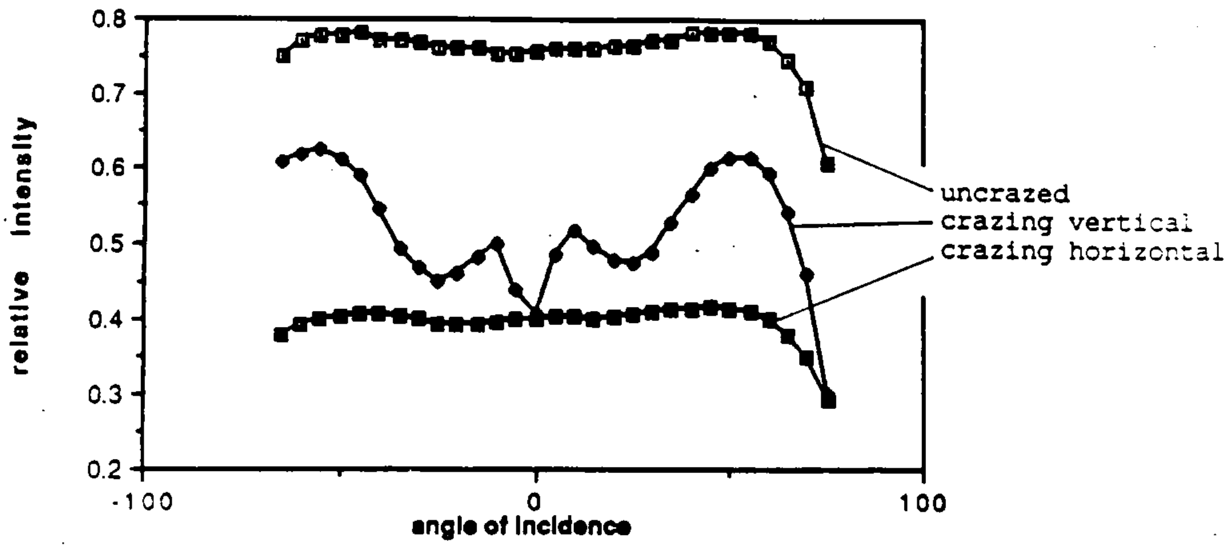
It can be seen from figures 5 to 12 that the angular dependence of transmittance is uniform within each of three testing categories; transmittance (1) previous to crazing, (2) with crazing set vertically, and (3) with crazing set horizontally. Each of these categories can be further divided into two more; testing in (1) air and (2) water.

Transmittance in uncrazed acrylic is consistent with transmittance calculated using the Fresnel Equations. Graphs of transmittance through uncrazed acrylic in air and water as calculated by Fresnel's Equations for light incident in TM mode are shown in Figure 13. With the exception of series 'F' which was polarized TM $\pm 5^\circ$), the polarization was $21^\circ \pm 5^\circ$ from pure TM. The similarity between Figure 13 and the experimental transmittance in uncrazed acrylic is evident, even though in all cases except series 'F', only 88% of the incident energy was TM radiation.

Transmittance through acrylic with crazing oriented horizontally decreases at an increasing rate as angle of incidence increases. The transmittance at $\theta_i = 0^\circ$ is roughly the same as that of vertical crazing at normal incidence, which is no surprise (at $\theta_i = 0^\circ$, horizontal crazing= vertical crazing). As-

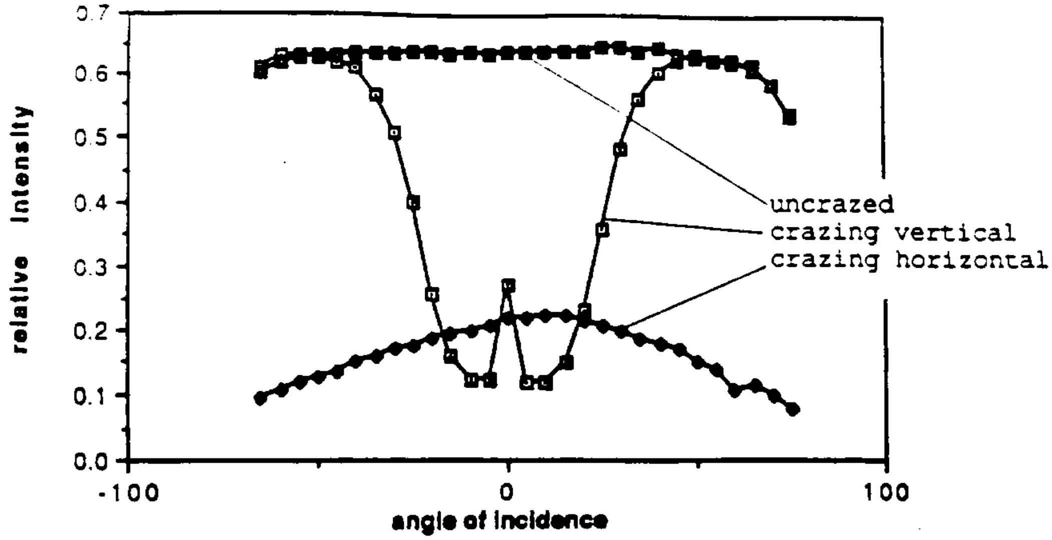


A2 10% ethanol, 5.5min.
radius of curvature= 89mm
flat crazing; w=.25mm d=immeasureable
line crazing; w=.04mm d<<.02mm
(line, d < measureable)
tested in air

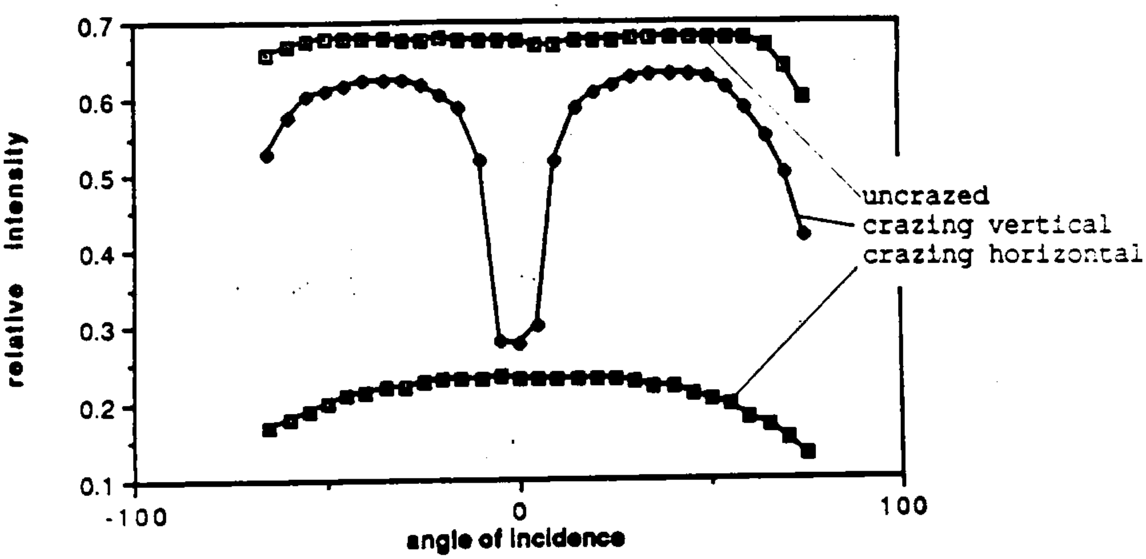


A4 100% ethanol, 10min.
r of c= 89mm
flat; w=.08mm d=.07mm
line; w=immeasureable d<<.02mm
tested in air

Figure 5: Transmission as a function of angle - Series A.

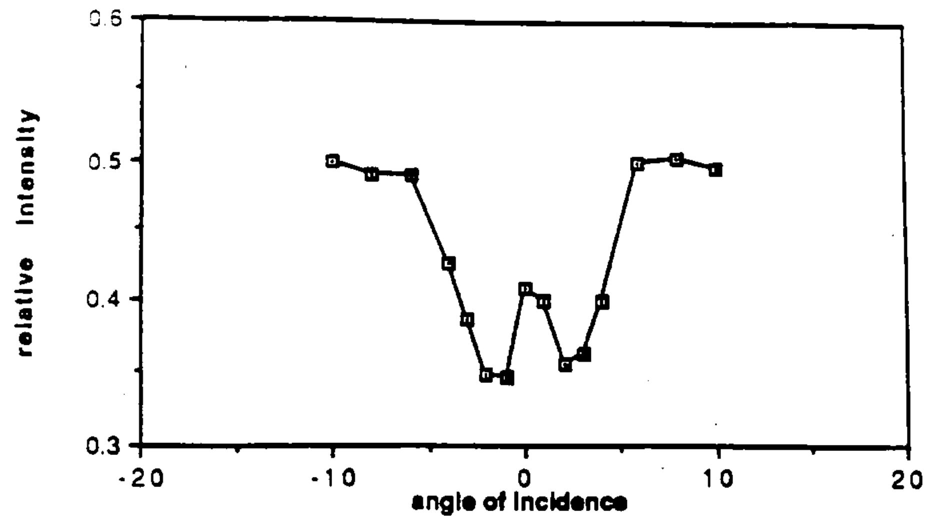


A6 10% ethanol, 11min.
r of c= 89mm
flat; w=.25mm d=immeasurable
line; w=.04mm d<<.02mm
tested in water

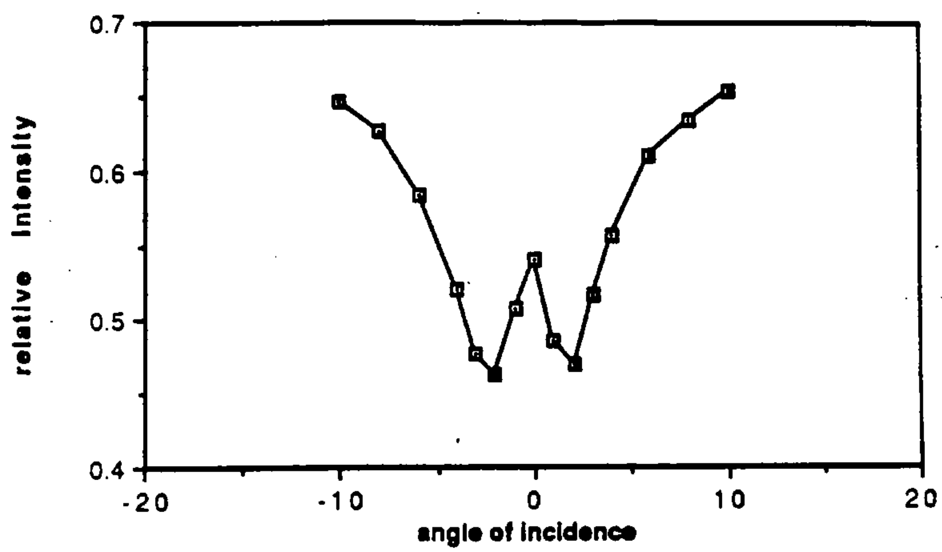


A7 100% ethanol, 5.5min.
r of c= 89mm
flat; w=.13mm d=.08mm
line; w=.04mm d<<.02mm
tested in water

Figure 6: Transmission as a function of angle - Series A.

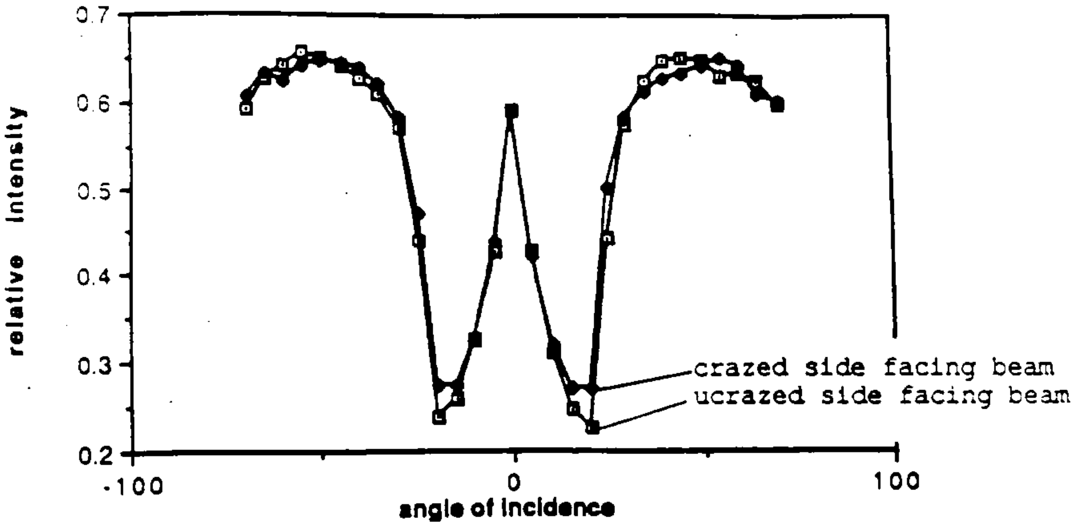


A4, small angle, demontrates
spike at 0 degrees not apparent
on other graph

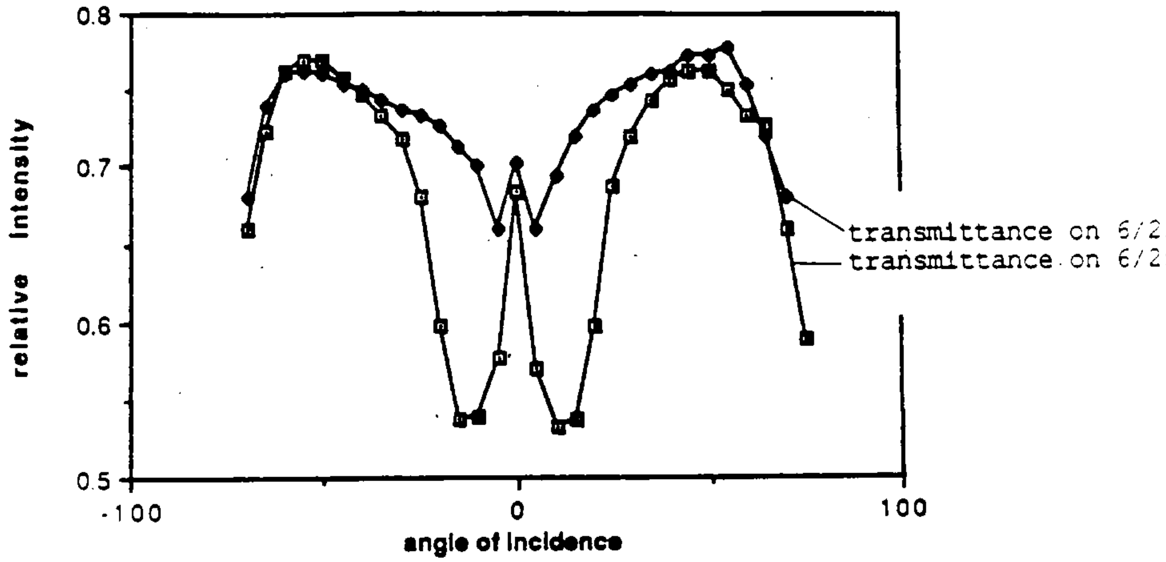


A7, with central maximum not
visible on other graph

Figure 7: Central maxima of A4 and A7 with higher resolution.

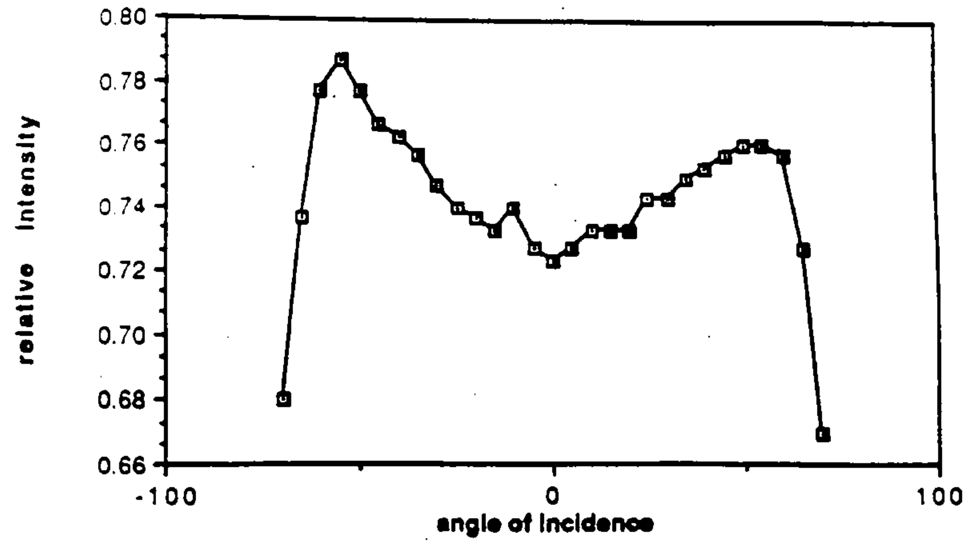


W1 crazed in water, 15.5 hrs
r of c= 127mm
flat; w= .23mm d= .06mm
line; w= .04mm d<<.02mm
transmittance identical for
either side of the sample
facing the laser

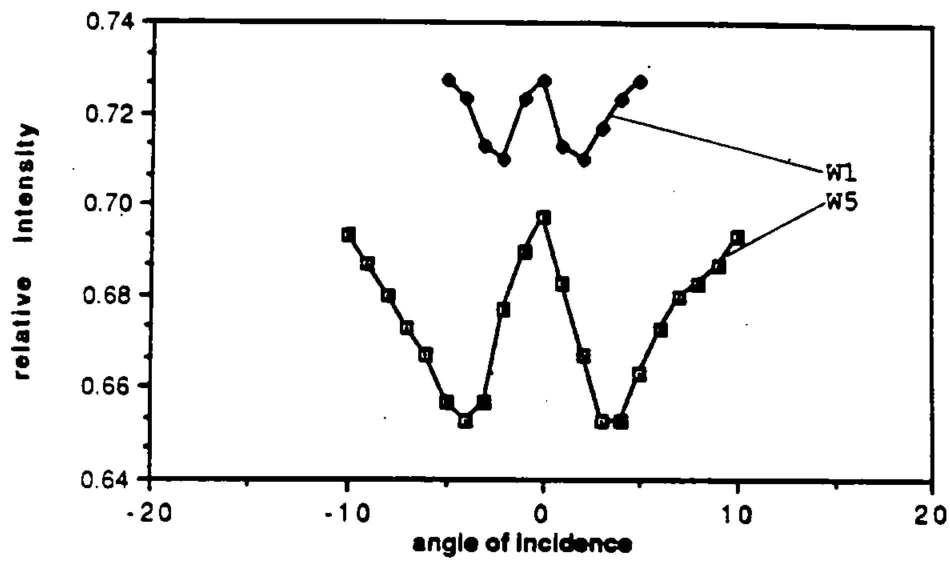


W1 retested three days later
demonstrates the effect of allowing
a curved sample to straighten

Figure 8: Transmission as a function of angle - Series W.

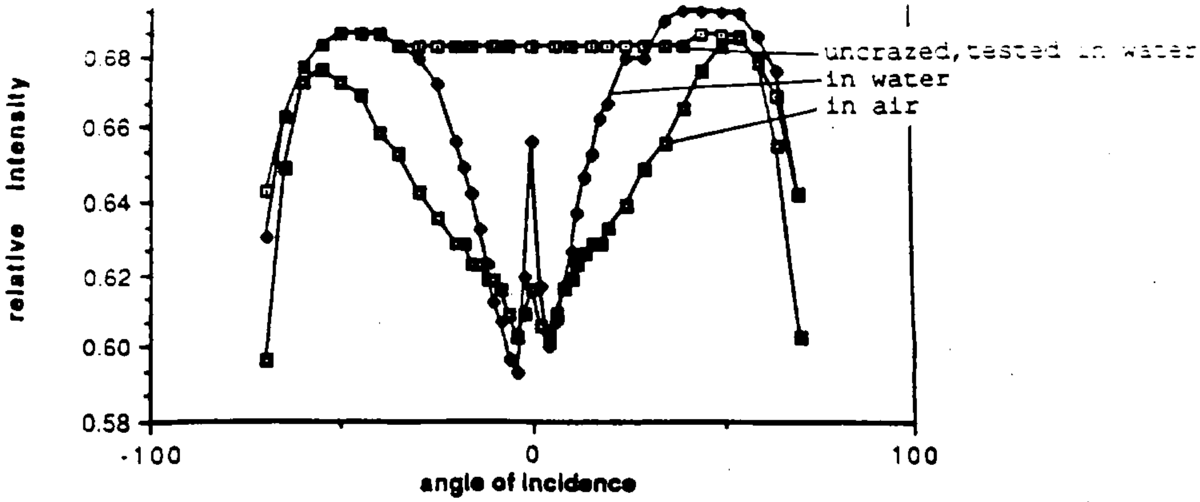


W5 crazed in air, 1hr.
r of c= 127mm
flat; w= .13mm d=.05mm
line crazing appears as flat
crazing in early stages.

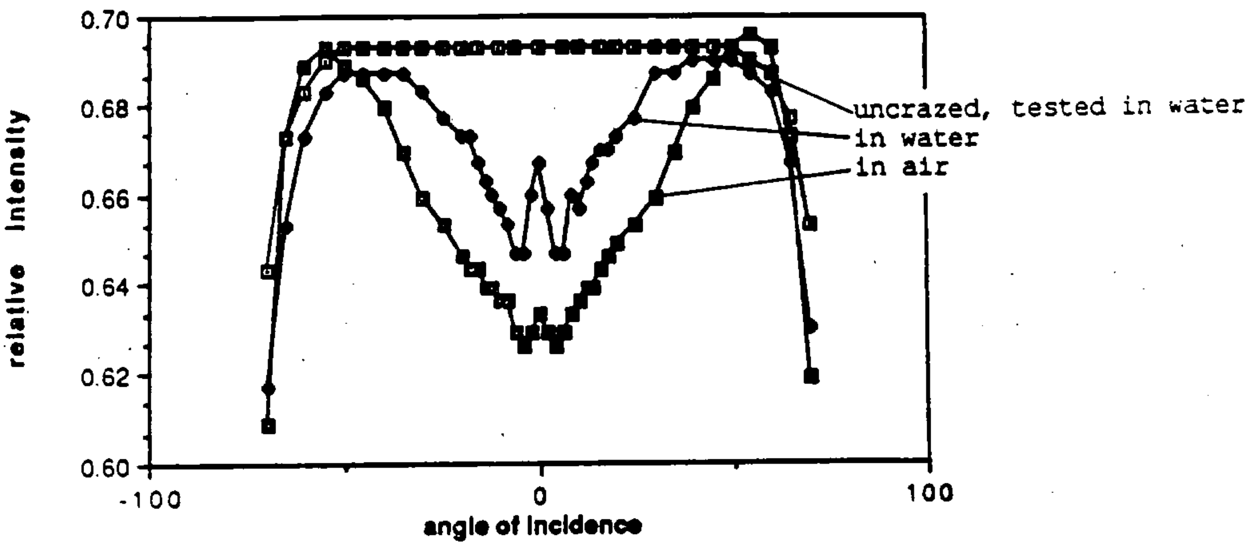


W1 and W5 at small angles
demonstrating central maxima

Figure 9: Transmission in W5 (top), and W1 and W5 with higher resolution (bottom).

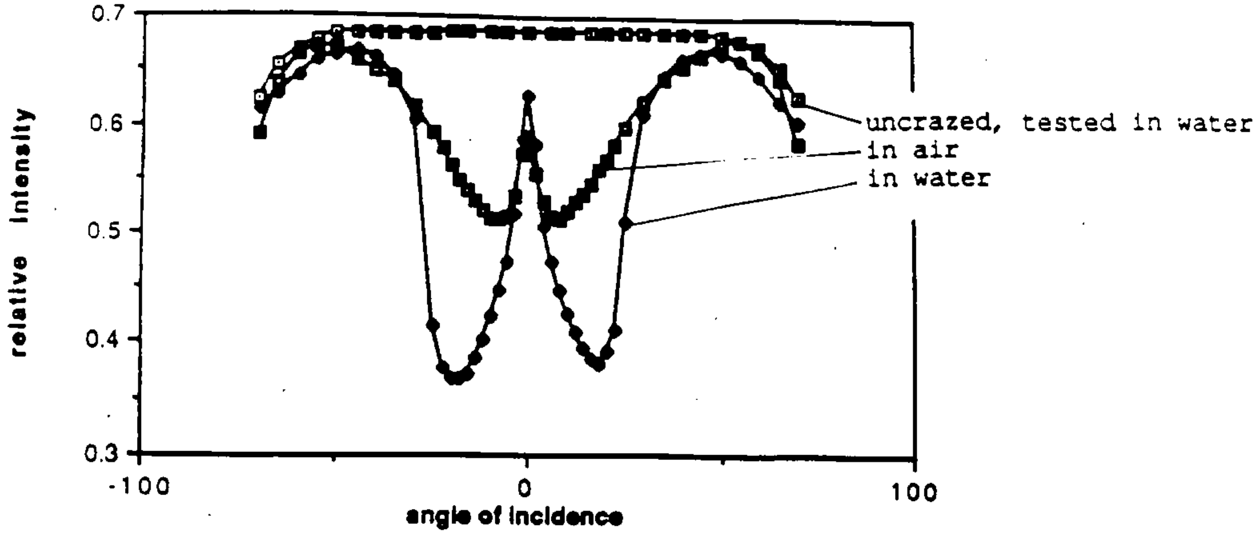


F1 crazed in water, 2min.
flat crazing; (crazing with depth)
tested in water and air
difference in unobstructed beam
intensity in water and air normalized
for comparison for F1 - F4
w= .09mm d=.025mm

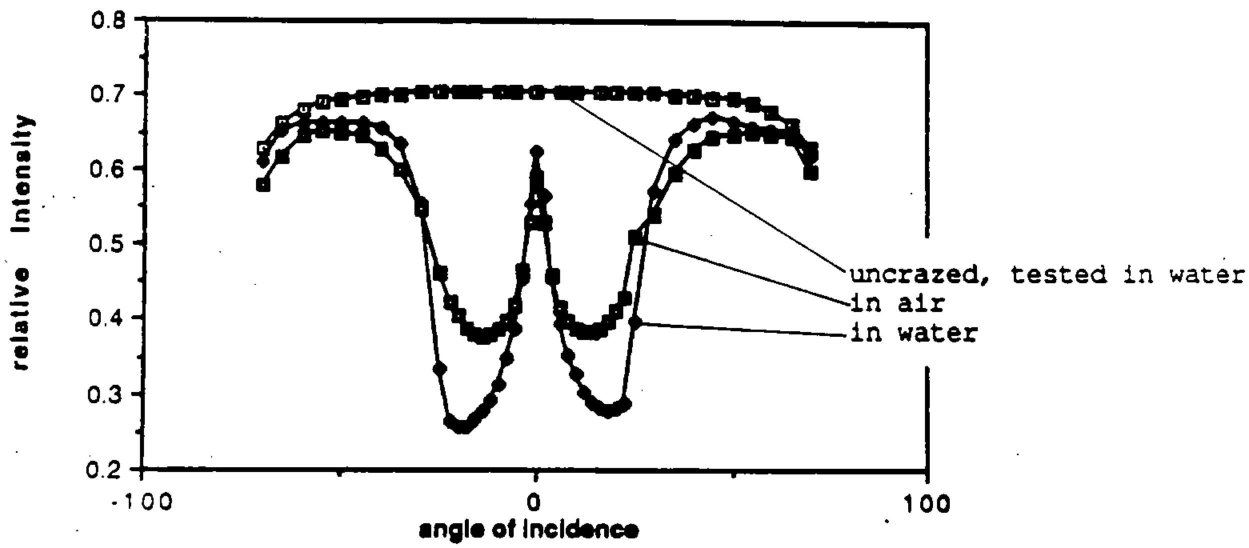


F2 crazed in water, 10min.
tested in water and air
like F1, not crazed long enough
for plate to remain bent
differences entirely due to bath
w= .20mm d= .05mm

Figure 10: Transmission as a function of angle - Series F.

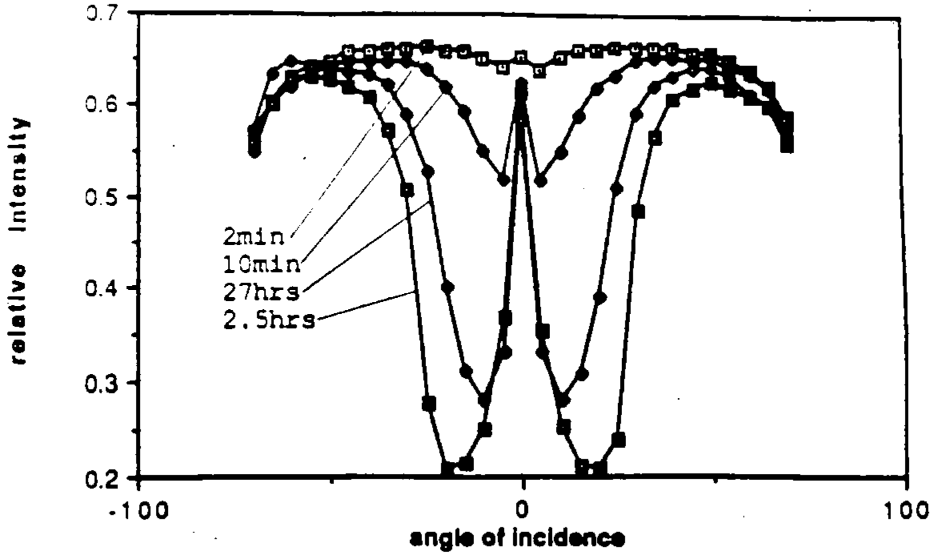


F3 crazed in water, 1hr.
tested in water and air
difference due to difference
in curvature of sample at time
of testing
w= .17mm d= .08mm

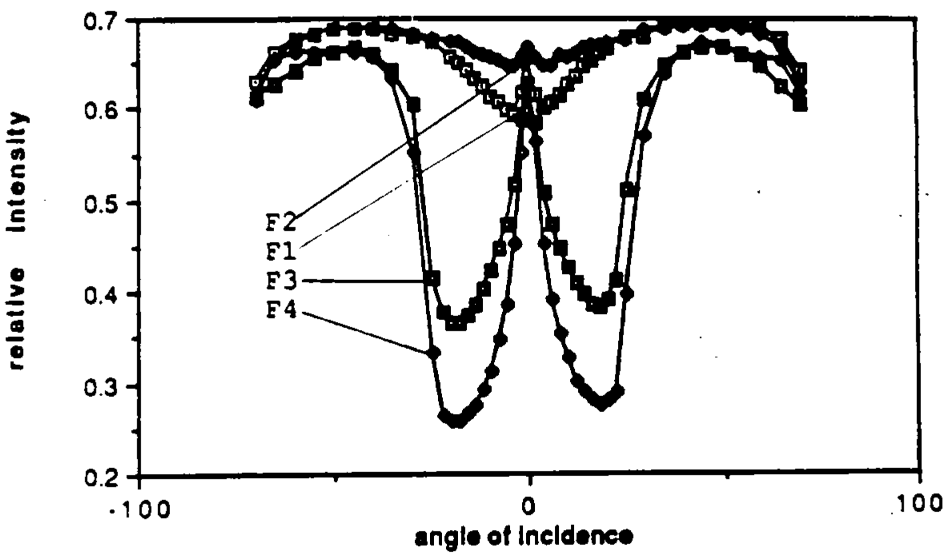


F4 crazed in water, 10.5hrs.
tested in water and air
w= .25mm d= .38mm

Figure 11: Transmission as a function of angle - Series F.

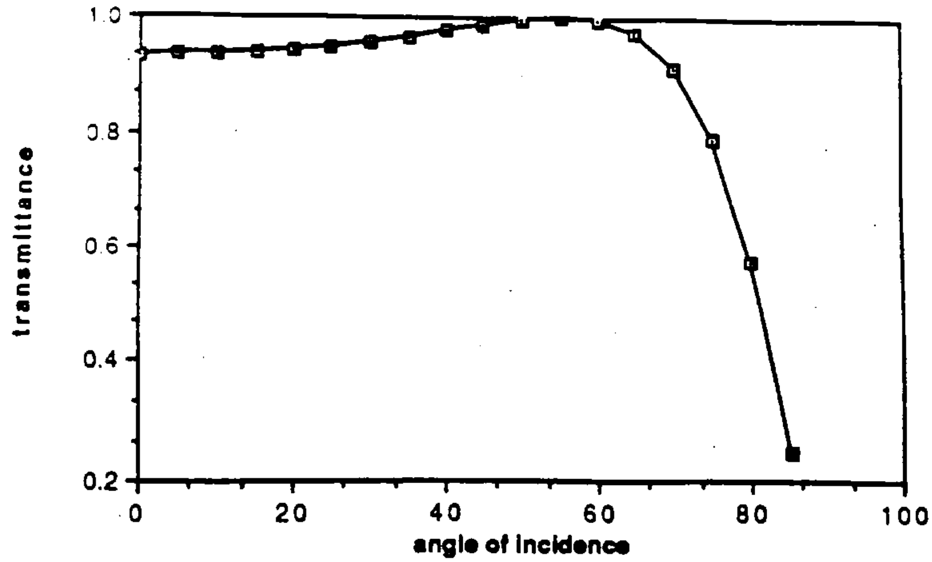


2min., 10min., 2.5hrs., 27hrs.
all crazed in water, r of c= 127mm
crazing not examined.
longer crazing means deeper trough
except for sample '27hrs.'

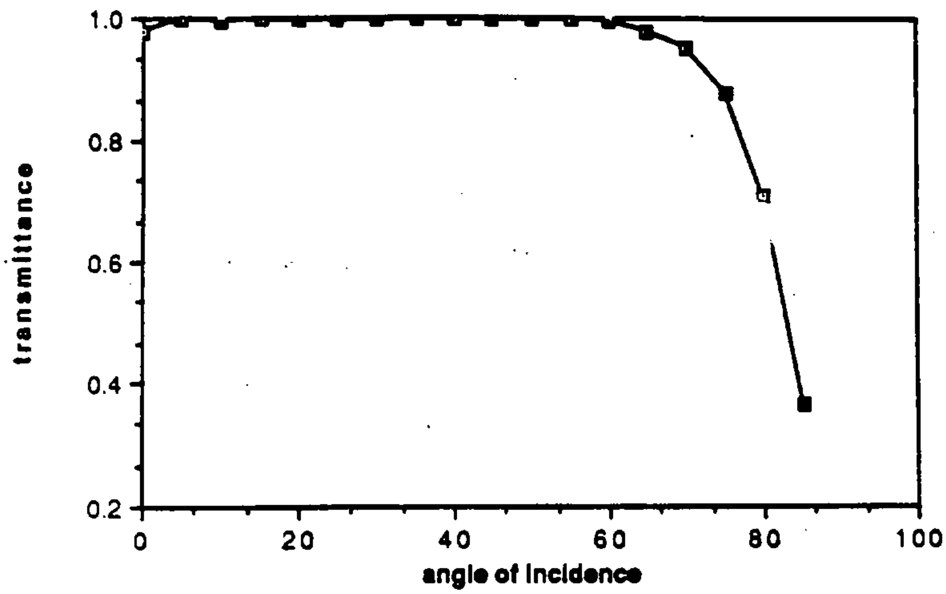


F1-F4 in water

Figure 12: Transmission as a function of angle - Series F.



transmittance in uncrazed acrylic in air



transmittance in uncrazed acrylic in water

Figure 13: Transmittance through uncrazed acrylic in air and water

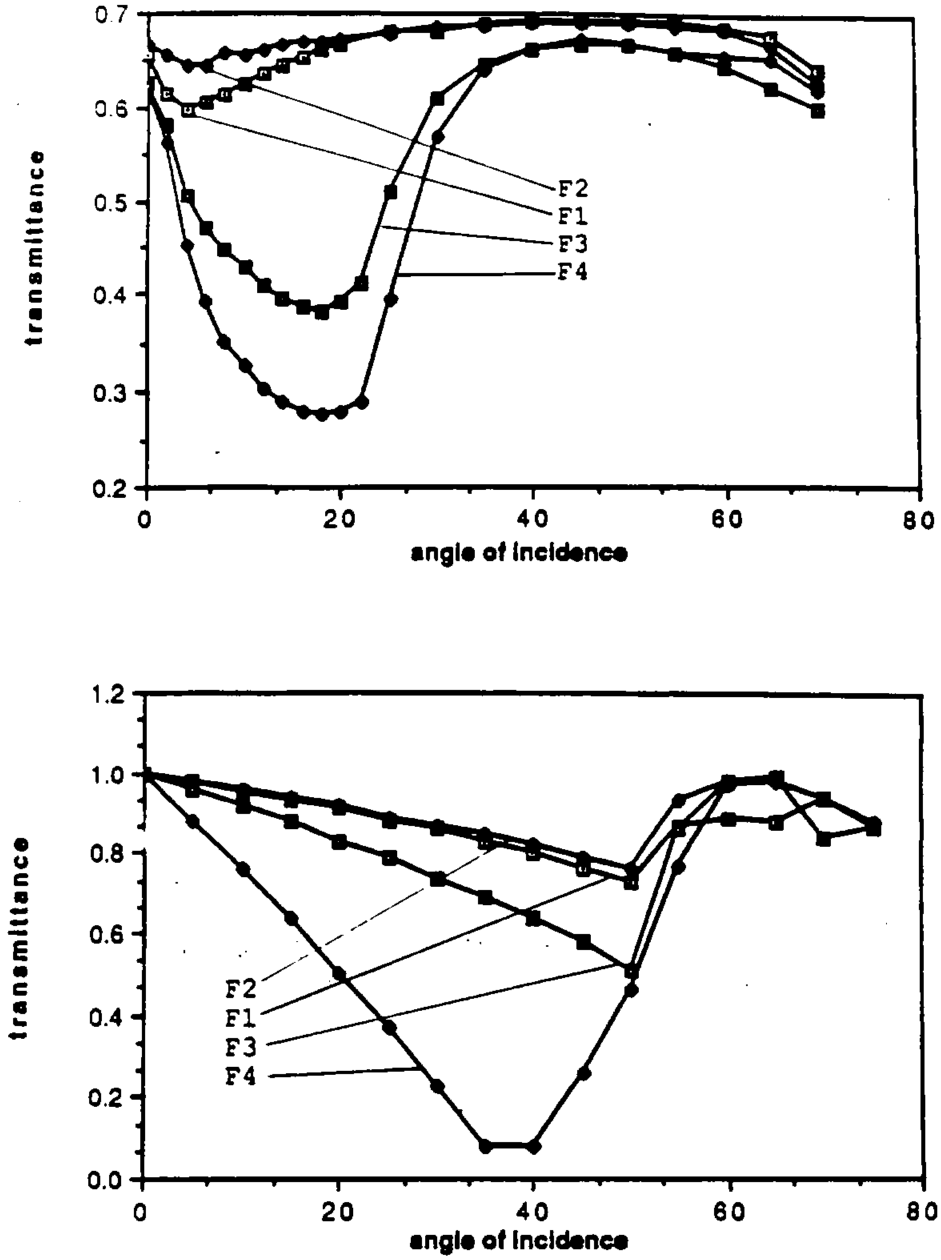
suming that the cracks grow into the acrylic normally, for horizontal crazing the incident beam strikes the crazing at $\theta_i = 90^o$ for all angles of incidence to the face of the acrylic sample. In this simplified view, transmittance would not be affected by the crazing depending on angle of incidence, and would behave similarly to the uncrazed case. Transmittance steadily decreased with increasing angle of incidence, unlike transmittance in uncrazed acrylic. A more severe crazing on the outside fringes of the crazed region of each sample may be the cause. The effect is most pronounced in sample A2 in which the uneven crazing, unavoidable for that crazing technique, is most pronounced. The fact that transmittance is typically 50% below transmittance in uncrazed acrylic demonstrates that, even for normal incidence, ~ half of the light passing through the acrylic is interupted by crazing. Since, following series 'A', it was decided that transmittance through horizontal crazing did not yield particularly interesting results, samples were not tested in this orientation for the remainder of the experiment.

Transmission through acrylic with crazing directed along the axis of incident angle (vertical crazing) proved to be most complicated (as one might expect, considering the geometry of the crazing) and most interesting. In all cases the angular variance of transmittance began with a local maximum at 0 degrees , fall to a minimum within $\approx 20^o$, increased steadily toward the uncrazed transmittance, meeting it at $\approx 55^o$, and afterward descended toward zero as if no crazing were present. With two exceptions, the depth of the trough increased as crazing time increased. In the case of the first exception, sample 27 hrs, the dicrepancy can be can be attributed to the fact that this sample was left to straighten for 48 hrs after having been crazed. On occasions in which a sample was tested immediately following crazing and again one or two days later, transmittance later increases, as if the sample were tested immediately after having been bent *for a shorter time*. This tendency is depicted in Figure 8. Sample 2.5 hrs, with a deeper trough, was tested within an hour after crazing, the sample still curved from having been bent for a relatively long 150 minutes. In the case of the second exception, F1, which crazed 1/5th as long as F2, was found to have more extensive crazing. The reason for this is not understood.

A qualitative correlation between band width and width of the central maxima was observed without exception in all samples examined including series 'A' (photos of only series 'A' were taken) and series 'F'. The central maxima present in all gathered spectra was concluded to be the result of the scattering of incident beam by the crazing into a red band perpendicular to the direction of the crazing whose angular width was seen to vary from approx. $2^\circ \rightarrow 20^\circ$. At small angles, a portion of the band would fall on the detector with the transmitted beam. In addition to the unobstructed portion of the incident beam, the detector measured the intensity along the band of scattered light from a central maximum at 0° outward as the band faded. As a reflection from the cracks the scattered band was located at twice the angle that the acrylic was turned. That the band turned at twice the rate that the acrylic turned was checked for series 'A'. It was apparent that the band-like structure of the scattered light resulted from crazing that was not entirely perpendicular to the surface of the acrylic. Some cracks (or only portions thereof) were angled slightly to either side, the greater the twist the less frequent the case, spreading an incident beam into a band that was perpendicular to both the direction of the crazing and the beamline.

In order to explain transmittance outside the central maximum, The model described in the theory section was applied to the samples of series 'F', in which the acrylic was crazed and tested in water. The depth and distance between cracks were estimated, and it was assumed that the cracks did not fill with water, even though the samples were crazed in a water bath. Water-filled cracks would have been far less visible than air filled cracks, the difference in indices of refraction of water (1.33) and acrylic (1.46) being less than a third of difference between those of acrylic and air. Throughout the experiment no difference in visibility was noticed.

A comparison of the observed transmittance and the modeled transmittance (refer to THEORY) are displayed in Figure 14. To a first approximation, the model mimics the experiment. Between $40^\circ \rightarrow 50^\circ$ the transmittance is by mode (1), whose contribution continues to decrease for increasing angle whereupon mode (2) kicks in to boost transmittance to unity around 60°. Mode (3) contributes only in the case of F4, in which crazing is densest, to initialize the increase in transmittance at 40°. If crazing is not entirely perpendicular to the acrylic surface as was suggested above, the "bird's head" of the model would widen to mimic more closely the behavior of the experimental transmittance between $40^\circ \rightarrow 80^\circ$ incidence. In addition, the contribution by mode (1) would decrease, yielding lower transmittance at less than 40°. Since time did not permit, modeling of crazed acrylic in air was omitted. In



transmittance in `F' series for water bath
experiment (top) modelled (bottom)

Figure 14: Comparison of observed and modeled transmission.

this case mode (2) wou d never have contributed since the critical angle of transmission from acry to air is 43.2°, and light incident on crazing would have struck only at gre ter than 46.8°. Mode (3) would have assumed the role that mode (2) played previously to some degree, giving what would have probably been similar results, with the effects of imperfect crazing acting similarly in this case as before.

6 SUMMARY

It has been found that crazed acrylic significantly degrades light transmission for angles of incidence $<\sim 60°$. At greater angles of incidence, transmittance decreases regardless of crazing. The method by which the light is scattered appears to be a simple effect in which the cracks in the acrylic act as mirrors to deflect incident light out of its initial path.

In this experiment, only samples of acrylic 7mm thick were examined. It may happen that cracks in thicker acrylic open wider to fill with water, in which case the degradation would not be as pronounced. In any case , a significantly crazed vessel at Sudbury would result in greater difficulty, if not impossibility, in reconstructing information on secondary charged particles by Čerenkov radiation.

If it is anticipated that the stresses on the acrylic vessel at sudbury may be sufficient to induce crazing within the duration of the experiment, thickening the vessel walls or applying pressure to the vessel as appropriate to reduce stress might be considered.

References

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[3] J. D. Stachiw, "Acrylic Plastic Viewports", Marcel Dekker, Inc. 1982

[4] E. H. Andrews, L. Bevan, "Mechanics and Mechanism of Environmental Crazing in a Polymeric Glass", Polymer, 1972, Vol. 13, pp. 337-346.

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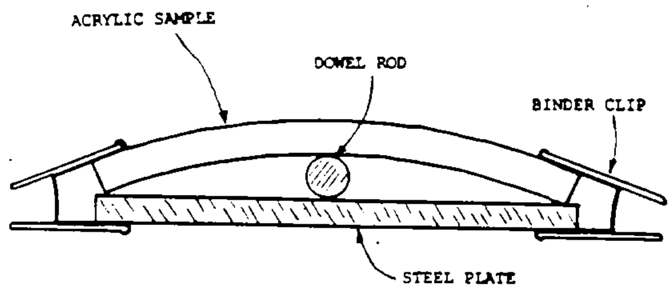

Figure 15: bending tech # 1

APPENDIX 1; CRAZING TECHNIQUES

Although crazing will eventually occur in any sample of acrylic subjected to tensile stress, the process may demand years (in the case of low stress), or can be accelerated to seconds by applying organic solvents to the stressed surface [2]. It may be noted that a fingerprint becomes etched on acrylic under high tensile stress after less than 10 minutes (although there is no apparent effect if the sample is unstressed, even after 2 hours of exposure). It was observed that finger oil acts as an agent to accelerate crazing just as ethyl alcohol does, which was employed in this experiment during the crazing of the samples of series 'A'.

Beginning with 1.6x50x50mm squares of acrylic, each piece was bent by hand over a dowel rod placed between the acrylic and a steel plate. The piece was then clamped to the plate with a 3.2mm binder clip on each side, as shown in figure 15, and squirted with pure ethanol. This bending techinique was quickly abandoned because the resulting region of crazing was too narrow for testing over a wide range of angles of incidence. In addition, the crazes and/or cracks appeared to extend to a depth comparable to the thickness of the acrylic. To minimize possible dependence of the nature of crazing on the

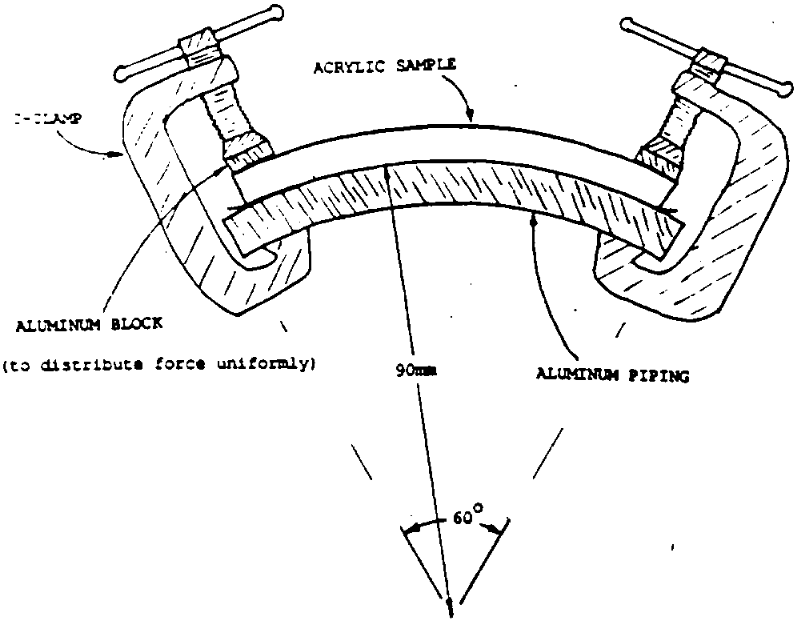

Figure 16: Bending tech. # 2

thickness of the acrylic, we turned to 6.4mm plates (the thickest available). In the interest of achieving uniform crazing over a wider region, the acrylic was clamped down to a 60° section of scrap aluminum piping 180mm in diameter (piping was chosen for a more uniform distribution of stress) using four C-clamps as shown above in Figure 16.

Roughly 7mm thick, no flattening of the aluminum to a larger radius of curvature during bending was visible, nor could any bowing of the acrylic away from the pipe between the clamped ends be seen. The modulus of tensile elacticity of acrylic is 3,400MPa [3] from which the stress at the surface of an acrylic plate 6.4mm thick is calculated to be 245MPa. In this method and the one to follow, a folded kimwipe was sandwiched between the acrylic and the aluminum to avoid scratching the sample. Plates of series 'A', 6.4X50x50mm, were bent using this procedure, which demanded roughly 40 minutes to complete. Upon bending, samples A2 and A6 were immersed in a 10% ethanol, 90% tap water solution to craze, while samples A1, A4, and A7 were immersed in baths of 100% ethanol.

Every attempt to bend 3.2mm plates in this manner resulted in a snapped plate. It was concluded that 3.2mm acrylic, while only slightly more flexible than 6.4mm. is co ›iderably weaker. 6.4mm plates, although tougher to bend, were in most ‹ ses strong enough to resist snapping when clamped flush to the pipe.

Following series 'A', a faster and safer method of bending the acrylic was adopted. A 360 degree section of scrap aluminum piping 254mm in diameter and ≈25mm thick was used in place of the smaller section used previously. Two hose clamps held the acrylic sample in place while large C-clamps pressed the ends of the sample to the pipe, as shown in figure 17. Pressure at the surface of a 6.4mm thick sample was reduced to 173MPa. (Although the stress was reduced using this method, at least half of the plates to be tested were broken. It was interesting that each time the cloth pressed between the acrylic and the pipe was wet with water, the sample snapped, but did not if the cloth was left dry. It is apparent that evaporation from the exposed area of the cloth cooled the sample enough to increase the modulus of elacticity to where the acrylic would snap).

All samples following series 'A', 6.4x50x100mm, (cut wider to achieve an even wider region of crazing) were bent and crazed using this method, which cut assembly time to roughly 10 minutes. Since it was noticed following series 'A' that samples could be crazed in minutes without ethanol, the remainder of the crazing would take place in tap water instead of an ethanol solution, with the C-clamps removed, leaving the tightened hose clamps holding the acrylic against the pipe.

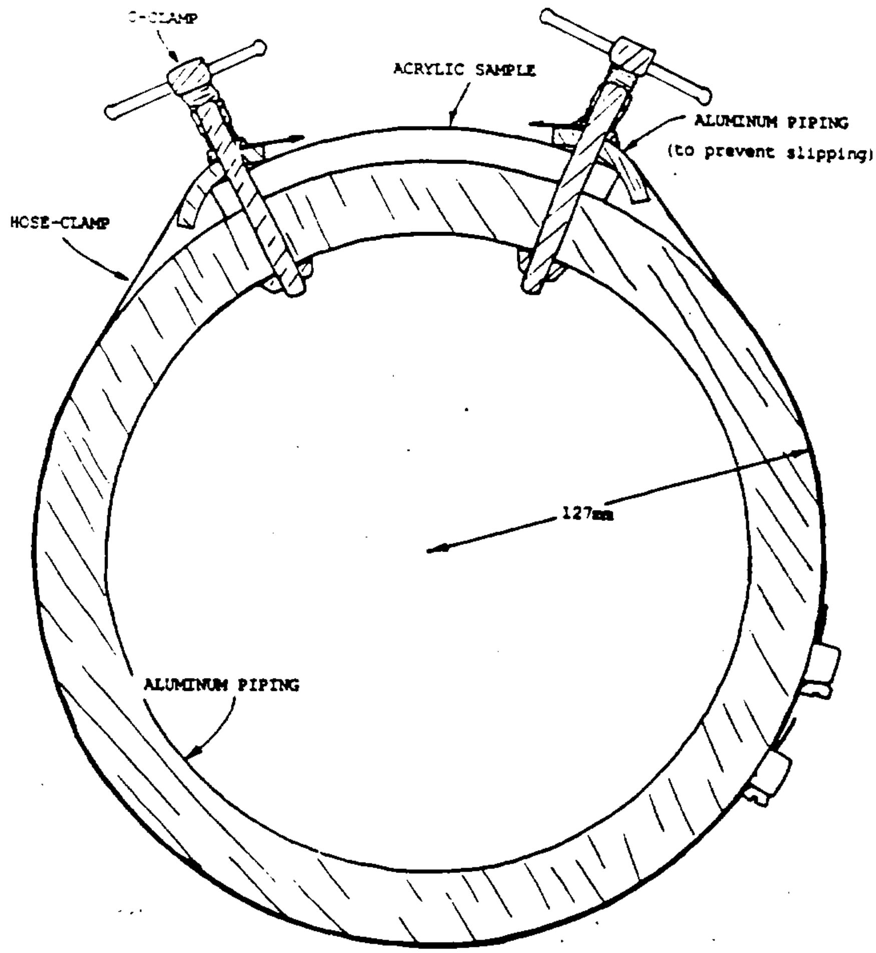

Figure 17: Bending tech. # 3

APPENDIX 2; CRACKS AND CRAZING

An American Optical model 570 microscope was employed for close examination of the samples following crazing and optical testing. Observations on the crazing of the samples of plate series 'A', 'W', and 'F' were collected. Examination of samples in series 'A' seemed to reveal two types of crazing. The larger of the two, observable to the unaided eye, was dubbed "flat" crazing, and appeared as planar fracturing perpendicular to the face of the sample and located ≈.25mm beneath the acrylic surface, extending another ≈.08mm into the acrylic. Always aligned perpendicular to the direction of the tensile stress on the acrylic, the cracks averaged roughly .64mm in length, with a frequency of between 4 to 10 per mm. The smaller crazing, only seen when viewed through a microscope, was dubbed "line" crazing, and appeared as short aligned scratches on the surface, having no depth. "Line" crazing, lying parallel to flat crazing averaged roughly .25mm in length with a frequency of about 30 "lines" per mm.

That "flat" crazing did not begin at the surface of the acrylic was a curious result, and was checked and rechecked in samples A2, A4, A6, and A7. When it was found that ethanol plasticizes acrylic [4], this mystery as well as that of the apparent dichotomy in craze effects was explained. Ethanol penetrated the acrylic resulting in a flexible surface layer atop relatively brittle pure acrylic. The cracking, expected to begin on the surface of the stressed acrylic, begins without the aid of ethanol on the upper 'surface' of the region of unelasticized acrylic, the tensile stress high enough to initiate the process in minutes. Crazing began on the upper layer as tiny stretchings, some as small as can be discerned with the microscope (about .025mm in length) and roughly 5 to 10 times as many per unit area as the cracking below. It is possible that "line" crazing is truely crazing while the "flat" crazing is actually cracking, although discerning between cracking and crazing was never possible. Using the terms loosely, two types of crazing were observed essentially because each took place in one of two different materials.

In the interest of achieving crazing that would best simulate what could occur in the Sudbury vessel, attempts were made at crazing samples in water. It was found that, with stresses on the acrylic as high as we applied, crazing could be achieved in a matter of minutes (as opposed to only seconds in ethanol solution), so ethanol was abandoned. Beginning with series 'W' it was observed that while "line" and "flat" crazing were both present, the "flat" crazing originated at the surface of the sample, and there was no distinguishing between the two types. Lengths of the crazings at the surface varied continuously from as small as could be discerned ($\leq$ .025mm) to about 8mm. The cracks did not extend in depth proportionally to their lengths. While larger cracks appeared geometrically similar, it is clear that when crazing begins most growth is along the surface, as cracks up to about .25mm in length had no apparent depth.