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Mechanical Properties of Degraded PMR-15 Resin

Luis C. Tsuji
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February 2000

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Prepared under Grant NAG3–2054

National Aeronautics and
Space Administration

Glenn Research Center

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Acknowledgments

This project would not have been possible without the generous help of many caring and dedicated individuals. Though they may not realize how important they were to me, I will not forget them. This program was sponsored by the MIT Engineering Internship Program (EIP). EIP set up my internship with NASA Lewis Research Center, in Cleveland, where this project was undertaken. Through the internship program, I spent three summers and one semester at Lewis. This project covered the final summer and one semester. At NASA Lewis Research Center there were many helpful people, many helpful friends. I first would like to thank Ken Bowles, who was my mentor on this project. Without his help and the constant support of many others, I would have been lost. Demetrios Papadopoulos, Dan Scheiman, Linda Inghram, Raymond Vannucci, Gary Roberts, Linda McCorkle, Vic Klans, John Kamvouris, and Joe Grady all were critical in my project. They were quick to help, and treated me like I was one of their own. They kept me sane, and were my family while I was in Cleveland those many months. At MIT I would like to thank my advisor, Prof. Hugh McManus, who patiently guided me through this process. His task was not always easy, for I was not the most time-motivated student. I would also like to thank Deb Bowser and Anne Maynard for their help in making things run more smoothly. Finally I would like to offer my apologies for making this process more difficult and lengthy than it should have been. I am grateful for the understanding and support that brought me through some turbulent times.

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This work was funded through the MIT Engineering Internship Program (EIP) by NASA Lewis Research Center. EIP funding covered work at NASA during the summers after my sophomore and junior years as well as a six-month period after my senior year. This thesis research was performed during the six-month period after my senior year.

After the six months at NASA, the experimental research was completed. Additional funding for data reduction and document preparation was then covered under a separate grant, NASA Lewis grant #NAG3-2054.

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NOMENCLATURE

α_c	CTE of the unoxidized material
$\alpha_{c(aged)}$	CTE of the aged unoxidized material
$\alpha_{c(0)}$	CTE of the unaged unoxidized material
α_s	CTE of the oxidized surface layer material
a,b,c,d	coefficients
ε_0	strain at the neutral axis
ε_s	shrinkage strain
ε_{sc}	shrinkage strain of the unoxidized material
ε_{ss}	shrinkage strain of the surface layer
E_c	Modulus of the unoxidized material
E_s	Modulus of the oxidized surface layer
h	height of the arc of curvature specimen
I_c	moment of inertia of unoxidized layer
I_s	moment of inertia of surface layer
k	curvature
k'	slope of k versus T
k''	curvature at the cure temperature of 316°C, where ΔT is zero.
L	length of support span
l_{aged}	length of aged specimen
l_0	length of unaged specimen
m	slope of tangent to the initial straight-line portion of the load-deflection curve
m_{CTE}	slope of the dimension change versus temperature
M	moment
P_s	percent shrinkage
s	span of the arc of curvature specimen
σ	stress
t	thickness of specimen
t_s	thickness of the surface layer
t_c	thickness of the unoxidized core material
ΔT	temperature difference between the aging temperature and room temperature
w	width of specimen
ζ	alternate coordinate
ζ_1	coordinate of top of oxidized surface layer
ζ_2	coordinate of oxidized layer/unoxidized layer interface
ζ_3	coordinate of bottom of unoxidized layer
z	original coordinate axis
z*	location of neutral axis

CHAPTER 1: INTRODUCTION

1.1 BACKGROUND

Polymer matrix composite materials are being increasingly considered for use in environments that challenge their durability. Such applications include turbine engine structures and high speed aircraft skins. In these environments the materials are exposed to high temperature and to oxygen, both of which contribute to the degradation of the polymer matrix.

Significant progress has been made in the understanding of the aging effects on the thermo-oxidative stability of polymer matrix composites [1,2,3]. Much of this work has focused on PMR-15 resin as a representative material. Thermo-oxidative aging produces a non-uniform degradation state in PMR-15 resin. While thermal degradation occurs throughout the material, oxidative degradation occurs only where oxygen diffuses into the material. This produces an oxidized surface layer that has different properties from the unoxidized inner material. Current models of coupled diffusion-reaction mechanisms [4,5,6] attempt to capture the behavior of this chemical degradation. However, there is a need for data on material properties of degraded material(s), in order to link the diffusion-reaction models of chemical degradation to thermo-mechanical models [7].

Air aged material specimens have an oxidized surface layer and an unoxidized inner material which have different material properties. Tests performed on such specimens as if they were homogeneous produce results that are difficult to interpret and may have little meaning. Tests must be carefully designed to separate the properties of the surface layer from the properties of the inner material.

1.2 PROBLEM

The problem addressed here is to separate the properties of the oxidized surface layer from the properties of the unoxidized inner material, in PMR-15 resin specimens aged in air for various times at 316°C. Specifically, the thickness of the oxidized surface layer and the modulus, CTE, and shrinkage of both surface and inner material are determined as functions of aging duration.

1.3 ASSUMPTIONS

This experiment rests on a few basic assumptions. First is that the surface layer has uniform properties throughout the layer. This assumption is supported by the work of Cunningham, who showed both experimentally and with models that the surface degradation occurs on a sharp front, with little apparent gradient in degradation level within the surface layer [8]. The second assumption is that unoxidized material is also uniform, since unoxidized material is degraded thermally and the temperature is constant throughout the specimen during aging. Third, it is assumed that the nitrogen-aged specimens and the apparently unoxidized core material in the air aged specimens have the same properties. Fourth is the assumption that the moduli of the surface and interior layers have the same temperature dependence. This assumption is as yet unsupported, but effects only the surface layer CTE calculations in this work. Lastly, it is assumed that viscoelastic relaxation is negligible. Relaxation would tend to make measurements of shrinkage underestimates of actual shrinkage.

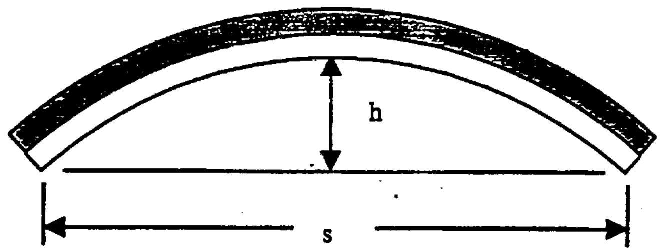
1.4 APPROACH

The approach to this problem is primarily experimental. The main challenge of this project, and the problem that drove the experimental design, is how to determine the shrinkage and CTE of the oxidized surface layer. The shrinkage is small, and the changes are slight. Typical measurements of length are confounded with the effects of surface erosion on the ends, and the stress and strain interactions of the surface layer and the unoxidized inner material. In order to determine the surface layer shrinkage and the surface layer CTE, a new test based on a bimaterial strip model was designed and used.

The new test involved the manufacturing of specimens that resembled a bimaterial strip, with the oxidized surface material on one side, and unoxidized inner material on the other side. These specimens were manufactured simply by slicing a piece of an aged specimen lengthwise through the thickness. When one side contracts or expands relative to the other, the specimen curves. By utilizing a bimaterial strip model, the amount of curvature and the change in curvature with temperature can be used to determine the surface layer shrinkage and the CTE. An illustration of the curvature specimen is shown in Figure 1.

In order to calculate the surface layer shrinkage and CTE from the curvature and change in curvature with temperature, several other properties must be known. These include surface layer thickness, modulus of both the oxidized surface layer and unoxidized material, shrinkage of unoxidized aged material, and CTE of unoxidized aged material. These properties are determined from other tests.

Surface layer thickness is measured simply by polishing a cross section of a specimen and measuring the surface layer. The modulus of unoxidized aged material is determined by standard four-point bend test, which is illustrated in Figure 2. The modulus of the oxidized surface layer is derived using basic beam theory from a bend test of an air aged specimen, as surface layer thickness and the modulus of the unoxidized material are known. Figure 2 also illustrates the bend test of an air-aged specimen. Shrinkage of unoxidized aged material is measured simply by measuring the length of a specimen both before and after aging. The CTE of unoxidized aged material is determined from a typical test using thermo-mechanical analysis, illustrated in Figure 3.



Test Gives:

- Oxidized surface layer shrinkage
- CTE

Measurements:

- Temperature
- Height of arc h and
- Span of arc s

or

- Temperature
- Coordinates of three points on arc

Required inputs:

- Layer thicknesses
- CTE of unoxidized material
- Moduli of both layers
- Shrinkage of unoxidized material

Figure 1 Curve test schematic

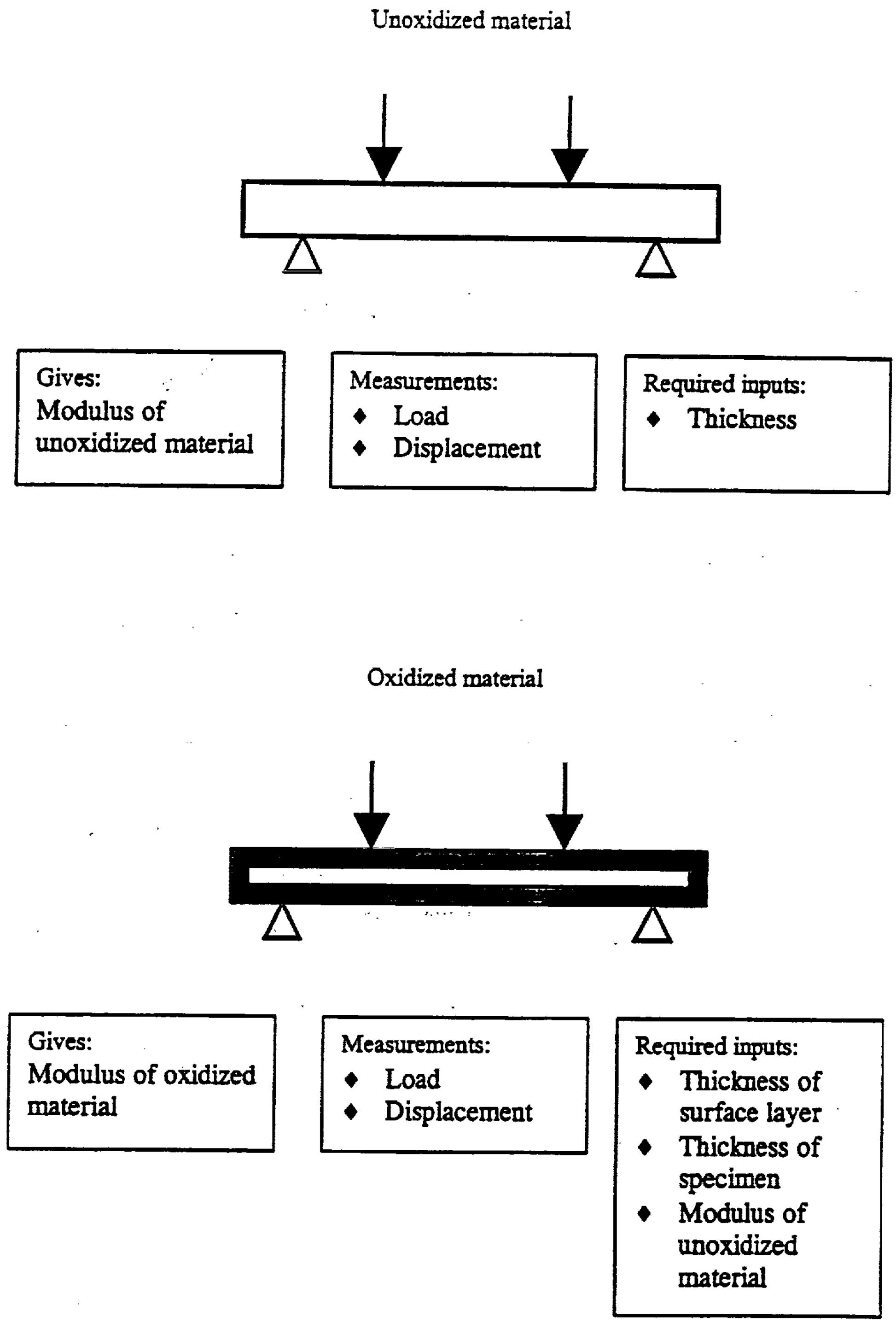
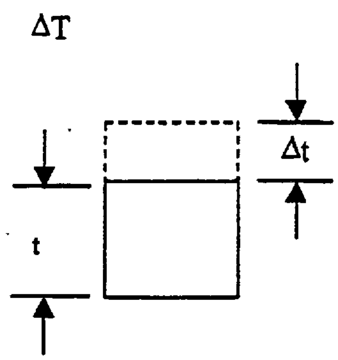


Figure 2 Four-point bend test schematics



Gives:	Measurements:	Required inputs:
CTE of unoxidized material	♦ T ♦ Δt	♦ Thickness t

Figure 3 CTE test schematic

CHAPTER 2: EXPERIMENTAL PROCEDURE

2.1 OVERVIEW

Specimens were cut from plaques of PMR-15 resin. Each specimen was then measured to determine initial dimensions. After initial measurements were completed, the specimens were aged in an oven at 316°C. Half of the specimens were aged in air in the oven, and half were aged in nitrogen in a nitrogen chamber placed inside the oven. Once specimens were removed from the aging ovens, their dimensions were remeasured. They were then tested to determine modulus by using four point bend tests. After bend testing, the specimens were cut again into smaller specimens for bimaterial strip curve tests, thermo-mechanical analysis (TMA), and for measuring surface layer thickness. Typically five specimens were used per test.

2.2 SPECIMEN PREPARATION

These experiments used 152.4 mm by 152.4 mm PMR-15 neat resin plaques from the same batch as the resin plaques used by Kamvouris and Roberts [9], so that comparisons could be made. The plaques were made from HyComp 100, a PMR-15 powder supplied by HyComp, Inc. The powder was compression molded using an automated heated press with vacuum. Both temperature and pressure were ramped gradually, to a 2-hour hold at 316°C and 9.3 MPa. Plots of the programmed cure cycle are shown in Figure 4 and Figure 5. Pressure was released after the 2-hour hold and the resin plaques cooled in the mold until the mold was cool enough to handle with insulated gloves. The resin plaques were then removed from the mold before they cooled completely, in order to prevent cracking. The material was

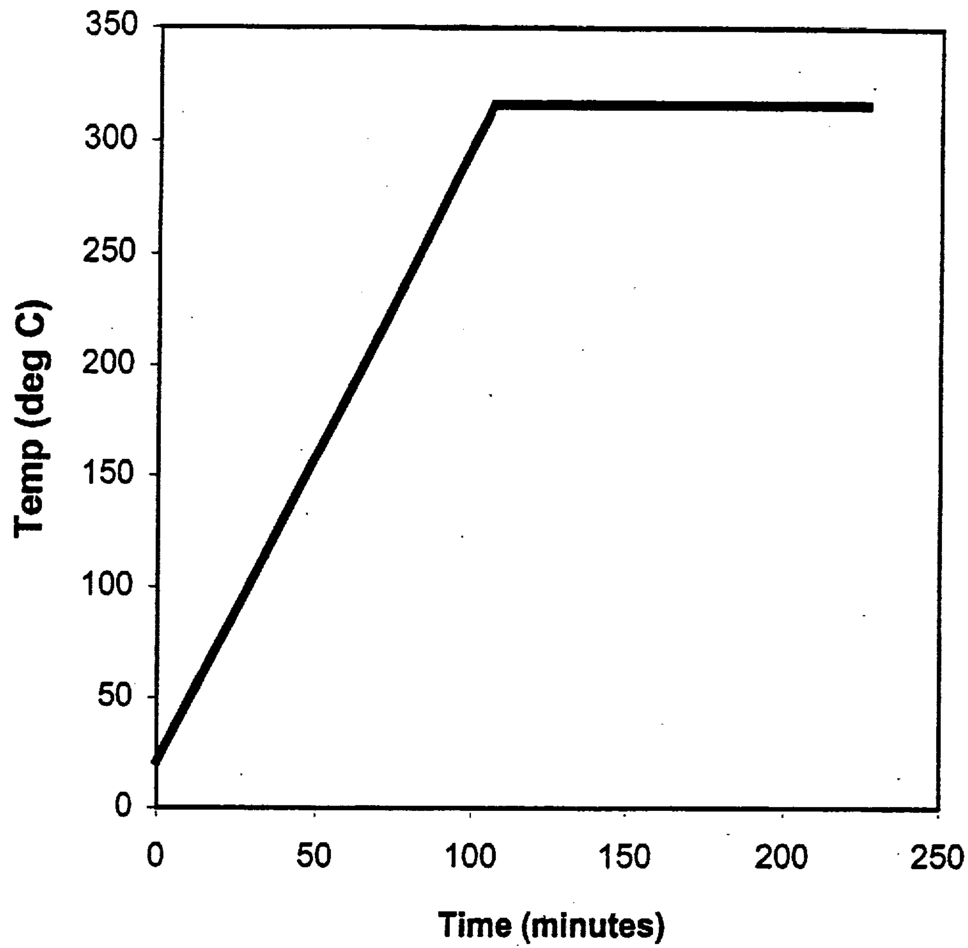


Figure 4 Cure Cycle, Temperature vs. Time

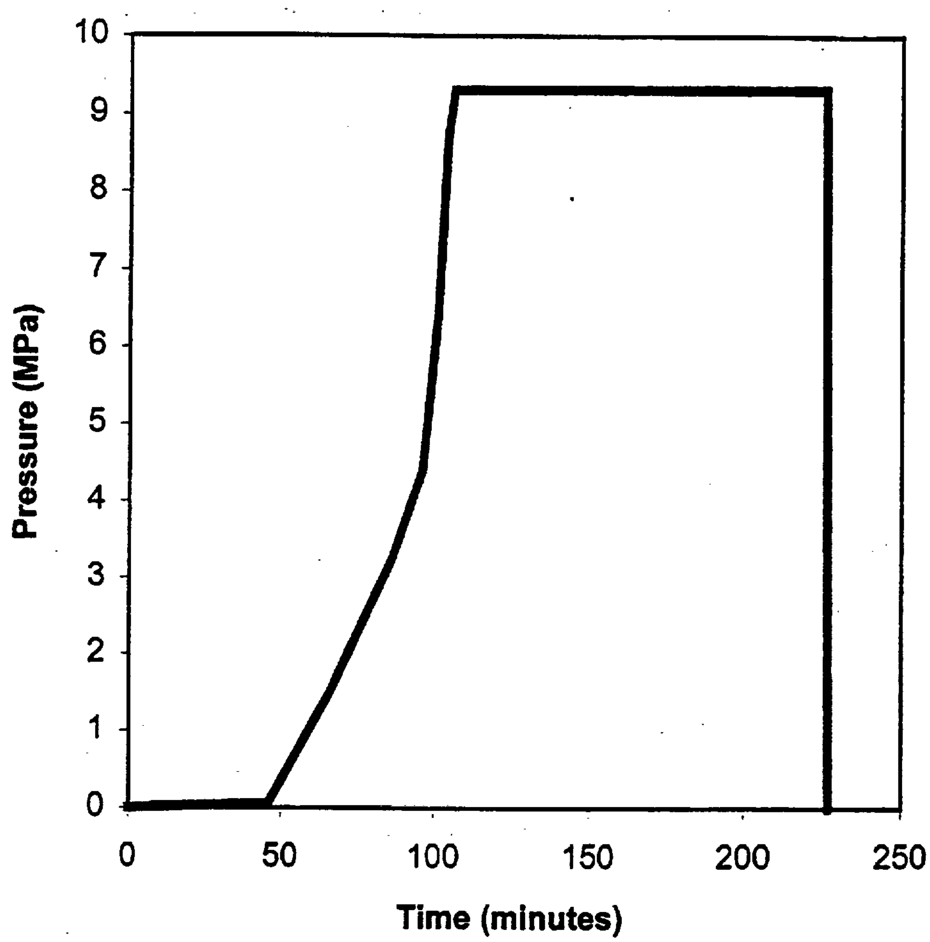


Figure 5 Cure Cycle, Oven Pressure vs. Time

not given a separate post cure before aging.

Specimens were cut from the plaques using a water-cooled micro-machining diamond saw, using the pattern shown in Figure 6. The specimens were cut to the dimensions specified for four-point bend testing in the ASTM Standard Test Method for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials (D 790M). Specimens measured approximately 54 mm by 10 mm by 2.5 mm. Each of the four plaques was given a letter, from A to D. Each specimen was then given a code, starting with the letter of the plaque, then the number of the specimen from that plaque. Specimens were then assigned to aging groups, as shown in Table 1. Groups were selected to minimize the effect of any slight differences in the four plaques used.

Specimens were aged in a Blue M oven at 316°C. Specimens aged in air were placed on a tray in the oven, while specimens aged in nitrogen were placed inside a nitrogen chamber inside the oven. Specimen groups were aged 24 hours, 48 hours, 96 hours, 168 hours, 240 hours, 336 hours, 465 hours, 633 hours, and 801 hours. One group was not aged.

Figure 7 gives a simple diagram of the aging oven with nitrogen chamber. Once the specimens were placed in the nitrogen chamber, the exhaust valve was closed and the inlet valve was opened, to pressurize the nitrogen chamber. The inlet valve was then closed and the system was checked for leaks by checking if the pressure inside the chamber was maintained. After the system was checked for leaks, the inlet and exhaust valves were fully opened. Nitrogen was allowed to flow through the system for several minutes to purge the chamber of air. After the initial purge, the exhaust valve was closed most of the way, so only a little

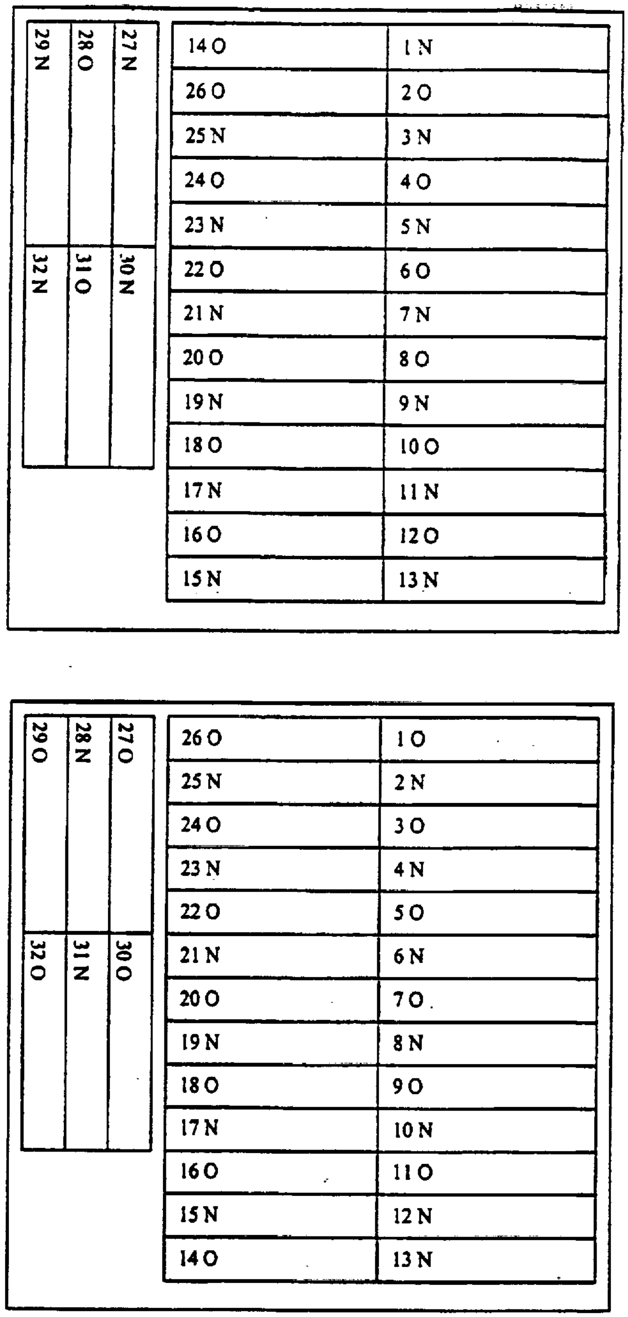


Figure 6 Specimen cutting pattern

The top illustration shows the pattern used for plaque D, while the lower illustration shows the pattern used for plaques A,B, and C.

Table 1 Specimen Group Assignments

Aging Duration (hours)	Nitrogen Specimens	Air Specimens
0 (control)	A1 A26 B20 C14 D8	A2 A25 B19 C13 D7
24	A6 B23 C17 C31 D11	A5 B24 C18 C30 D12
48	A8 B2 C19 D13 D27	A7 B1 C20 D16 D28
96	A10 A28 B4 C21 D15	A9 A27 B3 C22 D18
168	A12 B6 B25 C23 D17	A11 B5 B26 C24 D20
240	A13 B8 C2 C25 D19	A14 B7 C1 C26 D22
336	A15 B10 C4 D21 D30	A16 B9 C3 D24 D31
393	A17 A31 B12 C6 D23	A18 A30 B11 C5 D26
465	A19 B13 B28 C8 D1	A20 B14 B27 C7 D2
633	A21 B15 C10 C28 D3	A22 B16 C9 C27 D4
801	A23 B17 C12 D5 D25	A27 B18 C11 D6 D14

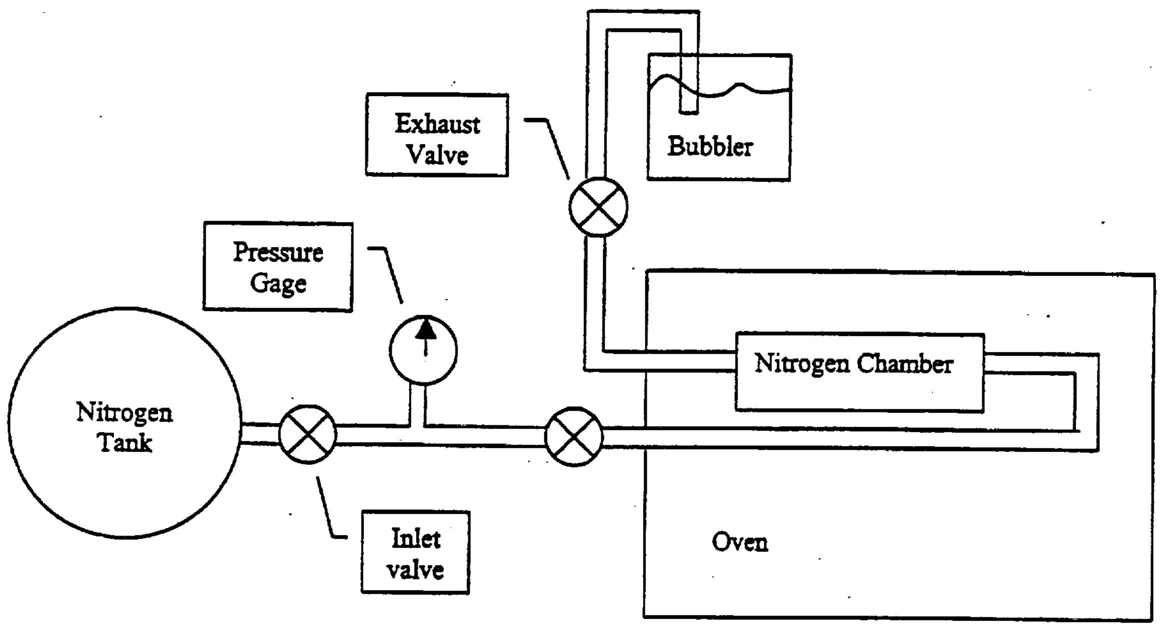


Figure 7 Oven Diagram

nitrogen flowed through the chamber. This was to prevent over-pressurization of the system as the temperature of the oven was raised to aging temperature, as well as to preserve nitrogen. Traditional procedure used in the lab for this type of experiment was to allow continuous flow of nitrogen. However, this was considered wasteful for this experiment. Once the oven reached temperature, the exhaust was opened and the system was again purged briefly. After the second purge, the exhaust valve was closed completely. A positive relative pressure of 69 kPa (10 psi) was maintained in the nitrogen chamber to ensure that if any minute leaks developed, nitrogen would flow out of the leak and air would not flow in. The oven was held at high temperature and the nitrogen chamber at pressure until it was time to remove specimens. Then the heat was shut off and the oven cooled down. Once the oven was cool enough to open, the nitrogen inlet and exhaust valves were closed and the chamber opened. Specimens were then removed, and new specimens were placed in the chamber and in the oven.

Because of the long durations of aging, the many durations being tested, and the limited amount of time in which to complete this project, aging groups could not be aged one at a time. Also, because of the small size of the nitrogen chamber, only four groups of specimens could be aged at once. Only 20 specimens could fit in the chamber at once and the aging groups consisted of five specimens. Since the oven and nitrogen chamber had to be cooled, opened, and then restarted every time specimens had to be removed or placed in the oven, an aging schedule was developed to minimize the number of times the oven had to be shut down. This schedule is shown in Figure 8. The numbers labeling the figure refer to aging durations. The oven only had to be shut down six times to complete the aging of the ten aging groups.

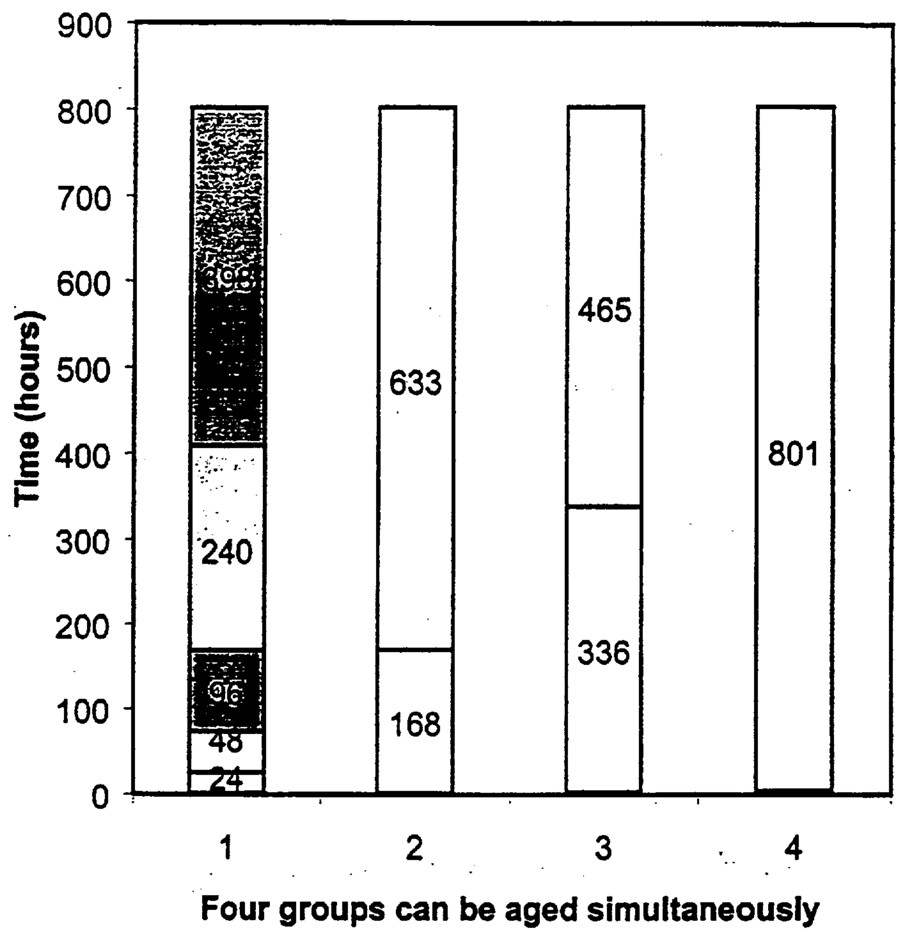


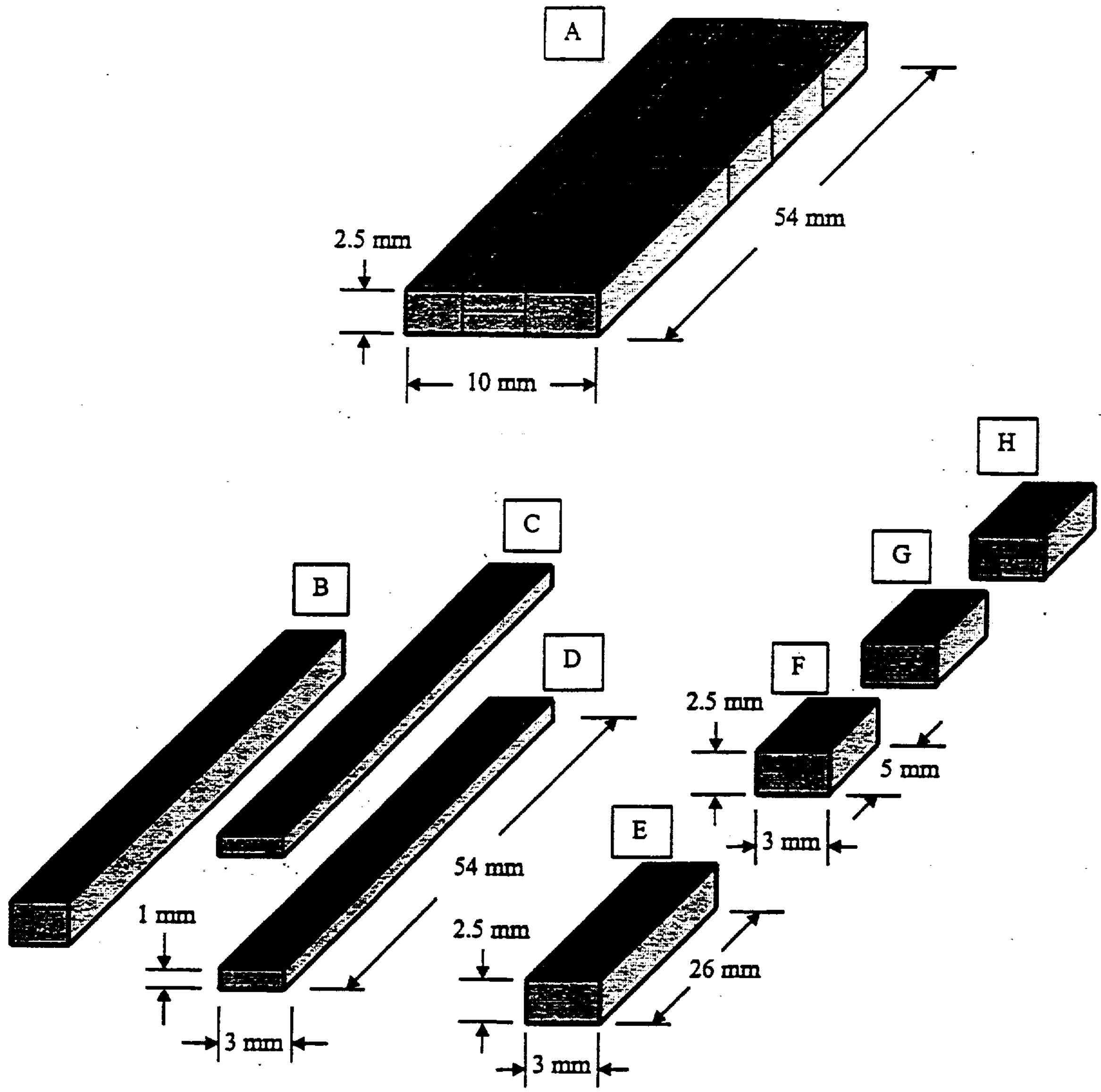
Figure 8 Aging Chart

Numbers labeling the bars indicate aging duration of specimens in that group.

It should be noted that there was no cracking observed in any of the aged specimens in this experiment. In previous experiments performed by Bowles, cracking was observed in PMR-15 resin specimens aged at 343°C after only 362 hours of aging, but not at all in specimens aged at 316°C [9].

After aging, dimensional measurements, and bend testing were completed, the specimens were further cut into smaller pieces for use in other tests. These pieces are illustrated in Figure 9. Long thin specimens approximately 53 mm x 3 mm x 1 mm were cut for use in bimaterial strip curvature tests. Specimens approximately 26 mm x 3 mm x 2.5 mm were cut for determining layer thickness. Specimens approximately 5 mm x 3 mm x 2.5 mm were cut for use in thermo-mechanical analysis.

Specimens were stored in sealed plastic bags inside a dessicator, and were dried before each measurement for at least 30 minutes in a 120°C oven. Specimens used for thermo-mechanical analysis were stored in sealed glass vials inside a dessicator and dried for two or more hours before testing.



A	Original 4-point bend test specimen (with cuts to be made illustrated)
B	Spare Material
C	Curve Test Specimen
D	Extra Curve Test Specimen
E	Surface Layer Thickness Specimen
F-H	Thermo-mechanical Test Specimens

Figure 9 Specimen cutting illustration

2.3 TESTS

2.3.1 Nitrogen Aged Specimen Shrinkage

Shrinkage of nitrogen aged specimens was determined from direct measurements at room temperature of the length of the bend test specimens before and after aging. Measurements were made using a traveling measuring microscope, which measured to 0.001 mm. The coordinates of each corner were recorded for both the top and bottom of each specimen. This produced four measurements of length for each specimen. The shrinkage could then be determined by comparing the length of each specimen before aging to the length after. Raw data for the measurement of length is included in Appendix A.

2.3.2 Bend Tests

An Instron 4505 load frame with a 4500 controller was used for the bend tests. The bend tests conformed to ASTM D 790M, with a few exceptions. Because of difficulties obtaining an accurate means of measuring center point deflection, load frame crosshead deflection was used instead. The necessary equations were modified to reflect this change. To compensate for slack and compliance of the load train, a test with a rigid bar in the fixture was performed to determine the compliance of the system. This was then used to correct the load vs. displacement data for the tested specimens.

Steel four point bend fixtures with ceramic cylinders for loading noses were used. The cylinders were attached to the fixtures with silicone RTV. The load span of the fixture was 40 mm and the support span was 20 mm, giving a load span to support span ratio of 0.5. The cylinders had a diameter of 4.75 mm, slightly smaller than the minimum of 6 mm specified in D790M. However, this fixture and cylinder combination was otherwise the most appropriate fixture available, so it was used. The loading nose size specification is to prevent excessive indentation or failure at the load points. Neither of these problems was witnessed as a result of the use of smaller cylinders.

Specimen width of 10 mm matched the specification of the ASTM D790M, and the length of 54 mm was appropriate for the support span of 40 mm. Five specimens per condition were tested, as specified. Specimens were kept in sealed plastic bags inside a dessicator and were dried before testing in order to properly condition the material. The load rate of 1.07 mm/min was as specified. Specimens were not tested to failure.

Raw results of load vs. displacement were consistently linear, as illustrated by Figure 10. Bend test data, including slope of load vs. displacement for all tests, as well as width and thickness data, is included in Appendix B.

2.3.3 Thermo-mechanical Analysis

Thermo-mechanical analysis was used to determine the CTE of nitrogen aged specimens. A TA Instruments model 2940 was used to measure the expansion of the small specimens as temperature was increased. Tests were performed in static air. Temperature was increased at 10°C per minute, with the specimens under a weighted expansion probe. The probe was weighted with a 5g weight, applying a force of 0.05 N to the sample. CTE was determined from the slope of expansion versus temperature, over the range of temperature from room temperature to 316°C. A sample plot, shown in Figure 11, illustrates that between room temperature and 316 C, expansion versus temperature is nearly linear. This was true for all specimens tested. A complete set of CTE data is included in Appendix C.

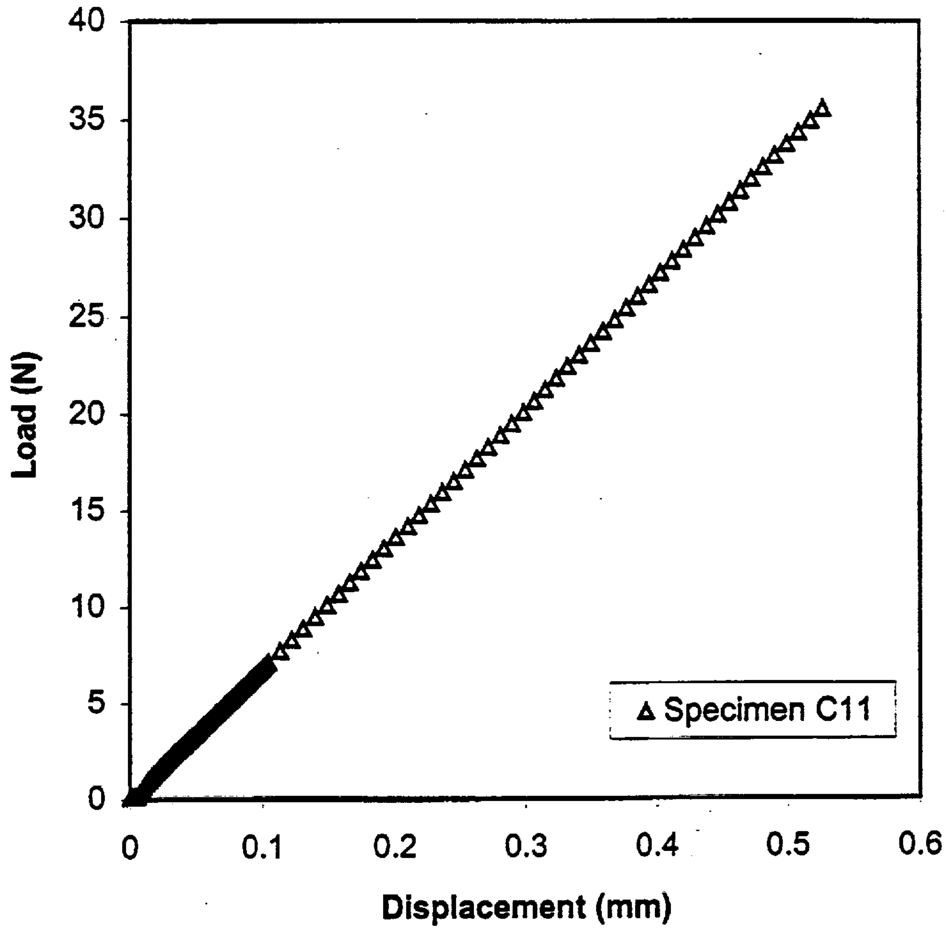


Figure 10 Example Load vs. Displacement plot, uncorrected data.

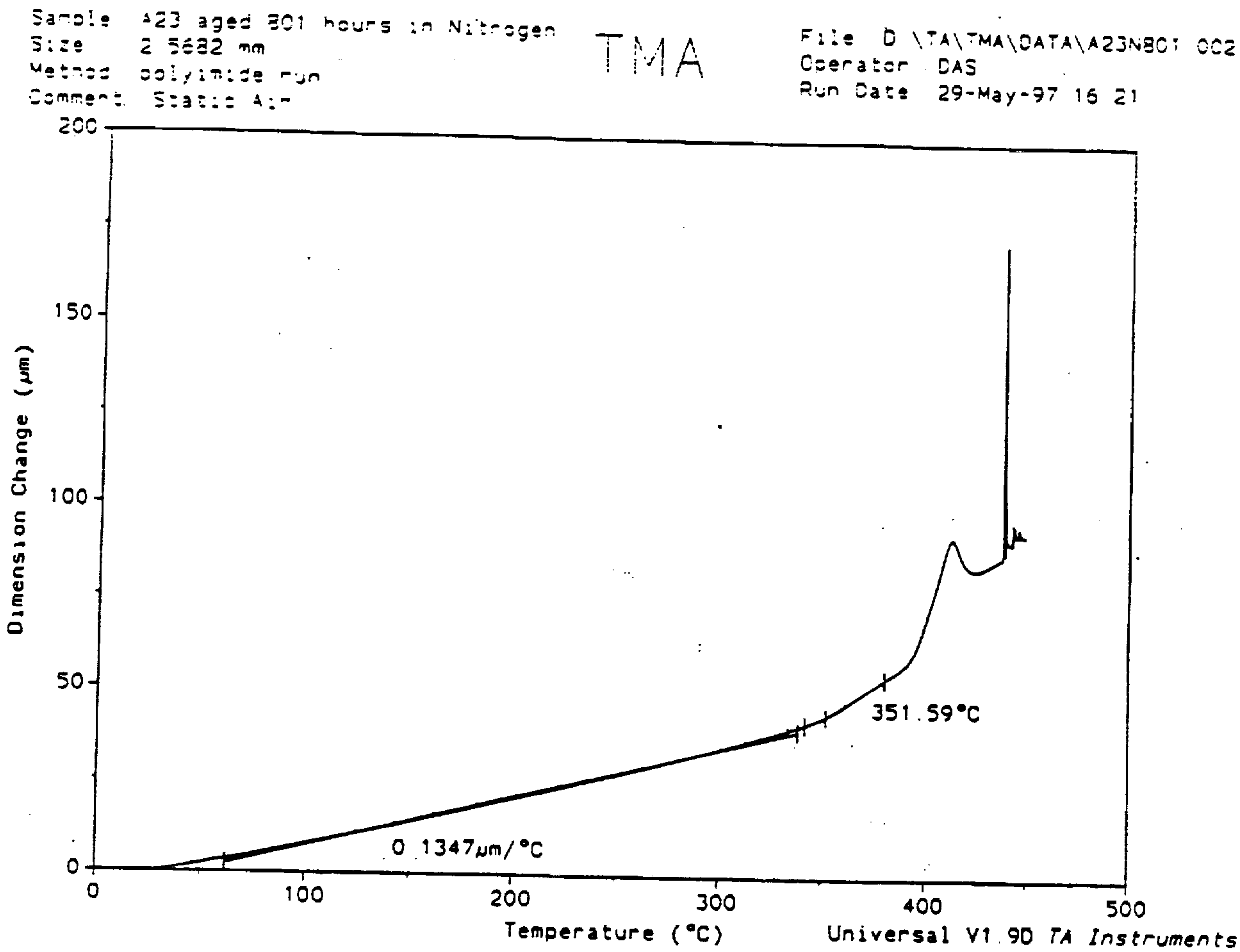


Figure 11 Example CTE plot.

2.3.4 Surface Layer Thickness

Surface layer thickness specimens were mounted in epoxy and the cross section of each specimen was polished, to enable viewing of the surface layer with microscopy. Photomicrographs were then taken of the specimen cross sections. The thickness of the surface layer was then determined from measurements taken from the photomicrographs. This method of examination was known to produce measurable results due to the experience of Bowles, using similar material and aging conditions[10]. Surface thickness data is shown in Appendix D.

2.3.5 Curvature Tests

Specimen curvature at room temperature was determined by measuring the location of three points on the edge of the curvature specimens, using a travelling measuring microscope that measured to 0.001mm. Measurements were taken on both sides of each specimen.

To make measurements at elevated temperatures, specimens were placed in the oven of the Instron 4505 test machine. Measurements of curvature were made using a cathetometer that looked through the oven window at the specimens. The cathetometer was manufactured by Gaertner Scientific corporation, and was equipped with a Gaertner Gold Tracer digital readout. Specimens were placed on small stands in the oven, and measurements were taken of the height and span of the arc, as shown in Figure 1. The measurements were made at temperatures between room temperature and the aging temperature of 316°C. Oven temperature was controlled by the oven's thermocouple, located near the back of the oven, but the temperature used for calculations was measured with a separate thermocouple placed near the specimens at the front of the oven. Raw data for both room temperature and elevated temperature curvature measurements is included in appendix E.

CHAPTER 3: ANALYSIS

3.1 ASSUMPTIONS

The following analysis rests on a few basic assumptions, which were described in section 1.3. First, the surface layer has uniform properties throughout the layer [11]. Second, the unoxidized material is also uniform. Third, the nitrogen aged specimens and the apparently unoxidized core material in the air aged specimens have the same properties. Fourth, the moduli of the surface and interior layers have the same temperature dependence. Lastly, it is assumed that viscoelastic relaxation is negligible.

3.2 NITROGEN AGED SPECIMEN SHRINKAGE

The shrinkage of a nitrogen-aged specimen, which represents the shrinkage of unoxidized aged resin, is simply as follows:

$$\varepsilon_{sc} = \frac{(l_{aged} - l_0)}{l_0} - (\alpha_{c(aged)} - \alpha_{c(0)})\Delta T \tag{1}$$

where ε_{sc} is the shrinkage strain of the unoxidized material, l_{aged} is the aged length, and l_0 is the unaged length. The second term compensates for the small difference between the aged and unaged core material CTEs, $\alpha_{c(aged)}$ and $\alpha_{c(0)}$. ΔT is the difference between the aging temperature and the temperature at which the lengths were measured.

3.3 BEND TESTS

Modulus of nitrogen aged specimens, E_C, was calculated according to ASTM D 790M:

$$E_c = \frac{0.17L^3 m}{wt^3} \tag{2}$$

Where L is the support span, w is the specimen width, t is the specimen thickness, and m is the slope of the tangent to the initial straight-line portion of the load-deflection curve. For the specimens tested, the load-deflection curves were very linear.

Modulus of the oxidized surface layer, E_s ,was determined by using composite beam theory:

$$E_s = \frac{1}{I_s}\left(\frac{L^3 m}{96} - E_c I_c\right) \tag{3}$$

where L is the support span, m is the slope of the tangent to the initial straight line portion of the load deflection curve, and:

$$I_c = \frac{(w-2t_s)(t-2t_s)^3}{12} \tag{4}$$

$$I_s = \frac{wt^3}{12} - I_c \tag{5}$$

where t is the total thickness, and t_s is the thickness of the surface layer.

3.4 THERMO-MECHANICAL ANALYSIS OF NITROGEN SPECIMENS

CTE of the unoxidized core material was determined from thermo-mechanical analysis of nitrogen aged specimens. The TMA testing machine determined the slope of dimensional change vs. temperature. From there calculating the CTE was simply

$$\alpha_c = \frac{m_{CTE}}{t} \tag{6}$$

where α_c is the coefficient of thermal expansion and m_{CTE} is the slope of the dimension change versus temperature.

3.5 SURFACE LAYER THICKNESS

Surface layer thickness was determined by optical microscope measurement of prepared cross sections. Calculations were only to convert scale.

3.6 CURVATURE TESTS

The curvature tests are based on a model of a bimaterial beam, as illustrated in Figure 1. Since the beam is unrestrained, the moment balance is of the form

$$M = 0 = \int \sigma z dz \tag{7}$$

where the stress includes a thermal expansion term and a shrinkage term

$$\sigma = E(\varepsilon - \alpha \Delta T - \varepsilon_s) \tag{8}$$

Using Bernoulli-Euler beam theory, the strain term can be expressed as

$$\varepsilon = kz + \varepsilon_0 \tag{9}$$

where k is the curvature and ε_0 is the strain at the neutral axis. Thus stress can be expressed as

$$\sigma = E(kz + \varepsilon_0 - \alpha \Delta T - \varepsilon_s) \tag{10}$$

and the moment is then of the form

$$M = \int E(kz + \varepsilon_0 - \alpha \Delta T - \varepsilon_s) z dz \tag{11}$$

It would be desirable to transfer coordinates to the neutral axis before integrating. The location of the neutral axis, as shown in Figure 12 is

$$z^* = \frac{E_s\left(t_c + \frac{t_s}{2}\right)t_s + E_c\left(\frac{t_c}{2}\right)t_c}{E_s t_s + E_c t_c} \tag{12}$$

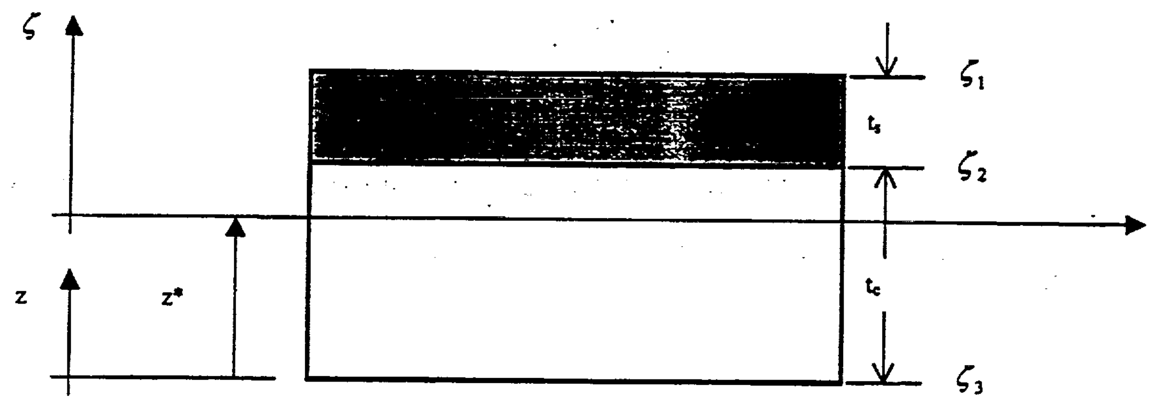


Figure 12 Neutral axis and coordinate system

where t_s is the thickness of the surface layer and t_c is the thickness of the unoxidized core material. Establishing the new coordinate system we have

$$\begin{aligned} \zeta_1 &= t_s + t_c - z^* \\ \zeta_2 &= t_c - z^* \\ \zeta_3 &= -z^* \end{aligned} \tag{13}$$

Thus the moment balance equation becomes

$$M = 0 = \int_{\zeta_2}^{\zeta_1} E_s(k\zeta + \varepsilon_0 - \alpha_s \Delta T - \varepsilon_{ss})\zeta d\zeta + \int_{\zeta_3}^{\zeta_2} E_c(k\zeta + \varepsilon_0 - \alpha_c \Delta T - \varepsilon_{sc})\zeta d\zeta \tag{14}$$

Where α_s and α_c are the surface layer and core CTEs respectively, and ε_{ss} and ε_{sc} are the surface layer and core shrinkage strains.

Curvature k can be determined from measurements as

$$k = \frac{8h}{s^2} \tag{15}$$

Where h is the height of the arc and s is the span. Plotting values of k versus temperature and fitting a line to the data produces a graph like Figure 13, where k' is the slope of k versus T and k'' is the curvature at the cure temperature of 316°C, where ΔT is zero. Thus k can be expressed as

$$k = k'\Delta T + k'' \tag{16}$$

Integrating and simplifying the moment balance equation leads to

$$M = 0 = \tfrac{1}{3}aE_s k + \tfrac{1}{3}bE_c k - \tfrac{1}{2}cE_s\varepsilon_{ss} - \tfrac{1}{2}dE_c\varepsilon_{sc} - \left[\tfrac{1}{2}cE_s\alpha_s + \tfrac{1}{2}dE_c\alpha_c\right]\Delta T \tag{17}$$

where

$$\begin{aligned} a &= \zeta_1^3 - \zeta_2^3 \\ b &= \zeta_2^3 - \zeta_3^3 \\ c &= \zeta_1^2 - \zeta_2^2 \\ d &= \zeta_2^2 - \zeta_3^2 \end{aligned} \tag{18}$$

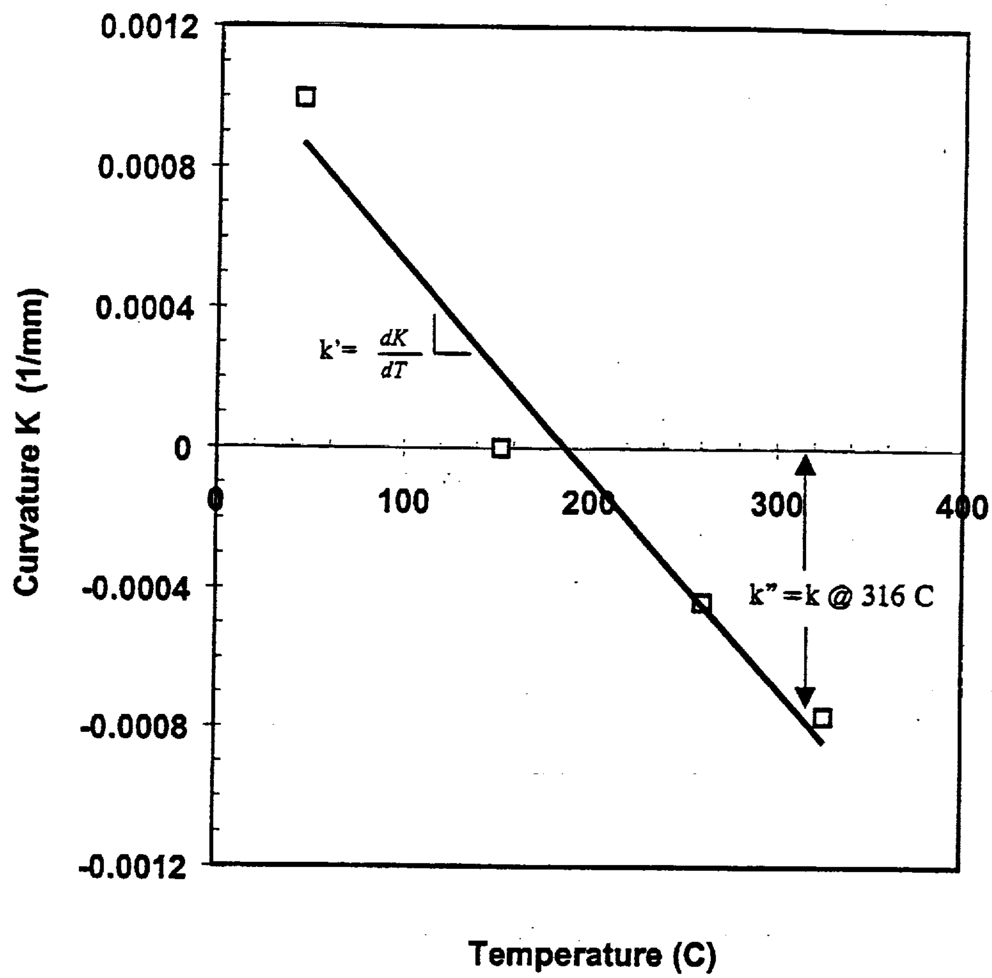


Figure 13 Sample graph of curvature vs. temperature, showing k' and k".

Squares represent actual data points, while the line is a least squares best fit to the data.

and, as a consequence of the choice of axis,

$$cE_s = -dE_c \tag{19}$$

For $\Delta T=0$, which occurs at the cure temperature, we can find

$$M = 0 = \tfrac{1}{3}aE_s k'' + \tfrac{1}{3}bE_c k'' - \tfrac{1}{2}cE_s\varepsilon_{ss} - \tfrac{1}{2}dE_c\varepsilon_{sc} \tag{20}$$

Solving for surface layer shrinkage,

$$\varepsilon_{ss} = \frac{\tfrac{2}{3}aE_s k'' + \tfrac{2}{3}bE_c k''}{cE_s} + \varepsilon_{sc} \tag{21}$$

Now for arbitrary ΔT it is possible to determine the coefficient of thermal expansion of the surface layer material. Inserting equation (19) into equation (17) and solving leads to

$$\alpha_s = \frac{\tfrac{2}{3}aE_s k + \tfrac{2}{3}bE_c k}{cE_s\Delta T} - \frac{\varepsilon_{ss}}{\Delta T} + \frac{\varepsilon_{sc}}{\Delta T} + \alpha_c \tag{22}$$

It is convenient to present shrinkage strain ε_s as a percent shrinkage P_s. This can be calculated simply from:

$$P_s = -100\varepsilon_s \tag{23}$$

CHAPTER 4: RESULTS AND DISCUSSION

4.1 FORMAT FOR PLOTTING

Data for each specimen was reduced individually. Results from replicate specimens (typically five per condition but occasionally as few as three) were then averaged, and the standard deviation were calculated. Symbols in the following plots indicate the mean, and error bars represent plus-minus one standard deviation.

4.2 SURFACE LAYER THICKNESS

Surface layer thickness is shown in Figure 14. Surface layer thickness increases with aging duration, but the rate of growth decreases. The curve very closely resembles similar measurements made by Bowles [10].

4.3 MODULUS

The results of the bend tests are shown in Figure 15. The measured value of the stiffness for the nitrogen aged specimens remained rather constant regardless of aging duration. The calculated value for the stiffness of the oxidized surface layer indicates a significant increase in the modulus over that of unoxidized material. However, the modulus of oxidized material also remains rather constant with aging duration.

4.4 SURFACE LAYER SHRINKAGE

Shrinkage of nitrogen aged specimens and calculations of the shrinkage of the oxidized surface layer are shown in Figure 16. Values for strain were derived using equations (1) and

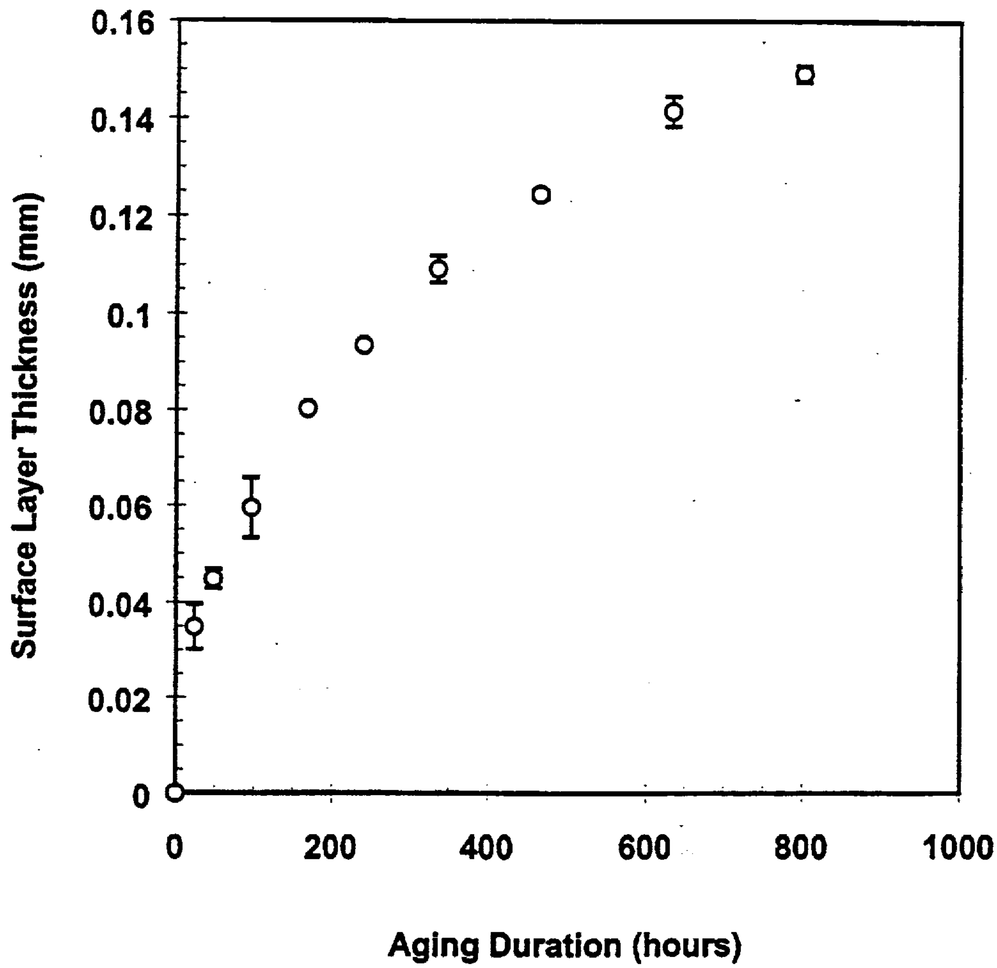


Figure 14 Oxidized surface layer thickness vs. aging duration

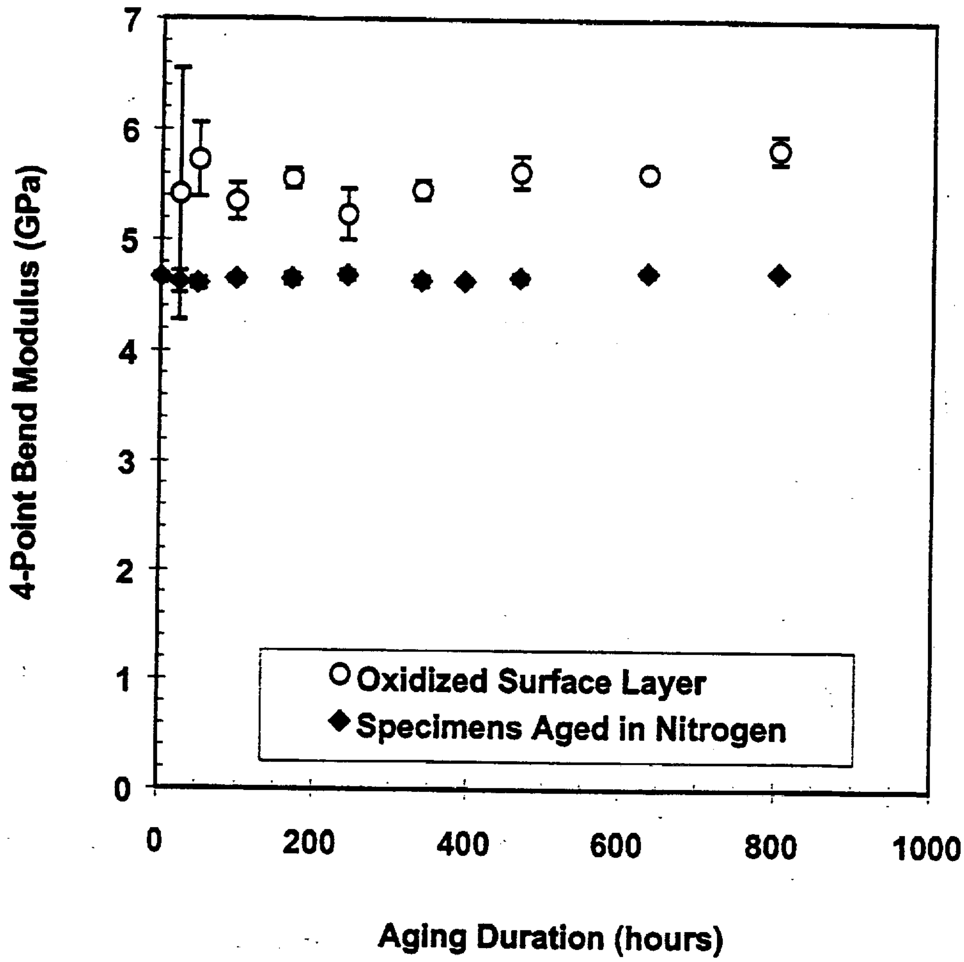


Figure 15 Bend modulus vs. aging duration

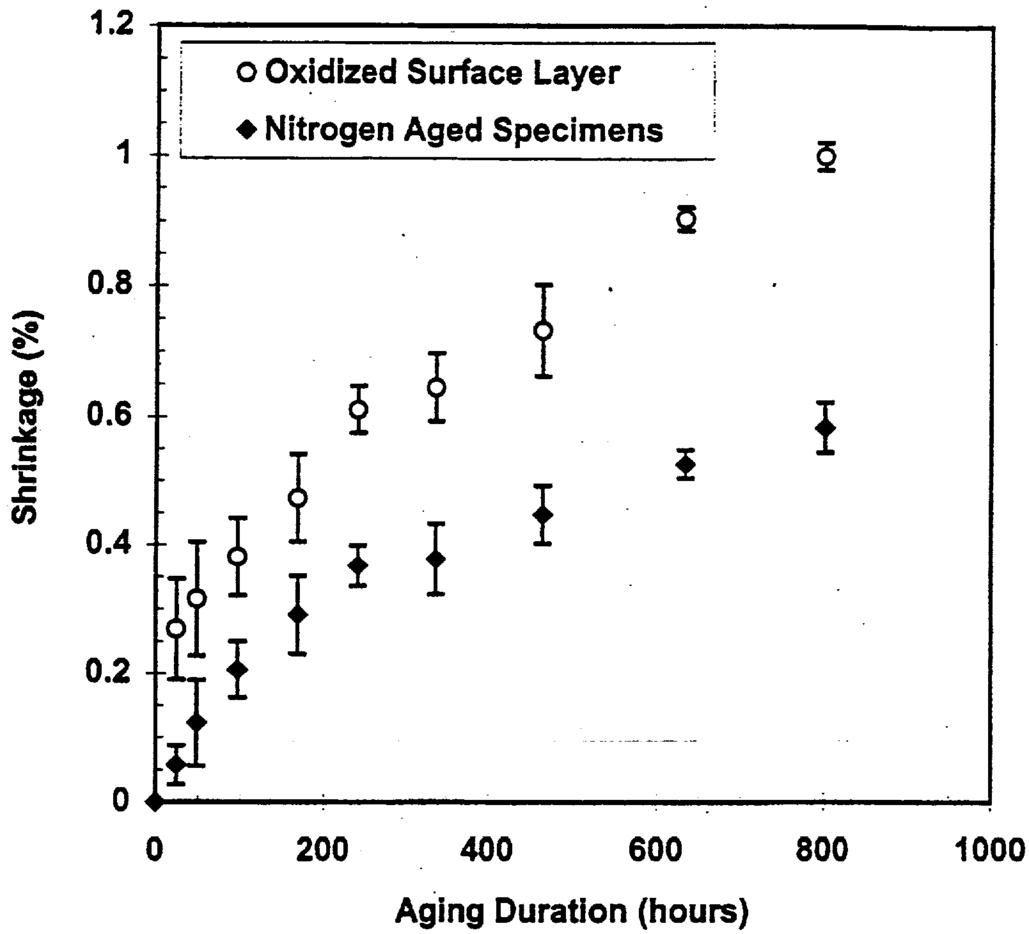


Figure 16 Shrinkage vs. aging duration

(21), then converted to percent shrinkage for plotting using equation (23). As shown in the figure, shrinkage generally increases as aging duration increases. The unoxidized nitrogen aged specimen shrinkage appears to approach a limit as aging duration increases. The oxidized surface layer shrinkage is significantly greater than that of the inner unoxidized material. Oxidized surface layer shrinkage does not appear to have a similar limiting behavior.

4.5 COEFFICIENT OF THERMAL EXPANSION

Thermo-mechanical testing was used to determine CTE of nitrogen aged specimens. The CTE of the oxidized surface layer was derived from curve test results as was shown in equation (22). A plot of CTE vs. aging duration is shown in Figure 17 for nitrogen aged specimens and for the calculated value of the oxidized surface layer. The data indicates that the CTE of material aged in nitrogen stays virtually unchanged, perhaps decreasing slightly as time increases. The calculated CTE of the oxidized surface layer decreases more markedly, and continues to decrease the longer the material is aged.

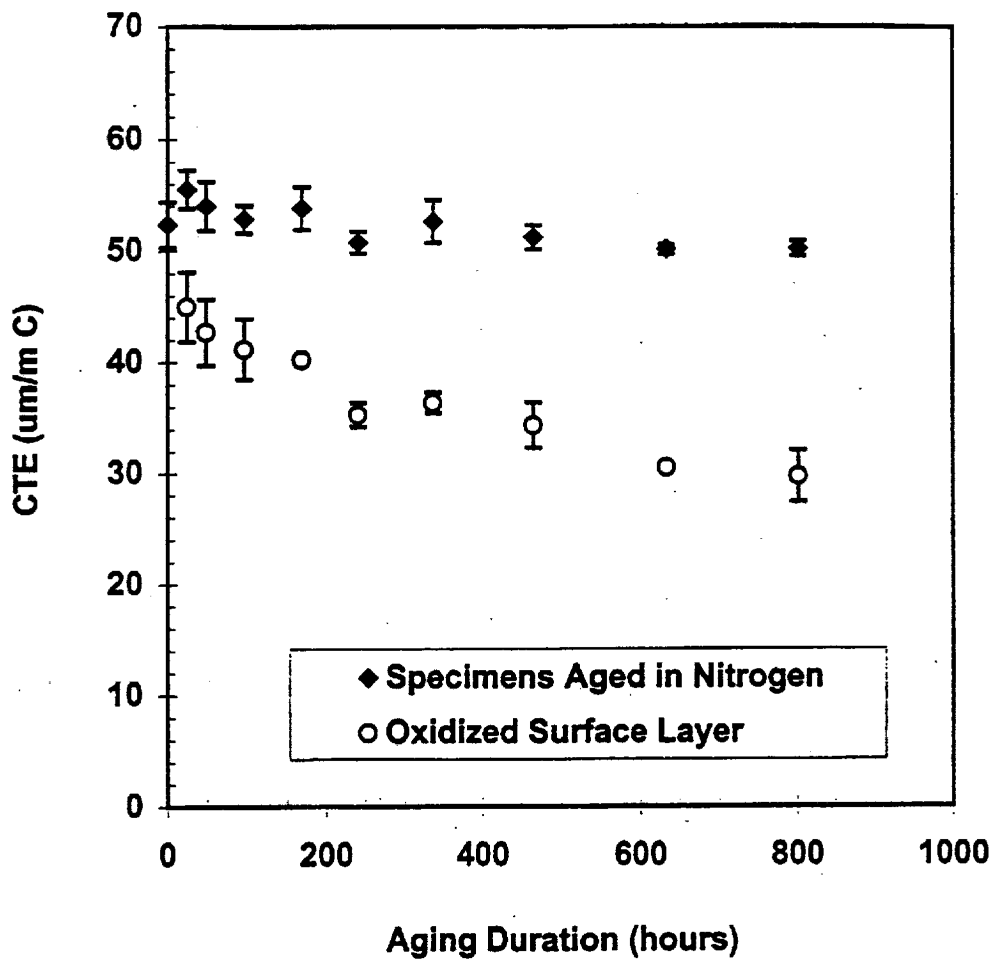


Figure 17 CTE vs. aging duration

Oxidized surface layer calculation at 168 hour duration based on data from only two samples.

CHAPTER 5: CONCLUSION

The results shown in Chapter 4 are consistent with prior qualitative observations, and provide needed quantitative measures. The results show that the core and surface layer material are notably different. This difference explains some of the complex observed behavior of thermo-oxidatively aged specimens. For example, it was observed that curvature specimens at room temperature curved towards the interior material, when it was initially assumed that the specimens would curve toward the shrunken surface layer. Curvature specimens at the aging temperature curve toward the surface layer. Changes in CTE revealed by this work explain this behavior.

The increased stiffness and shrinkage seen in the surface layer also helps to explain surface cracking observed in other investigations in air-aged specimens [3,10]. At elevated temperatures the shrinkage of the surface is restrained by the unoxidized core, resulting in tensile stresses in the surface layer. These stresses are only enhanced by the material's increased modulus. The low CTE of the surface layer compared to the core produces interesting results at lower temperatures. At room temperature, stress in the surface layer is compressive. Thus surface cracking is likely to only show up under high temperature service. Low temperature excursions, which can cause cracking in epoxy composites [11], and which can be used to accelerate damage in some materials [12], will not necessarily produce surface cracking in aged resin samples.

This set of experiments, utilizing a new curved specimen test method, successfully allowed determination of the separate material properties of the surface layer and the inner material of non-uniformly degraded PMR-15 resin. These results are valuable for greater qualitative understanding of aged material behavior, including such phenomenon as surface crazing. The data can also be used to help complete current models of thermo-oxidative degradation. Ultimately, it should prove useful in the design of composite parts subject to high temperature aging.

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APPENDIX A: LENGTH MEASUREMENT DATA

Initial Length			Corner 1		Corner 2		Corner 3		Corner 4		Length	Length
Unaged	Spec #	Side	x	y	x	y	x	y	x	y	(1 to 4)	(2 to 3)
24 hour	A6	1	0	0	0.034	10.012	53.959	9.884	53.924	-0.115	53.924	53.925
specimens		2	0	0	-0.002	10.074	53.989	10.021	53.95	-0.083	53.950	53.991
	B23	1	0	0	0.004	9.998	53.963	9.853	53.952	-0.188	53.952	53.959
		2	0	0	0.042	10.069	54.051	9.963	54.021	-0.125	54.021	54.009
	C17	1	0	0	0	10.005	53.963	9.964	53.962	-0.077	53.962	53.963
		2	0	0	0.061	10.08	54.078	9.835	54.018	-0.255	54.019	54.018
	C31	1	0	0	0.022	10.027	53.982	9.887	53.965	-0.099	53.965	53.960
		2	0	0	0.04	10.076	54.046	9.937	54.015	-0.126	54.015	54.006
	D11	1	0	0	-0.007	10.008	53.922	9.866	53.931	-0.142	53.931	53.929
		2	0	0	-1.942	9.214	52.044	9.086	51.986	-0.959	51.995	53.986
48 hour	A8	1	0	0	0.037	10.018	53.963	9.871	53.925	-0.135	53.925	53.926
specimens		2	0	0	0.021	10.081	54.011	9.94	54.038	-0.182	54.038	53.990
	B2	1	0	0	0.009	10.02	53.937	9.88	53.934	-0.106	53.934	53.928
		2	0	0	0.036	10.071	54.03	9.859	53.996	-0.123	53.996	53.994
	C19	1	0	0	0.013	10.002	53.977	9.862	53.964	-0.174	53.964	53.964
		2	0	0	0.037	10.065	54.047	9.938	54.01	-0.145	54.010	54.010
	D13	1	0	0	-0.005	10.013	53.921	10.135	53.921	0.162	53.921	53.926
		2	0	0	-0.009	10.129	53.978	9.977	53.979	-0.034	53.979	53.987
	D27	1	0	0	0.013	10.022	53.937	10	53.928	-0.035	53.928	53.924
		2	0	0	0.012	10.069	53.98	9.98	53.961	-0.11	53.961	53.968
96 hour	A10	1	0	0	0.028	10.016	53.959	9.94	53.931	-0.07	53.931	53.931
specimens		2	0	0	0.008	10.087	53.995	9.97	53.98	-0.158	53.980	53.987
	A28	1	0	0	-0.081	10.03	53.859	10.185	53.941	0.174	53.941	53.940
		2	0	0	0.069	10.085	54.035	9.994	53.972	-0.105	53.972	53.966
	B4	1	0	0	0.023	10.029	53.95	9.816	53.925	-0.181	53.925	53.927
		2	0	0	0.05	10.075	54.024	9.921	53.989	-0.124	53.989	53.974
	C21	1	0	0	0.038	9.995	53.998	9.707	53.951	-0.328	53.952	53.961
		2	0	0	0.074	10.07	54.07	9.763	53.997	-0.326	53.998	53.997
	D15	1	0	0	0	10.027	53.95	9.944	53.938	-0.058	53.938	53.950
		2	0	0	0.03	10.082	54.021	9.983	53.995	-0.097	53.995	53.991
168 hour	A12	1	0	0	0.05	10.039	53.984	9.828	53.935	-0.169	53.935	53.934
specimens		2	0	0	-0.004	10.092	53.986	9.958	53.985	-0.098	53.985	53.990
	B6	1	0	0	0.002	10.023	53.933	9.944	53.932	-0.054	53.932	53.931
		2	0	0	0.039	10.075	54.017	9.908	53.987	-0.131	53.987	53.978
	B25	1	0	0	-0.04	10.003	53.923	10.123	53.973	0.092	53.973	53.963
		2	0	0	0.072	10.073	54.097	9.778	54.017	-0.303	54.018	54.026
	C23	1	0	0	0.009	9.99	53.984	9.983	53.966	-0.141	53.966	53.975
		2	0	0	0.028	10.66	54.052	9.987	54.031	-0.087	54.031	54.028
	D17	1	0	0	0.018	10.032	53.974	9.846	53.955	-0.166	53.955	53.956
		2	0	0	-0.015	10.074	54	10.214	54.001	0.134	54.001	54.015
240 hour	A13	1	0	0	0.045	10.005	53.976	9.933	53.935	-0.051	53.935	53.931
specimens		2	0	0	-0.009	10.124	53.974	9.968	53.982	-0.06	53.982	53.983
	B8	1	0	0	0.018	10.021	53.941	9.879	53.932	-0.126	53.932	53.923
		2	0	0	0.037	10.082	54.029	9.892	53.987	-0.149	53.987	53.992
	C2	1	0	0	0.011	10.027	53.598	9.89	53.587	-0.108	53.587	53.587
		2	0	0	0.027	10.077	53.653	9.934	53.628	-0.098	53.628	53.626
	C25	1	0	0	0.01	9.998	53.974	9.865	53.96	-0.174	53.960	53.964
		2	0		0.04	10.103	54.059	9.892	54.018	-0.173	54.018	54.019
	D19	1	0	0	0.005	10.038	53.954	9.927	53.955	-0.076	53.955	53.949
		2	0	0	0.023	10.08	54.03	10.035	54.006	-0.038	54.006	54.007

Initial Length			Corner 1		Corner 2		Corner 3		Corner 4		Length	Length
Unaged	Spec #	Side	x	y	x	y	x	y	x	y	(1 to 4)	(2 to 3)
336 hour	A15	1	0	0	0.058	9.994	54.028	9.678	53.96	-0.351	53.961	53.971
specimens		2	0	0	0.05	10.082	54.058	9.773	54.009	-0.315	54.010	54.009
	B10	1	0	0	0.044	10.025	53.977	9.676	53.927	-0.319	53.928	53.934
		2	0	0	0.065	10.088	54.056	9.761	53.991	-0.29	53.992	53.992
	C4	1	0	0	0.004	10.021	53.599	9.931	53.596	-0.066	53.596	53.595
		2	0	0	0.029	10.067	53.665	9.939	53.638	-0.118	53.638	53.636
	D21	1	0	0	0.01	10.3	53.964	9.861	53.951	-0.131	53.951	53.956
		2	0	0	0.011	10.072	54.023	10.047	54.005	-0.025	54.005	54.012
	D30	1	0	0	0.006	9.985	53.955	9.992	53.949	-0.042	53.949	53.949
		2	0	0	0.04	10.072	54.041	9.822	53.986	-0.26	53.987	54.002
465 hour	A19	1	0	0	0.031	9.995	53.982	9.858	53.946	-0.165	53.946	53.951
specimens		2	0	0	0.024	10.093	54.022	9.912	54.002	-0.17	54.002	53.998
	B13	1	0	0	-0.008	10.039	53.921	9.859	53.927	-0.127	53.927	53.929
		2	0	0	0.082	10.141	54.056	9.9	53.982	-0.138	53.982	53.975
	B28	1	0	0	0.021	10.034	53.952	9.879	53.926	-0.142	53.926	53.931
		2	0	0	0.042	10.102	54.016	9.949	53.989	-0.141	53.989	53.974
	C8	1	0	0	0.021	10.019	53.606	9.828	53.582	-0.175	53.582	53.585
		2	0	0	0.034	10.076	53.67	9.909	53.629	-0.144	53.629	53.636
	D1	1	0	0	-0.002	10.014	53.917	9.848	53.919	-0.137	53.919	53.919
		2	0	0	0.053	10.077	54.02	9.911	53.959	-0.145	53.959	53.967
633 hour	A21	1	0	0	0.041	10.003	53.987	9.801	53.939	-0.238	53.940	53.946
specimens		2	0	0	0.041	10.083	54.035	9.831	53.999	-0.262	54.000	53.995
	B15	1	0	0	-0.006	9.956	53.944	9.892	53.958	-0.191	53.958	53.950
		2	0	0	0.072	10.053	54.061	9.897	53.996	-0.259	53.997	53.989
	C10	1	0	0	0.014	10.023	53.594	9.884	53.573	-0.129	53.573	53.580
		2	0	0	0.04	10.086	53.667	9.905	53.631	-0.159	53.631	53.627
	C28	1	0	0	0.02	10.026	53.946	9.865	53.924	-0.143	53.924	53.926
		2	0	0	0.052	10.087	54.019	9.836	53.976	-0.239	53.977	53.968
	D3	1	0	0	0.031	10.028	53.941	9.71	53.911	-0.28	53.912	53.911
		2	0	0	0.075	10.074	54.044	9.777	53.974	-0.269	53.975	53.970
801 hour	A23	1	0	0	0.049	10.013	54	9.78	53.949	-0.255	53.950	53.952
specimens		2	0	0	0.023	10.096	54.023	9.948	54.003	-0.144	54.003	54.000
	B17	1	0	0	0.003	9.999	53.96	9.899	53.962	-0.142	53.962	53.957
		2	0	0	0.021	10.078	54.046	10.059	54.024	-0.018	54.024	54.025
	C12	1	0	0	0.031	10.013	53.619	9.813	53.588	-0.182	53.588	53.588
		2	0	0	0.031	10.091	53.664	9.966	53.637	-0.1	53.637	53.633
	D5	1	0	0	0.038	10.02	53.955	9.65	53.919	-0.346	53.920	53.918
		2	0	0	0.093	10.07	54.063	9.713	53.972	-0.34	53.973	53.971
	D25	1	0	0	-0.05	10.033	53.905	10.153	53.947	0.164	53.947	53.955
		2	0	0	0.032	10.086	54.04	9.993	54.004	-0.078	54.004	54.008

Length after aging in Nitrogen	Spec #	side	Corner 1 x	Corner 1 y	Corner 2 x	Corner 2 y	Corner 3 x	Corner 3 y	Corner 4 x	Corner 4 y	Length (1 to 4)	Length (2 to 3)
24 hour	A6	1	0	0	0.032	9.998	53.893	9.872	53.86	-0.112	53.860	53.861
specimens		2	0	0	0.018	10.057	53.96	9.917	53.912	-0.157	53.912	53.942
	B23	1	0	0	0.005	9.983	53.906	9.851	53.902	-0.179	53.902	53.901
		2	0	0	0.047	10.051	53.981	9.954	53.952	-0.111	53.952	53.934
	C17	1	0	0	0.01	9.988	53.897	9.878	53.883	-0.143	53.883	53.887
		2	0	0	0.052	10.063	53.969	9.931	53.937	-0.14	53.937	53.917
	C31	1	0	0	0.021	10.021	53.896	9.881	53.875	-0.099	53.875	53.875
		2	0	0	0.049	10.068	53.962	9.813	53.916	-0.234	53.917	53.914
	D11	1	0	0	0.016	9.997	53.867	9.73	53.848	-0.266	53.849	53.852
		2			-1.952	9.205	51.946	9.089	51.892	-0.969		53.898
48 hour	A8	1	0	0	0.04	9.999	53.8	9.862	53.845	-0.119	53.845	53.760
specimens		2	0	0	0.013	10.064	53.94	9.949	53.947	-0.154	53.947	53.927
	B2	1	0	0	0.01	10.004	53.875	9.855	53.861	-0.12	53.861	53.865
		2	0	0	0.036	10.051	53.941	9.92	53.903	-0.119	53.903	53.905
	C19	1	0	0	0.012	9.973	53.879	9.869	53.877	-0.147	53.877	53.867
		2	0	0	0.035	10.045	53.951	9.913	53.914	-0.145	53.914	53.916
	D13	1	0	0	0.031	10.001	53.862	9.902	53.825	-0.067	53.825	53.831
		2	0	0	0.003	10.102	53.879	9.964	53.883	-0.045	53.883	53.876
	D27	1	0	0	0.017	10.01	53.871	9.924	53.852	-0.084	53.852	53.854
		2	0	0	0.018	10.053	53.898	9.946	53.876	-0.127	53.876	53.880
96 hour	A10	1	0	0	0.039	9.99	53.847	9.824	53.808	-0.153	53.808	53.808
specimens		2	0	0	-0.003	10.059	53.863	10.009	53.874	-0.084	53.874	53.866
	A28	1	0	0	-0.027	10.004	53.782	9.857	53.809	-0.135	53.809	53.809
		2	0	0	0.087	10.064	53.926	9.885	53.848	-0.187	53.848	53.839
	B4	1	0	0	0.031	10.006	53.855	9.755	53.823	-0.225	53.823	53.825
		2	0	0	0.051	10.05	53.915	9.84	53.871	-0.177	53.871	53.864
	C21	1	0	0	0.024	9.973	53.865	9.802	53.84	-0.215	53.840	53.841
		2	0	0	0.034	10.043	53.909	9.908	53.872	-0.144	53.872	53.875
	D15	1	0	0	0.017	10.015	53.84	9.817	53.812	-0.174	53.812	53.823
		2	0	0	0.051	10.063	53.909	9.891	53.871	-0.168	53.871	53.858
168 hour	A12	1	0	0	0.045	10.008	53.828	9.837	53.778	-0.132	53.778	53.783
specimens		2	0	0	0.01	10.062	53.83	9.867	53.821	-0.159	53.821	53.820
	B6	1	0	0	0.016	9.996	53.812	9.849	53.796	-0.123	53.796	53.796
		2	0	0	0.039	10.041	53.871	9.879	53.831	-0.131	53.831	53.832
	B25	1	0	0	-0.001	9.974	53.818	9.869	53.823	-0.135	53.823	53.819
		2	0	0	0.043	10.043	53.904	9.915	53.859	-0.132	53.859	53.861
	C23	1	0	0	0	9.961	53.819	9.865	53.798	-0.139	53.798	53.819
		2	0	0	0.056	10.036	53.869	9.923	53.853	-0.121	53.853	53.813
	D17	1	0	0	0.027	10.007	53.807	9.786	53.79	-0.203	53.790	53.780
		2	0	0	0.032	10.042	53.872	9.897	53.826	-0.151	53.826	53.840
240 hour	A13	1	0	0	0.053	9.97	53.811	9.836	53.75	-0.102	53.750	53.758
specimens		2	0	0	0.002	10.089	53.783	9.892	53.799	-0.091	53.799	53.781
	B8	1	0	0	0.018	9.987	53.797	9.805	53.776	-0.158	53.776	53.779
		2	0	0	0.041	10.042	53.865	9.825	53.821	-0.173	53.821	53.824
	C2	1	0	0	0.016	9.99	53.446	9.807	53.42	-0.158	53.420	53.430
		2	0	0	0.046	10.039	53.491	9.839	53.459	-0.143	53.459	53.445
	C25	1	0	0	0.025	9.961	53.811	9.781	53.79	-0.211	53.790	53.786
		2	0	0	0.04	10.047	53.877	9.852	53.831	-0.169	53.831	53.837
	D19	1	0	0	0.019	10.004	53.787	9.791	53.768	-0.173	53.768	53.768
		2	0	0	0.043	10.043	53.858	9.864	53.818	-0.174	53.818	53.815

Length after aging			Corner 1		Corner 2		Corner 3		Corner 4		Length	Length
Nitrogen Aged	Spec #	side	x	y	x	y	x	y	x	y	(1 to 4)	(2 to 3)
336 hour	A15	1	0	0	0.015	9.947	53.759	9.882	53.747	-0.101	53.747	53.744
specimens		2	0	0	0.001	10.05	53.812	9.997	53.809	-0.048	53.809	53.811
	B10	1	0	0	0.002	9.986	53.743	9.918	53.736	-0.044	53.736	53.741
		2	0	0	0.018	10.051	53.787	9.971	53.788	-0.033	53.788	53.769
	C4	1	0	0	0.011	9.978	53.403	9.867	53.394	-0.09	53.394	53.392
		2	0	0	0.017	10.027	53.441	9.971	53.424	-0.041	53.424	53.424
	D21	1	0	0	-0.004	10.001	53.727	9.907	53.731	-0.05	53.731	53.731
		2	0	0	0.018	10.033	53.801	9.971	53.772	-0.062	53.772	53.783
	D30	1	0	0	0.01	9.947	53.765	9.907	53.754	-0.089	53.754	53.755
		2	0	0	0.016	10.032	53.808	9.973	53.798	-0.065	53.798	53.792
465 hour	A19	1	0	0	0.009	9.947	53.735	9.949	53.726	-0.024	53.726	53.726
specimens		2	0	0	-0.008	10.042	53.773	10.035	53.786	0.003	53.786	53.781
	B13	1	0	0	-0.036	10	53.671	10.004	53.705	0.055	53.705	53.707
		2	0	0	0.035	10.101	53.762	10.072	53.746	0.079	53.746	53.727
	B28	1	0	0	-0.007	9.992	53.696	10.021	53.707	0.046	53.707	53.703
		2	0	0	0.008	10.057	53.752	10.042	53.754	0.003	53.754	53.744
	C8	1	0	0	-0.008	9.976	53.376	9.975	53.382	0.014	53.382	53.384
		2	0	0	0.009	10.031	53.418	10.004	53.405	-0.008	53.405	53.409
	D1	1	0	0	-0.016	9.975	53.692	9.962	53.715	0.012	53.715	53.708
		2	0	0	0.018	10.03	53.759	10.008	53.724	0.002	53.724	53.741
633 hour	A21	1	0	0	0.006	9.957	53.689	9.963	53.682	-0.026	53.682	53.683
specimens		2	0	0	-0.001	10.036	53.744	10.004	53.747	-0.036	53.747	53.745
	B15	1	0	0	-0.01	9.914	53.697	9.888	53.706	-0.159	53.706	53.707
		2	0	0	0.048	10.006	53.778	9.991	53.737	-0.135	53.737	53.730
	C10	1	0	0	0.001	9.978	53.34	9.941	53.344	-0.023	53.344	53.339
		2	0	0	0.015	10.03	53.387	9.987	53.374	-0.03	53.374	53.372
	C28	1	0	0	0.002	9.982	53.67	9.912	53.668	-0.046	53.668	53.668
		2	0	0	0.019	10.036	53.714	9.985	53.694	-0.037	53.694	53.695
	D3	1	0	0	-0.011	9.975	53.664	9.914	53.674	-0.031	53.674	53.675
		2	0	0	0.023	10.023	53.735	9.975	53.719	-0.028	53.719	53.712
801 hour	A23	1	0	0	-0.005	9.958	53.641	10.005	53.643	0.024	53.643	53.646
specimens		2	0	0	0.003	10.041	53.712	9.986	53.72	-0.046	53.720	53.709
	B17	1	0	0	-0.016	9.949	53.661	9.924	53.675	-0.057	53.675	53.677
		2	0	0	0.026	10.021	53.744	9.993	53.728	-0.031	53.728	53.718
	C12	1	0	0	0.002	9.96	53.316	9.92	53.311	-0.01	53.311	53.314
		2	0	0	0.006	10.035	53.349	10.016	53.349	0.017	53.349	53.343
	D5	1	0	0	-0.025	9.963	53.626	9.975	53.647	0.034	53.647	53.651
		2	0	0	0.028	10.012	53.711	9.969	53.684	-0.035	53.684	53.683
	D25	1	0	0	-0.008	9.983	53.653	9.913	53.66	-0.024	53.660	53.661
		2	0	0	0.017	10.034	53.709	9.984	53.683	-0.036	53.683	53.692

APPENDIX B: BEND TEST DATA

INCLUDING SLOPE OF LOAD VS. DEFLECTION, SPECIMEN WIDTH, AND SPECIMEN THICKNESS

Nitrogen Specimens		Slope of Load vs. Displacement (corrected)	Specimen Width	Specimen Thickness
24 hour	A6	88.77883612	10.03	2.487
	B23	92.31615056	10.05	2.492
	C17	77.42461744	10.05	2.348
	C31	75.05967618	10.04	2.328
	D11	124.6841027	10.04	2.727
48 hour	A8	87.56698523	10.04	2.487
	B2	79.40547527	10.03	2.393
	C19	78.40206562	10.03	2.380
	D13	121.2798263	10.04	2.765
	D27	129.1899002	10.04	2.795
96 hour	A10	88.06283112	10.03	2.482
	A28	99.10022733	10.02	2.577
	B4	80.80251654	10.03	2.400
	C21	81.92646117	10.02	2.408
	D15	129.8969233	10.03	2.812
168 hour	A12	88.64517703	10.03	2.483
	B6	81.86835603	10.02	2.412
	B25	89.98630298	10.02	2.486
	C23	83.27337804	10.02	2.433
	D17	124.9261549	10.02	2.765
240 hour	A13	89.56739539	10.01	2.484
	B8	82.29862242	10.01	2.418
	C2	90.89380164	10	2.495
	C25	86.658568	10	2.455
	D19	122.4782645	10.02	2.741
336 hour	A15	92.72768256	10	2.53
	B10	82.30212344	10.01	2.42
	C4	87.27027664	10	2.468
	D21	117.4673323	10.02	2.717
	D30	118.4732643	10.01	2.718
465 hour	A19	95.54781187	10	2.548
	B13	82.91524268	10	2.426
	B28	99.69577632	10.02	2.567
	C8	82.52541133	10.01	2.414
	D1	99.33307633	10.01	2.565
633 hour	A21	97.41162879	10	2.548
	B15	93.27297312	10.02	2.51
	C10	79.20646941	10	2.383
	C28	81.16143489	10	2.399
	D3	105.0304608	9.99	2.604
801 hour	A23	97.0507482	10	2.544
	B17	93.43498332	10.01	2.505
	C12	76.64613766	9.99	2.352
	D5	107.9114916	9.99	2.63
	D25	110.229171	10	2.654

Air Specimens		Slope of Load vs. Displacement (corrected)	Surface Layer Thickness	Specimen Width	Specimen Thickness
24 hour	A5	92.19817659	0.03	10.41	2.479
	B24	94.38212677	0.04	10.41	2.482
	C18	80.05415099	0.03	10.42	2.357
	C30	74.25194253	0.04	10.43	2.296
	D12	123.3283907	0.03	10.29	2.738
48 hour	A7	91.55326272	0.04	10.28	2.475
	B1	82.97563931	0.05	10.39	2.38
	C20	83.62083337	0.04	10.4	2.382
	D16	131.7542543	0.04	10.4	2.782
	D28	133.5659015	0.05	10.4	2.789
96 hour	A9	91.2020347	0.06	10.39	2.462
	A27	103.0095398	0.07	10.38	2.564
	B3	83.45760342	0.06	10.38	2.376
	C22	85.51492351	0.06	10.27	2.403
	D18	126.0803866	0.05	10.4	2.739
168 hour	A11	91.725481	0.08	10.38	2.448
	B5	83.45887607	0.08	10.37	2.372
	B26	91.86228137	0.08	10.36	2.451
	C24	87.46610175	0.08	10.36	2.414
	D20	124.4719627	0.08	10.36	2.701
240 hour	A14	94.50187131	0.09	10.33	2.488
	B7	83.48907086	0.09	10.35	2.375
	C1	94.6091587	0.09	10.33	2.468
	C26	89.56199497	0.09	10.33	2.429
	D22	116.0727916	0.09	10.23	2.663
336 hour	A16	94.34094034	0.11	10.33	2.48
	B9	82.74216087	0.11	10.33	2.365
	C3	90.28661692	0.11	10.33	2.428
	D24	113.0483769	0.11	10.35	2.617
	D31	120.6525891	0.11	10.33	2.67
465 hour	A20	95.25677611	0.12	10.18	2.471
	B14	92.42389969	0.13	10.3	2.445
	B27	101.7830931	0.12	10.32	2.512
	C7	83.54577704	0.13	10.3	2.36
	D2	102.0974658	0.13	10.3	2.518
633 hour	A22	93.71358161	0.14	10.28	2.442
	B16	89.69462448	0.14	10.28	2.403
	C9	78.09453784	0.14	10.28	2.296
	C27	76.19394785	0.15	10.28	2.279
	D4	100.9391497	0.14	10.14	2.514
801 hour	A24	91.20618927	0.15	10.25	2.415
	B18	88.63716951	0.15	10.24	2.375
	C11	73.87627074	0.15	10.23	2.235
	D6	102.5563967	0.15	10.23	2.508
	D14	101.9435238	0.15	10.24	2.499

Thickness		(Table Measurements)									
		Side 1			Side 2			Side1	Side2	Overall	Rounded
Specimen		Mid	R 0.1	L 0.1	Mid	R 0.1	L 0.1	Avg	Avg	Avg	Avg
Unaged 1	A2	2.48	2.48	2.479	2.485	2.485	2.484	2.479667	2.484667	2.482167	2.482
	A25	2.555	2.555	2.556	2.558	2.558	2.558	2.555333	2.558	2.556667	2.557
	B19	2.511	2.51	2.511	2.513	2.513	2.515	2.510667	2.513667	2.512167	2.512
	C13	2.351	2.351	2.351	2.335	2.339	2.337	2.351	2.337	2.344	2.344
	D7	2.662	2.664	2.664	2.676	2.687	2.675	2.663333	2.679333	2.671333	2.671
	A1	2.479	2.482	2.482	2.481	2.484	2.482	2.481	2.482333	2.481667	2.482
	A26	2.557	2.558	2.559	2.557	2.558	2.559	2.558	2.558	2.558	2.558
	B20	2.505	2.505	2.507	2.51	2.51	2.512	2.505667	2.510667	2.508167	2.508
	C14	2.301	2.303	2.301	2.287	2.285	2.285	2.301667	2.285667	2.293667	2.294
	D8	2.679	2.679	2.678	2.691	2.69	2.692	2.678667	2.691	2.684833	2.685
Unaged 2	A4	2.482	2.485	2.483	2.479	2.48	2.483	2.483333	2.480667	2.482	2.482
	B21	2.503	2.502	2.502	2.504	2.506	2.504	2.502333	2.504667	2.5035	2.504
	B31	2.604	2.604	2.603	2.579	2.579	2.58	2.603667	2.579333	2.5915	2.592
	C15	2.324	2.324	2.325	2.307	2.309	2.306	2.324333	2.307333	2.315833	2.316
	D9	2.694	2.694	2.691	2.703	2.704	2.705	2.693	2.704	2.6985	2.699
	A3	2.481	2.481	2.479	2.482	2.481	2.482	2.480333	2.481667	2.481	2.481
	B22	2.496	2.496	2.496	2.499	2.498	2.497	2.496	2.498	2.497	2.497
	B30	2.624	2.623	2.624	2.604	2.603	2.605	2.623667	2.604	2.613833	2.614
	C16	2.341	2.341	2.341	2.324	2.323	2.323	2.341	2.323333	2.332167	2.332
	D10	2.706	2.708	2.708	2.722	2.722	2.722	2.707333	2.722	2.714667	2.715
24 Hour	A6	2.487	2.487	2.487	2.486	2.487	2.485	2.487	2.486	2.4865	2.487
	B23	2.489	2.489	2.49	2.494	2.493	2.494	2.489333	2.493667	2.4915	2.492
	C17	2.354	2.354	2.355	2.342	2.34	2.343	2.354333	2.341667	2.348	2.348
	C31	2.319	2.321	2.322	2.334	2.335	2.334	2.320667	2.334333	2.3275	2.328
	D11	2.718	2.721	2.721	2.735	2.736	2.733	2.72	2.734667	2.727333	2.727
	A5	2.478	2.477	2.479	2.479	2.479	2.48	2.478	2.479333	2.478667	2.479
	B24	2.479	2.481	2.48	2.484	2.482	2.484	2.48	2.483333	2.481667	2.482
	C18	2.364	2.365	2.365	2.349	2.35	2.348	2.364667	2.349	2.356833	2.357
	C30	2.286	2.284	2.282	2.307	2.308	2.31	2.284	2.308333	2.296167	2.296
	D12	2.728	2.728	2.729	2.748	2.746	2.749	2.728333	2.747667	2.738	2.738
48 Hour	A8	2.488	2.488	2.489	2.486	2.485	2.485	2.488333	2.485333	2.486833	2.487
	B2	2.394	2.392	2.393	2.393	2.394	2.394	2.393	2.393667	2.393333	2.393
	C19	2.385	2.387	2.385	2.373	2.375	2.373	2.385667	2.373667	2.379667	2.38
	D13	2.757	2.758	2.758	2.771	2.771	2.773	2.757667	2.771667	2.764667	2.765
	D27	2.79	2.791	2.791	2.798	2.8	2.8	2.790667	2.799333	2.795	2.795
	A7	2.474	2.475	2.474	2.475	2.476	2.476	2.474333	2.475667	2.475	2.475
	B1	2.379	2.38	2.379	2.38	2.38	2.381	2.379333	2.380333	2.379833	2.38
	C20	2.39	2.39	2.39	2.372	2.373	2.374	2.39	2.373	2.3815	2.382
	D16	2.77	2.769	2.77	2.794	2.793	2.794	2.769667	2.793667	2.781667	2.782
	D28	2.788	2.787	2.788	2.79	2.791	2.79	2.787667	2.790333	2.789	2.789
96 Hour	A10	2.482	2.48	2.481	2.482	2.483	2.484	2.481	2.483	2.482	2.482
	A28	2.584	2.582	2.583	2.569	2.57	2.571	2.583	2.57	2.5765	2.577
	B4	2.395	2.395	2.395	2.403	2.405	2.405	2.395	2.404333	2.399667	2.4
	C21	2.41	2.411	2.412	2.405	2.405	2.403	2.411	2.404333	2.407667	2.408
	D15	2.804	2.804	2.805	2.819	2.817	2.82	2.804333	2.818667	2.8115	2.812
	A9	2.463	2.465	2.463	2.461	2.46	2.461	2.463667	2.460667	2.462167	2.462
	A27	2.562	2.561	2.562	2.565	2.565	2.566	2.561667	2.565333	2.5635	2.564
	B3	2.374	2.377	2.375	2.375	2.377	2.375	2.375333	2.375667	2.3755	2.376
	C22	2.409	2.409	2.41	2.395	2.397	2.395	2.409333	2.395667	2.4025	2.403
	D18	2.733	2.732	2.733	2.745	2.746	2.745	2.732667	2.745333	2.739	2.739
168 Hours	A12	2.482	2.484	2.482	2.485	2.483	2.484	2.482667	2.484	2.483333	2.483
	B6	2.409	2.409	2.409	2.415	2.415	2.417	2.409	2.415667	2.412333	2.412
	B25	2.482	2.485	2.485	2.487	2.486	2.488	2.484	2.487	2.4855	2.486
	C23	2.438	2.439	2.439	2.427	2.427	2.427	2.438667	2.427	2.432833	2.433
	D17	2.762	2.763	2.762	2.77	2.767	2.768	2.762333	2.768333	2.765333	2.765
	A11	2.447	2.446	2.448	2.449	2.449	2.45	2.447	2.449333	2.448167	2.448
	B5	2.37	2.369	2.37	2.375	2.375	2.375	2.369667	2.375	2.372333	2.372
	B26	2.451	2.449	2.449	2.453	2.453	2.453	2.449667	2.453	2.451333	2.451
	C24	2.419	2.421	2.421	2.409	2.407	2.406	2.420333	2.407333	2.413833	2.414
	D20	2.695	2.697	2.695	2.706	2.705	2.707	2.695667	2.706	2.700833	2.701

Thickness		(Table Measurements)									
		Side 1			Side 2			Side1	Side2	Overall	Rounded
Specimen		Mid	R 0.1	L 0.1	Mid	R 0.1	L 0.1	Avg	Avg	Avg	Avg
240 Hour	A13	2.483	2.483	2.485	2.486	2.486	2.482	2.483667	2.484667	2.484167	2.484
	B8	2.418	2.418	2.42	2.418	2.416	2.419	2.418667	2.417667	2.418167	2.418
	C2	2.502	2.5	2.498	2.488	2.49	2.491	2.5	2.489667	2.494833	2.495
	C25	2.463	2.461	2.462	2.449	2.446	2.448	2.462	2.447667	2.454833	2.455
	D19	2.735	2.734	2.735	2.748	2.748	2.747	2.734667	2.747667	2.741167	2.741
	A14	2.487	2.485	2.487	2.49	2.488	2.49	2.486333	2.489333	2.487833	2.488
	B7	2.374	2.373	2.373	2.376	2.376	2.376	2.373333	2.376	2.374667	2.375
	C1	2.475	2.474	2.475	2.459	2.462	2.462	2.474667	2.461	2.467833	2.468
	C26	2.435	2.433	2.436	2.421	2.422	2.424	2.434667	2.422333	2.4285	2.429
	D22	2.656	2.657	2.656	2.67	2.669	2.67	2.656333	2.669667	2.663	2.663
336 Hour	A15	2.529	2.53	2.53	2.53	2.531	2.53	2.529667	2.530333	2.53	2.53
	B10	2.422	2.419	2.419	2.421	2.42	2.42	2.42	2.420333	2.420167	2.42
	C4	2.475	2.475	2.474	2.461	2.462	2.461	2.474667	2.461333	2.468	2.468
	D21	2.711	2.71	2.71	2.723	2.723	2.723	2.710333	2.723	2.716667	2.717
	D30	2.717	2.715	2.715	2.72	2.72	2.721	2.715667	2.720333	2.718	2.718
	A16	2.479	2.477	2.48	2.479	2.48	2.482	2.478667	2.480333	2.4795	2.48
	B9	2.364	2.365	2.365	2.364	2.366	2.365	2.364667	2.365	2.364833	2.365
	C3	2.435	2.437	2.435	2.42	2.421	2.42	2.435667	2.420333	2.428	2.428
	D24	2.612	2.613	2.61	2.622	2.622	2.625	2.611667	2.623	2.617333	2.617
	D31	2.67	2.671	2.669	2.669	2.668	2.67	2.67	2.669	2.6695	2.67
465 Hour	A19	2.547	2.547	2.546	2.549	2.548	2.55	2.546667	2.549	2.547833	2.548
	B13	2.423	2.425	2.425	2.424	2.429	2.427	2.424333	2.426667	2.4255	2.426
	B28	2.576	2.577	2.577	2.558	2.555	2.556	2.576667	2.556333	2.5665	2.567
	C8	2.425	2.423	2.42	2.406	2.405	2.404	2.422667	2.405	2.413833	2.414
	D1	2.549	2.549	2.549	2.58	2.581	2.581	2.549	2.580667	2.564833	2.565
	A20	2.478	2.478	2.477	2.457	2.456	2.477	2.477667	2.463333	2.4705	2.471
	B14	2.448	2.449	2.449	2.442	2.44	2.44	2.448667	2.440667	2.444667	2.445
	B27	2.522	2.521	2.52	2.503	2.502	2.502	2.521	2.502333	2.511667	2.512
	C7	2.37	2.366	2.368	2.352	2.352	2.351	2.368	2.351667	2.359833	2.36
	D2	2.513	2.513	2.513	2.524	2.522	2.523	2.513	2.523	2.518	2.518
633 Hours	A21	2.548	2.548	2.547	2.548	2.549	2.548	2.547667	2.548333	2.548	2.548
	B15	2.508	2.507	2.506	2.513	2.511	2.514	2.507	2.512667	2.509833	2.51
	C10	2.39	2.389	2.39	2.377	2.377	2.376	2.389667	2.376667	2.383167	2.383
	C28	2.393	2.391	2.391	2.406	2.405	2.406	2.391667	2.405667	2.398667	2.399
	D3	2.598	2.597	2.599	2.609	2.61	2.611	2.598	2.61	2.604	2.604
	A22	2.446	2.446	2.447	2.437	2.436	2.44	2.446333	2.437667	2.442	2.442
	B16	2.404	2.404	2.408	2.401	2.398	2.401	2.405333	2.4	2.402667	2.403
	C9	2.308	2.308	2.306	2.285	2.286	2.284	2.307333	2.285	2.296167	2.296
	C27	2.269	2.268	2.269	2.289	2.287	2.289	2.268667	2.288333	2.2785	2.279
	D4	2.511	2.513	2.511	2.516	2.516	2.517	2.511667	2.516333	2.514	2.514
801 Hours	A23	2.543	2.542	2.544	2.543	2.544	2.545	2.543	2.544	2.5435	2.544
	B17	2.504	2.507	2.505	2.504	2.503	2.504	2.505333	2.503667	2.5045	2.505
	C12	2.355	2.357	2.359	2.347	2.346	2.346	2.357	2.346333	2.351667	2.352
	D5	2.623	2.622	2.625	2.636	2.634	2.637	2.623333	2.635667	2.6295	2.63
	D25	2.646	2.645	2.646	2.664	2.663	2.661	2.645667	2.662667	2.654167	2.654
	A24	2.422	2.423	2.424	2.407	2.407	2.407	2.423	2.407	2.415	2.415
	B18	2.383	2.382	2.381	2.368	2.367	2.37	2.382	2.368333	2.375167	2.375
	C11	2.253	2.252	2.255	2.216	2.215	2.217	2.253333	2.216	2.234667	2.235
	D6	2.509	2.508	2.509	2.506	2.505	2.51	2.508667	2.507	2.507833	2.508
	D14	2.513	2.512	2.513	2.486	2.487	2.485	2.512667	2.486	2.499333	2.499

APPENDIX C: CTE DATA

Nitrogen Aged Specimens		CTE (um/mmC)					
Hrs Aged	Specimen	Sample 1	Sample 2	Sample 3	Specimen Avg.	Group Avg.	Std. Dev.
Unaged	A25	0.05229			0.05229	0.05234	0.002024
	B19	0.05453	0.04991		0.05222		
	B3						
	C13	0.05294	0.04870		0.05082		
	D7	0.05437	0.05397		0.05417		
	A2	0.05184	0.05078	0.05410	0.05224		
24 hours	A6	0.05439	0.05390		0.05415	0.05534	0.001451
	B23						
	B23						
	C17	0.05511	0.05485		0.05498		
	C31	0.05761	0.05725		0.05743		
	D11	0.05378	0.05581		0.05480		
48 hours	A8	0.05246	0.04973		0.05109	0.05366	0.002225
	B2	0.05549	0.05445		0.05497		
	C19	0.05556	0.05204		0.05380		
	D13	0.05620			0.05620		
	D27	0.05177	0.05523		0.05350		
96 hours	A10	0.05018	0.05320		0.05169	0.05278	0.001605
	A28	0.05190			0.05190		
	B4	0.05416			0.05416		
	C21	0.05458	0.05264		0.05361		
168 hours	A12	0.05391	0.05640		0.05515	0.05324	0.002237
	B6						
	C23						
	D17	0.05050	0.05441		0.05245		
	B25	0.05085	0.05339		0.05212		
240 hours	A13					0.05063	0.001465
	B8	0.05018	0.05045		0.05031		
	C2	0.05194	0.05110		0.05152		
	C25	0.05156	0.04763		0.04960		
	D19		0.05156		0.05156		
336 hours	A15	0.05304	0.05310		0.05307	0.05269	0.002188
	B10	0.05448	0.05592		0.05520		
	C4	0.05327	0.04782		0.05054		
	D21	0.05246	0.05202		0.05224		
	D30	0.05389	0.05093		0.05241		
465 hours	A19					0.05120	0.001735
	B13	0.05275	0.04760		0.05017		
	B28	0.05070	0.05003		0.05037		
	C8	0.05192	0.05231		0.05211		
	D1	0.05161	0.05267		0.05214		
633 hours	A21					0.05020	0.000594
	B15	0.05049	0.04968		0.05008		
	C10	0.05002	0.05109		0.05055		
	C28						
	D3	0.04971			0.04971		
801 hours	A23	0.05316	0.05245		0.05280	0.05102	0.001805
	B17						
	C12	0.04940			0.04940		
	D5	0.05059	0.05058		0.05058		
	D25	0.05264	0.04831		0.05048		

Air Aged Specimens		CTE (um/mmC)					
Hours Aged	Specimen	Sample 1	Sample 2	Sample 3	Specimen Avg.	Group Avg.	Std. Dev.
24 hours	A5	0.05514	0.05623		0.05568	0.05563	0.001646
	B24	0.05762			0.05762		
	C18	0.05590			0.05590		
	C30	0.05346			0.05346		
	D12	0.05741	0.05369		0.05555		
48 hours	A7	0.05487	0.05227		0.05357	0.05358	0.002574
	B1	0.05548	0.04783		0.05166		
	C20	0.05529	0.05610		0.05570		
	D16	0.05500			0.05500		
	D28	0.05248	0.05295		0.05271		
96 hours	A9	0.05255	0.05415		0.05335	0.05440	0.003837
	A27	0.05539	0.04585		0.05062		
	B3	0.05735	0.05747		0.05741		
	C22						
	D18	0.05678	0.05571		0.05624		
168 hours	A11	0.05733	0.05319		0.05526	0.05341	0.003009
	B5	0.05675			0.05675		
	B26	0.04994	0.05382		0.05188		
	C24	0.04774	0.05435		0.05104		
	D20	0.05418	0.05343		0.05381		
240 hours	A14	0.05720	0.05884		0.05802	0.05409	0.003412
	B7	0.05541	0.05767		0.05654		
	C1	0.05005	0.04788		0.04897		
	C26	0.05260	0.05369		0.05315		
	D22	0.05325	0.05427		0.05376		
336 hours	A16	0.05344	0.05515		0.05429	0.05407	0.002651
	B9	0.05987			0.05987		
	C3	0.05462	0.05271		0.05366		
	D24	0.05315	0.05031		0.05173		
	D31	0.05237	0.05503		0.05370		
465 hours	A20	0.05447	0.05530		0.05488	0.05522	0.000868
	B14						
	B27	0.05470	0.05641		0.05555		
	C7						
	D2						
633 hours	A22		0.05001		0.05001	0.05296	0.003249
	B16	0.04988	0.05274		0.05131		
	C9	0.05567			0.05567		
	C27	0.05796			0.05796		
	D4	0.05147			0.05147		
801 hours	A24					0.05379	0.003005
	B18	0.05351	0.05666		0.05509		
	C11	0.04908	0.05438		0.05173		
	D6	0.05769	0.05604		0.05687		
	D14	0.05225	0.05068		0.05146		

APPENDIX D: SURFACE LAYER THICKNESS DATA

Layer thicknesses		From photo						
Air Specimens		measured (mm)	scale	thickness	round	avg.	stdev.	round avg.
24 hour	A5	10	300	0.033333	0.03	0.034854	0.00474	0.03
	B24	1.3	32	0.040625	0.04			
	C18	1	32	0.03125	0.03			
	C30	1.25	32	0.039063	0.04			
	D12	9	300	0.03	0.03			
48 hour	A7	13	300	0.043333	0.04	0.04475	0.00194	0.04
	B1	1.5	32	0.046875	0.05			
	C20	13	300	0.043333	0.04			
	D16	13	300	0.043333	0.04			
	D28	1.5	32	0.046875	0.05			
96 hour	A9	17	300	0.056667	0.06	0.059458	0.0062	0.06
	A27	2.1	32	0.065625	0.07			
	B3	2	32	0.0625	0.06			
	C22	2	32	0.0625	0.06			
	D18	1.6	32	0.05	0.05			
168 hour	A11	24	300	0.08	0.08	0.08025	0.000559	0.08
	B5	24	300	0.08	0.08			
	B26	2.6	32	0.08125	0.08			
	C24	24	300	0.08	0.08			
	D20	24	300	0.08	0.08			
240 hour	A14	28	300	0.093333	0.09	0.093417	0.000186	0.09
	B7	28	300	0.093333	0.09			
	C1	28	300	0.093333	0.09			
	C26	3	32	0.09375	0.09			
	D22	28	300	0.093333	0.09			
336 hour	A16	34	300	0.113333	0.11	0.109083	0.002735	0.11
	B9	3.5	32	0.109375	0.11			
	C3	3.5	32	0.109375	0.11			
	D24	32	300	0.106667	0.11			
	D31	32	300	0.106667	0.11			
465 hour	A20	37	300	0.123333	0.12	0.124333	0.000913	0.12
	B14	4	32	0.125	0.13			
	B27	37	300	0.123333	0.12			
	C7	4	32	0.125	0.13			
	D2	4	32	0.125	0.13			
633 hour	A22	42	300	0.14	0.14	0.141375	0.003075	0.14
	B16	42	300	0.14	0.14			
	C9	42	300	0.14	0.14			
	C27	4.7	32	0.146875	0.15			
	D4	42	300	0.14	0.14			
801 hour	A24	44	300	0.146667	0.15	0.149167	0.001667	0.15
	B18	4.8	32	0.15	0.15			
	C11				0.15			
	D6	4.8	32	0.15	0.15			
	D14	4.8	32	0.15	0.15			

APPENDIX E: CURVATURE DATA

INCLUDING ROOM TEMPERATURE MEASUREMENTS AND ELEVATED TEMPERATURE MEASUREMENTS

Measurements of room temperature curvature using three points to define arc curvature												
		Coordinates of three points on arc						Calculated center		Radius	Curvature	Specimen
		X1	Y1	X2	Y2	X3	Y3	X0	Y0			Avg. Curv.
Unaged	A2	0	0	40.611	0.055	20.306	-0.124	18.4627	1360.718	1360.843	0.000735	0.000734
		0	0	41.658	-0.178	20.829	-0.248	26.65827	1364.156	1364.416	0.000733	
	A25	0	0	39.425	0.02	19.713	-0.119	18.94848	1506.077	1506.196	0.000664	0.000654
		0	0	39.804	0.049	19.902	-0.103	17.98992	1553.256	1553.36	0.000644	
	B19	0	0	38.952	0.011	19.476	-0.07	18.76662	2511.985	2512.055	0.000398	0.000403
		0	0	40.242	-0.057	20.121	-0.111	23.59639	2453.6	2453.713	0.000408	
	C13	0	0	43.469	-0.199	21.735	-0.212	31.34612	2099.435	2099.669	0.000476	0.000483
		0	0	43.649	0.045	21.825	-0.094	19.71705	2044.201	2044.296	0.000489	
	D17	0	0	43.598	0.073	21.799	-0.093	18.72704	1834.712	1834.808	0.000545	0.000543
		0	0	43.582	0.025	21.791	-0.116	20.73116	1847.605	1847.722	0.000541	
24 hour	A5	0	0	40.387	-0.309	20.194	-0.272	33.47041	1735.168	1735.491	0.000576	0.000583
		0	0	40.146	0.04	20.098	-0.099	18.38661	1692.569	1692.669	0.000591	
	B24	0	0	42.54	-0.515	20.27	-0.317	59.43481	3152.23	3152.79	0.000317	0.000315
		0	0	43.059	-0.347	21.53	-0.246	47.29347	3196.861	3197.211	0.000313	
	C18	0	0	43.198	-0.302	21.599	-0.198	56.2968	4963.013	4963.332	0.000201	0.000211
		0	0	42.925	-0.596	21.463	-0.349	84.18694	4517.23	4518.014	0.000221	
	C30	0	0	42.151	-0.568	21.076	-0.338	76.51288	4113.696	4114.408	0.000243	0.000247
		0	0	42.99	-0.314	21.495	-0.215	50.58871	3983.087	3983.408	0.000251	
	D12	0	0	39.545	-0.34	19.773	-0.215	57.12669	4344.452	4344.828	0.000230	0.000211
		0	0	40.117	-0.479	20.059	-0.278	82.46659	5226.536	5227.186	0.000191	
48 hour	A7	0	0	44.148	-0.024	22.074	-0.218	22.71688	1182.559	1182.777	0.000845	0.000859
		0	0	44.831	0.074	22.416	-0.182	20.52214	1147.083	1147.267	0.000872	
	B1	0	0	42.967	-0.088	21.484	-0.241	23.88249	1171.292	1171.535	0.000854	0.000869
		0	0	43.016	0.065	21.509	-0.172	19.79909	1130.961	1131.135	0.000884	
	C20	0	0	44.724	0.027	22.362	-0.155	21.46624	1483.785	1483.94	0.000674	0.000688
		0	0	44.938	-0.14	22.47	-0.247	26.91187	1426.027	1426.281	0.000701	
	D16	0	0	42.026	-0.454	21.013	-0.335	43.0981	2044.153	2044.607	0.000489	0.000490
		0	0	42.553	-0.258	21.275	-0.24	33.63898	2038.865	2039.143	0.000490	
	D28	0	0	43.412	0.035	21.706	-0.075	19.65277	2546.732	2546.808	0.000393	0.000398
		0	0	43.718	-0.169	21.859	-0.181	31.42935	2475.634	2475.834	0.000404	
96 hour	A9	0	0	41.947	0.032	20.972	-0.154	19.98657	1293.728	1293.882	0.000773	0.000780
		0	0	41.037	-0.005	20.519	-0.168	20.67346	1271.845	1272.013	0.000786	
	A27	0	0	42.738	0.135	21.369	-0.073	16.23605	1625.046	1625.127	0.000615	0.000645
		0	0	43.275	-0.054	21.637	-0.185	23.48617	1481.477	1481.663	0.000675	
	B3	0	0	41.606	-0.136	20.803	-0.213	25.68076	1492.168	1492.389	0.000670	0.000654
		0	0	41.386	0.059	20.694	-0.107	18.45706	1568.447	1568.556	0.000638	
	C22	0	0	41.13	0.067	20.565	-0.099	17.96537	1595.893	1595.994	0.000627	0.000630
		0	0	42.453	0.023	21.227	-0.131	20.37003	1580.865	1580.996	0.000633	
	D18	0	0	42.216	-0.019	21.108	-0.144	21.85342	1656.235	1656.379	0.000604	0.000643
		0	0	42.227	0.076	21.113	-0.114	18.47443	1466.357	1466.473	0.000682	
168 hour	A11	0	0	41.135	0.027	20.568	-0.284	20.10094	710.8257	711.1099	0.001406	0.001409
		0	0	41.547	0.087	20.773	-0.261	19.28999	708.4983	708.7608	0.001411	
	B5	0	0	42.78	0.048	21.39	-0.258	20.47994	811.1111	811.3697	0.001232	0.001232
		0	0	42.824	-0.243	21.411	-0.404	26.01578	811.205	811.6221	0.001232	
	B26	0	0	42.456	0.016	21.228	-0.279	20.93219	784.9308	785.2098	0.001274	0.001317
		0	0	42.455	0.073	21.228	-0.27	19.96381	734.9678	735.2389	0.001360	
	C24	0	0	43.786	-0.075	21.893	-0.43	22.93851	610.3457	610.7766	0.001637	0.001648
		0	0	43.889	0.175	21.945	-0.312	19.54209	602.5991	602.9158	0.001659	
	D20	0	0	43.178	-0.144	21.598	-0.377	24.13698	763.9327	764.3139	0.001308	0.001307
		0	0	42.954	0.074	21.477	-0.264	20.15724	766.1039	766.3691	0.001305	
240 hour	A14	0	0	42.496	-0.047	21.248	-0.32	22.08987	761.174	761.4945	0.001313	0.001309
		0	0	42.088	0.126	21.043	-0.226	18.75067	766.1097	766.3391	0.001305	
	B7	0	0	41.569	-0.029	20.784	-0.494	21.09859	450.2101	450.7042	0.002219	0.002226
		0	0	40.849	0.148	20.425	-0.392	18.80364	447.4419	447.8369	0.002233	
	C1	0	0	41.496	0.051	20.748	-0.473	20.21764	431.5517	432.0251	0.002315	0.002313
		0	0	42.403	0.034	21.202	-0.503	20.85515	431.9719	432.4751	0.002312	
	C26	0	0	44.578	-0.019	22.288	-0.535	22.49036	472.4197	472.9547	0.002114	0.002152
		0	0	45.199	0.087	22.599	-0.516	21.7215	456.1893	456.7061	0.002190	
	D22	0	0	43.287	0.017	21.643	-0.223	21.2462	1011.646	1011.869	0.000988	0.001000
		0	0	43.111	0.072	21.556	-0.199	19.90464	988.5126	988.713	0.001011	

Measurements of room temperature curvature using three points to define arc curvature												
		Coordinates of three points on arc						Calculated center		Radius	Curvature	Specimen
		X1	Y1	X2	Y2	X3	Y3	X0	Y0			Avg. Curv.
336 hour	A16	0	0	42.184	-0.015	21.092	-0.446	21.2723	507.0395	507.4856	0.001970	0.001987
		0	0	41.945	0.07	20.972	-0.406	20.14062	498.5082	498.9149	0.002004	
	B9	0	0	41.922	-0.045	20.961	-0.507	21.44745	453.1553	453.6626	0.002204	0.002214
		0	0	42.015	0.144	21.007	-0.419	19.46805	449.2377	449.6593	0.002224	
	C3	0	0	39.642	0.1	19.821	-0.252	18.18056	650.3535	650.6076	0.001537	0.001528
		0	0	40.67	-0.01	20.335	-0.319	20.49686	658.297	658.616	0.001518	
	D24	0	0	41.612	0.107	20.806	-0.334	19.3702	558.4307	558.7666	0.001790	0.001781
		0	0	40.945	0.003	20.472	-0.37	20.43118	563.9117	564.2817	0.001772	
	D31	0	0	40.391	0.028	20.195	-0.264	19.68708	733.4342	733.6984	0.001363	0.001389
		0	0	40.945	0.019	20.472	-0.287	20.14459	706.6465	706.9336	0.001415	
465 hour	A20	0	0	42.002	0.025	21.001	-0.376	20.66326	567.4401	567.8162	0.001761	0.001766
		0	0	41.6	0.124	20.8	-0.321	19.117	564.6797	565.0032	0.001770	
	B14	0	0	41.33	0.04	20.665	-0.359	20.11993	563.2113	563.5705	0.001774	0.001787
		0	0	41.904	0.09	20.952	-0.35	19.75895	555.5289	555.8802	0.001799	
	B27	0	0	41.932	-0.445	20.966	-0.61	26.98389	566.8388	567.4807	0.001762	0.001761
		0	0	41.769	0.186	20.885	-0.291	18.35634	567.8287	568.1253	0.001760	
	C7	0	0	40.941	0.008	20.471	-0.348	20.35422	595.0571	595.4051	0.001680	0.001687
		0	0	41.372	0.109	20.686	-0.308	19.13145	590.0989	590.4089	0.001694	
	D2	0	0	41.4	-0.268	20.7	-0.445	25.15867	688.63	689.0895	0.001451	0.001451
		0	0	40.655	0.081	20.328	0.081	30.4915	-5101.41	5101.5	0.000196	bad data
633 hour	A22	0	0	40.451	0.003	20.226	-0.388	20.18657	524.9297	525.3177	0.001904	0.001906
		0	0	41.216	0.013	20.607	-0.399	20.44289	523.4659	523.865	0.001909	
	B16	0	0	40.722	-0.037	20.361	-0.499	20.75275	431.1363	431.6355	0.002317	0.002320
		0	0	43.437	0.059	21.719	-0.519	21.13483	429.7402	430.2596	0.002324	
	C9	0	0	44.596	0.094	22.298	-0.642	21.5382	360.5175	361.1603	0.002769	0.002769
		0	0	44.42	-0.002	22.21	-0.002	33.315	-246642	246642.1	0.000004	bad data
	C27	0	0	37.211	-0.413	18.605	-0.676	22.69498	368.2522	368.9509	0.002710	0.002710
		0	0	35.844	0.567	17.922	-0.152	12.09059	368.9274	369.1254	0.002709	
	D4	0	0	42.256	0.169	21.128	-0.498	19.59668	382.9688	383.4699	0.002608	0.002598
		0	0	42.975	-0.012	21.488	-0.604	21.59521	385.7425	386.3465	0.002588	
801 hour	A24	0	0	42.422	0.126	21.221	-0.565	20.14805	357.941	358.5076	0.002789	0.002808
		0	0	42.519	-0.053	21.295	-0.666	21.69961	353.0525	353.7188	0.002827	
	B18	0	0	44.281	0.015	22.139	-0.631	22.01057	383.5584	384.1894	0.002603	0.002603
		0	0	44.66	0.106	22.33	0.106	33.495	-4703.99	4704.112	0.000213	bad data
	C11	0	0	43.05	-0.092	21.525	-0.66	22.33066	376.9497	377.6106	0.002648	0.002659
		0	0	41.999	0.246	21	-0.466	18.80851	374.185	374.6574	0.002669	
	D6	0	0	39.149	-0.25	19.575	-0.652	21.89438	363.1589	363.8183	0.002749	0.002758
		0	0	43.039	0.143	21.519	-0.57	20.32129	360.6979	361.2699	0.002768	
	D14	0	0	39.069	0.163	19.534	-0.352	17.69908	440.0091	440.3649	0.002271	0.002284
		0	0	38.366	-0.072	19.183	-0.459	19.9989	434.7274	435.1872	0.002298	

Specimen Curvature with Temperature data   Note: Values of 1for length and 0 for height merely indicate that there was no measurable curvature

Specimen		Temp	Length	Height	Temp	Length	Height	Temp	Length	Height	Temp	Length	Height	Temp	Length	Height
24 hour	A5	44	54.081	0.374	153	1	0	261	54.244	-0.174	326	54.432	-0.256			
			53.841	0.359		1	0		54.169	-0.144		54.347	-0.28			
			53.956	0.351		1	0		54.221	-0.165		54.362	-0.315			
			53.797			1			54.166			54.283				
	B24	30	53.842	0.115	154	54.086	-0.176	263	54.288	-0.234	329	54.357	-0.392			
			53.756	0.111	155	53.878	-0.136	267	54.067	-0.263		54.163	-0.398			
			53.838	0.097		54.015	-0.174		54.265	-0.228		54.353	-0.355			
			53.73			53.893			54.156			54.153				
	C18	38	53.843	0.082	153	53.869	-0.096	265	54.238	-0.264	325	54.45	-0.368			
		41	53.656	0.119	154	53.93	-0.143	267	54.13	-0.227	327	54.234	-0.383			
			53.753	0.074		53.837	-0.104		54.271	-0.236		54.419	-0.365			
			53.643			54.066			54.09			54.156				
	C30	45	1	0	152	53.965	-0.066	260	54.304	-0.229	324	54.424	-0.228			
			1	0	153	53.876	-0.089	266	54.154	-0.272	326	54.332	-0.296			
			1	0		54.035	-0.103		54.305	-0.245		54.393	-0.235			
			1			53.904			54.119			54.286				
48 hour	A7	44	53.747	0.4	153	53.868	-0.109	266	54.129	-0.287	324	54.278	-0.464			
			53.604	0.358		53.767	-0.089		53.954	-0.337	327	54.18	-0.473			
			53.82	0.358		53.907	-0.075		54.089	-0.265		54.353	-0.452			
			53.659			53.806			53.978			54.142				
	B1	30	54.102	0.329	154	54.295	-0.137	265	54.465	-0.339	328	54.636	-0.517			
			53.984	0.321	155	54.097	-0.126	269	54.377	-0.335	329	54.438	-0.471			
			54.061	0.278		54.293	-0.135		54.518	-0.3		54.602	-0.507			
			53.94			54.134			54.355			54.598				
	C20	38	54.056	0.236	153	54.333	-0.125	265	54.507	-0.26	325	54.636	-0.374			
		41	54.003	0.25	154	54.103	-0.108	267	54.354	-0.268		54.541	-0.368			
			54.097	0.249		54.356	-0.121		54.61	-0.233		54.582	-0.359			
			53.993			54.106			54.374			54.48				
	D16	47	54.147	0.17	152	1	0	263	54.526	-0.125	325	54.625	-0.244			
			53.987	0.166		1	0	265	54.35	-0.095		54.455	-0.246			
			54.126	0.181		1	0		54.523	-0.102		54.636	-0.222			
			53.951			1			54.41			54.457				
96 hour	A9	45	54.052	0.39	153	1	0	267	54.377	-0.104	322	54.563	-0.269			
			53.937	0.387		1	0		54.226	-0.112	328	54.411	-0.247			
			54.056	0.396		1	0		54.302	-0.114		54.528	-0.219			
			53.94			1			54.316			54.311				
	A27	37	53.87	0.335	153	1	0	264	54.223	-0.246	326	54.085	-0.337			
		42	53.61	0.321		1	0	266	53.973	-0.221	327	54.188	-0.32			
			53.878	0.334		1	0		54.234	-0.24		54.206	-0.322			
			53.554			1	0		54.004			54.202				
	B3	30	53.682	0.251	153	53.954	0	266	54.147	-0.244	327	54.299	-0.318			
			53.545	0.238		53.816	0	267	54.009	-0.199	329	54.099	-0.301			
			53.735	0.259		53.934	0		54.23	-0.203		54.352	-0.352			
			53.527			53.703			53.982			54.124				
	C22	43	53.954	0.182	152	1	0	265	54.17	-0.154	324	54.412	-0.172			
		46	53.622	0.154		1	0	267	53.908	-0.156	327	54.198	-0.2			
			53.763	0.161		1	0		54.203	-0.133		54.392	-0.19			
			53.689			1			53.958			54.223				
168 hour	A11	45	53.648	0.71	153	1	0	264	53.956	-0.219	325	54.106	-0.534			
			53.679	0.762		1	0	265	53.881	-0.181	328	54.126	-0.434			
			53.617	0.646		1	0		54.053	-0.23		54.158	-0.465			
			53.619			1			53.935			54.098				
	B5	30	53.931	0.564	152	54.197	0	265	54.475	-0.305	328	54.51	-0.548			
			53.8	0.479		54.017	0	267	54.229	-0.324		54.438	-0.529			
			53.899	0.521		54.178	0		54.332	-0.329		54.548	-0.541			
			53.817			54.013			54.214			54.385				
	B26	38	53.942	0.29	153	54.17	-0.11	263	54.465	-0.469	326	54.54	-0.618			
		41	53.866	0.281	155	54.011	-0.125	266	54.277	-0.4	327	54.379	-0.561			
			54.009	0.314		54.091	-0.101		54.484	-0.416		54.585	-0.62			
			53.848			53.955			54.244			54.367				
	C24	43	54.007	0.34	152	1	0	264	54.447	-0.415	326	54.597	-0.592			
		46	53.886	0.321		1	0	265	54.2	-0.395	328	54.357	-0.569			
			53.98	0.327		1	0		54.48	-0.398		54.556	-0.571			
			53.886			1			54.238			54.321				
240 hour	B7	29	53.675	1.356	148	53.955	-0.083	266	53.924	-0.665	330	54.151	-1.016	413	54.197	-2.002
			53.576	1.372		53.857	-0.094	265	54.049	-0.642	327	54.211	-1.022		54.124	-1.965
			53.663	1.355		53.959	-0.071		54.028	-0.588		54.082	-1.036		54.188	-1.996
			53.509			53.862			54.12			54.145			54.075	
	C1	44	53.339	0.662	150	53.567	-0.035	263	53.759	-0.567	327	53.811	-0.994			
			53.259	0.633		53.525	-0.097		53.626	-0.544		53.706	-1.042			
			53.376	0.655		53.551	-0.084		53.73	-0.532		53.862	-1.02			
			53.303			53.458			53.62			53.754				
	C26	37	53.663	0.664	154	53.957	-0.083	264	54.123	-0.543	329	54.206	-1.052			
			53.566	0.682		53.816	-0.081		53.995	-0.555		54.162	-1.102			
			53.679	0.665		54.059	-0.1		54.159	-0.51		54.185	-1.067			
			53.616			53.782			54.059			54.124				
	D22	31	53.632	0.434	154	53.824	0	262	54.054	-0.251	329	54.176	-0.439			
			53.438	0.446		53.712	0	269	54.05	-0.275	322	54.153	-0.448			
			53.698	0.469		53.777	0		54.109	-0.279		54.245	-0.415			
			53.48			53.722			54.046			54.101				

Specimen Curvature with Temperature						Note: Values of 1for length and 0 for height merely indicate that there was no measurable curvature										
Specimen		Temp	Length	Height	Temp	Length	Height	Temp	Length	Height	Temp	Length	Height	Temp	Length	Height
336 hour	B9	29	53.455	1.284	150	53.84	0	265	54.02	-0.603	323	53.874	-0.905	415	54.162	-1.74
			53.45	1.253		53.592	0		53.781	-0.56		53.883	-0.875		54.017	-1.749
			53.434	1.268		53.782	0		54.002	-0.532		53.897	-0.883		54.214	-1.749
			53.49			53.634			53.779			53.864			54.048	
	C3	46	53.157	0.471	150	53.32	0	261	53.586	-0.421	327	53.76	-0.638			
			53.184	0.438		53.297	0	266	53.474	-0.401	329	53.7	-0.636			
			53.104	0.444		53.417	0		53.537	-0.395		53.744	-0.627			
			53.151			53.299			53.58			53.714				
	D24	31	53.528	0.834	154	53.643	0	262	54.006	-0.445	322	54.042	-0.85			
			53.3	0.758		53.597	0	267	53.859	-0.452		53.943	-0.845			
			53.522	0.799		53.734	0		54.058	-0.435		54.05	-0.855			
			53.349			53.583			53.842			53.891				
	D31	40	53.626	0.356	154	53.777	-0.155	264	53.859	-0.514	328	53.986	-0.917			
		38	53.541	0.403		53.667	-0.188		53.752	-0.539		53.906	-0.886			
			53.66	0.397		53.756	-0.121		53.721	-0.554		53.991	-0.878			
			53.507			53.639			53.775			53.929				
465 hour	B14	29	53.779	1.118	144	54.1	-0.088	263	54.254	-0.613	324	54.267	-0.87	413	54.488	-1.579
			53.779	1.037	153	53.923	-0.086	265	54.095	-0.594	329	54.287	-0.831		54.358	-1.601
			53.747	1.056		54.117	-0.112		54.163	-0.528		54.356	-0.878		54.466	-1.564
			53.77	1.057		53.899			54.097			54.264			54.305	
	B27	38	53.844	0.483	154	53.915	-0.227	263	54.039	-0.64	327	54.219	-1.052			
		41	53.691	0.448		53.867	-0.202	266	54.019	-0.647	329	54.124	-1.102			
			53.873	0.447		53.913	-0.216		54.074	-0.652		54.158	-1.067			
			53.672			53.821			54.003			54.122				
	C7	46	53.492	0.515	150	53.699	-0.186	262	53.688	-0.498	327	53.92	-0.839			
			53.466	0.491		53.549	-0.111	266	53.731	-0.464	325	53.857	-0.828			
			53.511	0.506		53.598	-0.112		53.718	-0.485	329	53.9	-0.825			
			53.442			53.565			53.685			53.842				
	D2	31	53.721	0.533	154	53.921	-0.146	264	54.089	-0.283	322	54.323	-0.734			
			53.68	0.502		53.787	-0.131	267	54.024	-0.388	328	54.179	-0.72			
			53.803	0.55		53.945	-0.114		54.099	-0.425		54.326	-0.797			
			53.735			53.857			54.055	-0.364		54.148				
633 hour	B16	29	53.359	1.611	140	53.537	-0.3	257	53.625	-1.144	318	53.588	-1.621	411	53.582	-2.987
			53.289	1.587	153	53.44	-0.349	268	53.548	-1.203	330	53.538	-1.579	413	53.38	-2.969
			53.366	1.604		53.638	-0.338		53.552	-1.183		53.611	-1.619		53.485	-2.909
			53.271			53.452			53.526			53.578			53.342	
	C9	47	52.96	0.668	150	53.181	-0.39	261	53.23	-1.308	323	53.146	-1.911			
			52.885	0.711	155	53.066	-0.484	267	53.187	-1.294	329	53.226	-1.912			
			52.976	0.642		53.215	-0.449		53.23	-1.301		53.314	-1.93			
			52.897			53.03	-0.436		53.21			53.154				
	C27	31	53.37	1.34	154	53.537	-0.408	265	53.604	-1.09	327	53.754	-1.674			
			53.183	1.36		53.382	-0.431	266	53.543	-1.067		53.593	-1.671			
			53.31	1.333		53.479	-0.437		53.676	-1.053		53.807	-1.692			
			53.19			53.446			53.59			53.627				
	D4	39	53.412	0.654	153	53.566	-0.488	263	53.567	-1.167	326	53.713	-1.75			
		41	53.319	0.727	154	53.425	-0.526	267	53.573	-1.186	329	53.534	-1.798			
			53.481	0.678		53.614	-0.532		53.628	-1.144		53.653	-1.771			
			53.304			53.422			53.548			53.558				
801 hour	B18	29	53.609	1.653	154	53.684	-0.53	259	53.955	-1.615	323	53.805	-2.235	411	53.475	-3.976
			53.436	1.599		53.721	-0.601	267	53.742	-1.627	330	53.824	-2.194	413	53.51	-3.908
			53.511	1.691		53.734	-0.602		53.891	-1.617		53.809	-2.203		53.503	-3.917
			53.432	1.623		53.722	-0.587		53.812			53.753			53.465	-3.971
	C11	48	53.261	0.694	151	53.346	-0.548	261	53.472	-1.341	324	53.543	-1.977			
			53.159	0.663		53.318	-0.434	267	53.433	-1.353	329	53.401	-1.99			
			53.196	0.693		53.362	-0.596		53.419	-1.373		53.6	-1.987			
			53.218			53.328	-0.6		53.436			53.41				
	D6	31	53.518	1.2	154	53.775	-0.569	264	53.904	-1.446	325	53.939	-2.091			
			53.406	1.218		53.612	-0.591	266	53.722	-1.425	327	53.846	-2.086			
			53.568	1.236		53.827	-0.603		53.911	-1.42		53.857	-2.02			
			53.486			53.64			53.777			53.81				
	D14	38	53.627	0.392	153	53.829	-0.638	263	53.855	-1.301	326	53.847	-1.807			
		42	53.584	0.387	154	53.717	-0.588	266	53.767	-1.287	329	54.138	-1.819			
			53.675	0.358		53.734	-0.626		53.873	-1.262		53.857	-1.863			
			53.562			53.749			53.756			54.077				

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	February 2000	Final Contractor Report

4. TITLE AND SUBTITLE

Mechanical Properties of Degraded PMR-15 Resin

5. FUNDING NUMBERS

WU–523–31–13–00
NAG3–2054

6. AUTHOR(S)

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8. PERFORMING ORGANIZATION REPORT NUMBER

E–12157

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
John H. Glenn Research Center at Lewis Field
Cleveland, Ohio 44135–3191

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

NASA CR—2000-209920

11. SUPPLEMENTARY NOTES

This report was submitted as a dissertation in partial fulfillment of the requirements for the degree of Master of Science in Aeronautics and Astronautics to the Massachusetts Institute of Technology, Cambridge, Massachusetts. Project Manager, Kenneth Bowles, Materials Division, NASA Glenn Research Center, organization code 5150, (216) 433–3197.

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Unclassified - Unlimited
Subject Category: 24 Distribution: Nonstandard

This publication is available from the NASA Center for AeroSpace Information, (301) 621–0390.

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 words)***

Thermo-oxidative aging produces a nonuniform degradation state in PMR-15 resin. A surface layer, usually attributed to oxidative degradation, forms. This surface layer has different properties from the inner material. A set of material tests was designed to separate the properties of the oxidized surface layer from the properties of interior material. Test specimens were aged at 316 °C in either air or nitrogen, for durations of up to 800 hr. The thickness of the oxidized surface layer in air aged specimens, and the shrinkage and coefficient of thermal expansion (CTE) of nitrogen aged specimens were measured directly. The nitrogen-aged specimens were assumed to have the same properties as the interior material in the air-aged specimens. Four-point-bend tests were performed to determine modulus of both the oxidized surface layer and the interior material. Bimaterial strip specimens consisting of oxidized surface material and unoxidized interior material were constructed and used to determine surface layer shrinkage and CTE. Results confirm that the surface layer and core materials have substantially different properties.

14. SUBJECT TERMS

Polymers; Durability; Degradation; Mechanical properties

15. NUMBER OF PAGES 81

16. PRICE CODE A05

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	