





L

This is to certify that the  
thesis entitled  
THE PHOTO-OXIDATIVE DEGRADATION OF WOVEN POLYPROPYLENE:  
CORRELATING OUTDOOR WEATHERING, SUNSHINE CARBON ARC  
TESTING AND FLUORESCENT ULTRA-VIOLET CONDENSATION  
TESTING

presented by  
Jessie Lorraine Layfield

has been accepted towards fulfillment  
of the requirements for

Master degree in Packaging

Major professor

Date 5/19/84

# LIBRARY Michigan State University

PLACE IN RETURN BOX to remove this checkout from your record.  
TO AVOID FINES return on or before date due.

DATE DUE	DATE DUE	DATE DUE
13383731 FEB 16 1996		
JAN 26 2000		

MSU is An Affirmative Action/Equal Opportunity Institution

c:\crl\dtdue\pm3-p.1

**THE PHOTO-OXIDATIVE DEGRADATION OF WOVEN POLYPROPYLENE:  
CORRELATING OUTDOOR WEATHERING, SUNSHINE CARBON ARC TESTING  
AND FLUORESCENT ULTRA-VIOLET CONDENSATION TESTING**

By

Jessie Lorraine Layfield

**A THESIS**

Submitted to  
Michigan State University  
in partial fulfillment of the requirements  
for the degree of

**MASTER OF SCIENCE**

School of Packaging

1994



**ABSTRACT**  
**THE PHOTO-OXIDATIVE DEGRADATION OF WOVEN POLYPROPYLENE:  
CORRELATING OUTDOOR WEATHERING, SUNSHINE CARBON ARC  
TESTING, AND FLUORESCENT ULTRA-VIOLET CONDENSATION TESTING**

By

Jessie Lorraine Layfield

Three woven polypropylene fabrics differing in proprietary additives were donated by various bag manufacturers. Replicates of each fabric were exposed to outdoor weathering in Florida, Sunshine Carbon Arc testing and fluorescent ultra-violet condensation testing. The results of the accelerated tests were compared to the results of the outdoor test and of each fabric was compared to one another.

The exposed fabrics were initially examined for physical degradation and then tested for a decrease in tensile strength. The tensile strength for all three fabrics, after being exposed to the various test methods, decreased. Generally, as the exposure time increased so did the amount of degradation. The results from the three test methods concluded that fabric B had the largest average tensile strength decrease. Correlation between test methods was determined using linear regression. The results show that the best correlation was obtained between carbon arc and outdoor test methods.

**Dedicated to my loving parents Dudley and Shirley Layfield.**

## **ACKNOWLEDGMENTS**

**Dr. Susan Selke:** thanks for your guidance, technical support, advice and patience. Most importantly, thanks for believing in me.

**Dr. Diana Twede:** thanks for your guidance, support and friendship.

**Dr. Charles Petty:** thanks for providing your technical expertise and guidance while serving on my committee.

**Damon Layfield and Michelle Snyder,** thanks for all your help.

**A special thanks to Dr. John Howard Jr. and Dr. Aurles Wiggins.**

**Thanks to United States Department of Agriculture, Textile Bag Manufacturers Association, and the Q-Panel Company for providing equipment and financial assistance.**

**A special thanks to Michigan State University, Dr. Jay, Frito Lay and the Urban League for sponsoring minority programs and scholarships.**

## **TABLE OF CONTENTS**

List of Tables . . . . .	vii
List of Figures . . . . .	viii
Nomenclature and Units . . . . .	xii
Introduction . . . . .	1
The Objectives of this study . . . . .	3
Literature Review . . . . .	4
Photo-Oxidative Degradation Mechanism . . . . .	5
Activation Spectrum . . . . .	7
Additives . . . . .	11
Test Methods . . . . .	13
Correlation . . . . .	16
Materials & Methods . . . . .	18
Outdoor Testing . . . . .	18
QUV Testing . . . . .	19
Sunshine Carbon Arc Accelerated Testing . . . . .	23
Instron Testing . . . . .	23
Results & Discussion . . . . .	26
Carbon Arc Exposed Samples . . . . .	26

Outdoor Exposed Samples . . . . .	28
QUV Exposed Samples . . . . .	30
Correlation . . . . .	46
Carbon Arc Exposed Samples . . . . .	46
Outdoor Exposed Samples . . . . .	48
QUV Exposed Samples . . . . .	48
Discussion . . . . .	49
Summary & Conclusions . . . . .	74
Recommendations . . . . .	76
Appendix . . . . .	77
List of References . . . . .	123

## **LIST OF TABLES**

<b>1</b>	<b>Carbon Arc Exposed Averages . . . . .</b>	<b>27</b>
<b>2</b>	<b>Outdoor Exposed Averages . . . . .</b>	<b>29</b>
<b>3</b>	<b>QUV Exposed Averages . . . . .</b>	<b>45</b>
<b>4</b>	<b>Load as a Function of X (time) . . . . .</b>	<b>47</b>
<b>5</b>	<b>Not Exposed Averages . . . . .</b>	<b>78</b>
<b>6</b>	<b>Not Exposed . . . . .</b>	<b>79</b>
<b>7</b>	<b>Carbon Arc Exposed . . . . .</b>	<b>80</b>
<b>8</b>	<b>Outdoor Exposed (1 month) . . . . .</b>	<b>90</b>
<b>9</b>	<b>Outdoor Exposed (2 month) . . . . .</b>	<b>92</b>
<b>10</b>	<b>Outdoor Exposed (3 month) . . . . .</b>	<b>94</b>
<b>11</b>	<b>Outdoor Exposed (4 month) . . . . .</b>	<b>96</b>
<b>12</b>	<b>Outdoor Exposed (5 month) . . . . .</b>	<b>98</b>
<b>13</b>	<b>QUV Exposed . . . . .</b>	<b>105</b>
<b>14</b>	<b>% Elongation as Function of X (time) . . . . .</b>	<b>116</b>

## **LIST OF FIGURES**

<b>1</b>	<b>Norrish Type I &amp; II Reactions . . . . .</b>	<b>8</b>
<b>2</b>	<b>Oxidative Photodegradation of Polypropylene . . . . .</b>	<b>9</b>
<b>3</b>	<b>QUV Weather-ometer . . . . .</b>	<b>20</b>
<b>4</b>	<b>Inside QUV . . . . .</b>	<b>21</b>
<b>5</b>	<b>QUV Sample Holders . . . . .</b>	<b>22</b>
<b>6</b>	<b>Sunshine Carbon Arc Apparatus . . . . .</b>	<b>24</b>
<b>7</b>	<b>100 Hour Samples, QUV Exposed . . . . .</b>	<b>31</b>
<b>8</b>	<b>200 Hour Samples, QUV Exposed . . . . .</b>	<b>32</b>
<b>9</b>	<b>250 Hour Samples, QUV Exposed . . . . .</b>	<b>33</b>
<b>10</b>	<b>300 Hour Samples, QUV Exposed . . . . .</b>	<b>34</b>
<b>11</b>	<b>350 Hour Samples, QUV Exposed . . . . .</b>	<b>35</b>
<b>12</b>	<b>400 Hour Samples, QUV Exposed . . . . .</b>	<b>36</b>
<b>13</b>	<b>450 Hour Samples, QUV Exposed . . . . .</b>	<b>37</b>
<b>14</b>	<b>500 Hour Samples, QUV Exposed . . . . .</b>	<b>38</b>
<b>15</b>	<b>550 Hour Samples, QUV Exposed . . . . .</b>	<b>39</b>
<b>16</b>	<b>600 Hour Samples, QUV Exposed . . . . .</b>	<b>40</b>
<b>17</b>	<b>700 Hour Samples, QUV Exposed . . . . .</b>	<b>41</b>

18	800 Hour Samples, QUV Exposed . . . . .	42
19	900 Hour Samples, QUV Exposed . . . . .	43
20	1000 Hour Samples, QUV Exposed . . . . .	44
21	Carbon Arc Exposed, Load Vs. Time, Sample A (warp) . . . . .	50
22	Carbon Arc Exposed, Load Vs. Time, Sample B (warp) . . . . .	51
23	Carbon Arc Exposed, Load Vs. Time, Sample C (warp) . . . . .	52
24	Carbon Arc Exposed, Load Vs. Time, Sample A (fill) . . . . .	53
25	Carbon Arc Exposed, Load Vs. Time, Sample B (fill) . . . . .	54
26	Carbon Arc Exposed, Load Vs. Time, Sample C (fill) . . . . .	55
27	Outdoor Exposed, Load Vs. Time, Sample A (warp) . . . . .	56
28	Outdoor Exposed, Load Vs. Time, Sample B (warp) . . . . .	57
29	Outdoor Exposed, Load Vs. Time, Sample C (warp) . . . . .	58
30	Outdoor Exposed, Load Vs. Time, Sample A (fill) . . . . .	59
31	Outdoor Exposed, Load Vs. Time, Sample B (fill) . . . . .	60
32	Outdoor Exposed, Load Vs. Time, Sample C (fill) . . . . .	61
33	QUV Exposed, Load Vs. Time, Sample A (warp) . . . . .	62
34	QUV Exposed, Load Vs. Time, Sample B (warp) . . . . .	63
35	QUV Exposed, Load Vs. Time, Sample C (warp) . . . . .	64
36	QUV Exposed, Load Vs. Time Sample A (fill) . . . . .	65
37	QUV Exposed, Load Vs. Time Sample B (fill) . . . . .	66



38	QUV Exposed, Load Vs. Time Sample C (fill) . . . . .	67
39	Carbon Arc & Outdoor (warp) . . . . .	68
40	Carbon Arc & QUV (warp) . . . . .	69
41	Outdoor & QUV (warp) . . . . .	70
42	Carbon Arc & Outdoor (fill) . . . . .	71
43	Carbon Arc & QUV (fill) . . . . .	72
44	Outdoor & QUV (fill) . . . . .	73
45	Carbon Arc Exposed, Extension Vs. Time, Sample A (warp) . . . . .	84
46	Carbon Arc Exposed, Extension Vs. Time, Sample B (warp) . . . . .	85
47	Carbon Arc Exposed, Extension Vs. Time, Sample C (warp) . . . . .	86
48	Carbon Arc Exposed, Extension Vs. Time, Sample A (fill) . . . . .	87
49	Carbon Arc Exposed, Extension Vs. Time, Sample B (fill) . . . . .	88
50	Carbon Arc Exposed, Extension Vs. Time, Sample C (fill) . . . . .	89
51	Outdoor Exposed, Extension Vs. Time, Sample A (warp) . . . . .	99
52	Outdoor Exposed, Extension Vs. Time, Sample B (warp) . . . . .	100
53	Outdoor Exposed, Extension Vs. Time, Sample C (warp) . . . . .	101
54	Outdoor Exposed, Extension Vs. Time, Sample A (fill) . . . . .	102
55	Outdoor Exposed, Extension Vs. Time, Sample B (fill) . . . . .	103
56	Outdoor Exposed, Extension Vs. Time, Sample C (fill) . . . . .	104
57	QUV Exposed, Extension Vs. Time, Sample A (fill) . . . . .	110
58	QUV Exposed, Extension Vs. Time, Sample B (fill) . . . . .	111
59	QUV Exposed, Extension Vs. Time, Sample C (fill) . . . . .	112

60	QUV Exposed, Extension Vs. Time Sample A (warp) . . . . .	113
61	QUV Exposed, Extension Vs. Time Sample B (warp) . . . . .	114
62	QUV Exposed, Extension Vs. Time Sample C (warp) . . . . .	115
63	Carbon Arc & QUV (warp) - % Elongation . . . . .	117
64	Carbon Arc & Outdoor (warp) - % Elongation . . . . .	118
65	Outdoor & QUV (warp) - % Elongation . . . . .	119
66	Carbon Arc & QUV (fill) - % Elongation . . . . .	120
67	Outdoor & QUV (fill) - % Elongation . . . . .	121
68	Outdoor & Carbon Arc (fill) - % Elongation . . . . .	122

## **NOMENCLATURE and UNITS**

<b>Fill</b>	Yarn that is carried by the shuttle in weaving and "fills" in the fabric perpendicular to the warp yarns.
<b>Carbon Arc Samples</b>	Represented in hours
<b>Degrees C</b>	Degrees Celsius
<b>Degrees F</b>	Degrees Fahrenheit
<b>Extn</b>	Extension (inches)
<b>Load</b>	Represented in pounds
<b>Outdoor Samples</b>	Represented in months
<b>% Elongation</b>	Change in length/gage length
<b>% Reduction</b>	Percent reduction, $((\text{initial load} - \text{final load}) / \text{initial load}) \times 100$
<b>UV</b>	Ultraviolet
<b>QUV Samples</b>	Represented in hours
<b>RH</b>	Relative Humidity
<b>Warp</b>	Yarn that is first threaded onto the loom.

## **INTRODUCTION**

The United States Department of Agriculture (USDA) is the largest food buyer in the world. Commodities purchased range from vegetable oil to grain and infant formula. The USDA has the largest on-going food assistance program the world has ever known, with approximately 70 million recipients overseas. Food products are donated to countries around the world including Mozambique, Peru, Croatia and India. Here in the United States, approximately 1 in 7 Americans receive food assistance (Miteff, 1993).

Multi-wall natural kraft bags, high density polyethylene bottles, tin plated steel cans and woven polypropylene bags are all containers used by the USDA to package products being shipped overseas. The products are transported overseas by large steamships owned by various steamship companies. Once the products reach their destination port, the products are usually stored in a warehouse or storage facility, but sometimes they are stored on the docks or in open areas for long periods of time.

Michigan State University (MSU) has been providing the USDA with packaging assistance for more than 15 years. MSU works for continual improvement in packages, develops performance standards, evaluates proposed packages and solves packaging related problems. This research was

requested by the USDA and the Textile Bag Manufacturers Association. This study focuses on the degradation involved when storing woven polypropylene bags outdoors for long periods of time in hot climates. The USDA currently buys between 40-60 million woven polypropylene bags per year, so this problem is of major significance (Miteff, 1993). Woven polypropylene bags stored outside are often exposed to ultraviolet radiation from the sun, atmospheric contaminants, and water from rain and the ocean. A combination of these variables and others often lead to the photo-oxidative degradation of woven polypropylene.

Presently, the USDA uses the Sunshine Carbon Arc as its standard test method for bag manufacturers to use when testing woven polypropylene bags. The Sunshine Carbon Arc is an accelerated weathering test used to simulate outdoor conditions in hot and humid climates. The USDA standard when using the Sunshine Carbon Arc test is a minimum of 70% load strength retention after 200 hours of exposure. However, the USDA is now considering allowing an alternative test method (fluorescent ultra-violet condensation type exposure test-QUV) for bag manufacturers to use. In this study woven polypropylene samples were exposed in the Sunshine Carbon Arc and QUV Weather-ometer and in actual outdoor tests conditions in Maimi, Florida. The exposed samples were visually examined for degradation and then tested for a decrease in tensile strength using an Instron tensile testing apparatus.

**The objectives of this study are:**

- 1      Compare the degree of degradation between fabrics.
- 2      Compare the degree of degradation between test methods.
- 3      Determine the correlation between test methods.

The study first reviews the literature pertaining to photo-oxidation degradation, ultraviolet rays, activation spectrums, accelerated testing, outdoor testing and correlation of outdoor test methods. The second chapter discusses the materials and methods used, followed by the results and discussion. The study concludes with a summary, followed by an appendix containing various data tables.

## **LITERATURE REVIEW**

Photo, chemical, thermal, oxidation, bio and mechanical are some of the types of degradation that can affect polymers. For the purpose of this study we will be focusing on photo-oxidative degradation (weathering) of polypropylene. Photodegradation is the degradation of a polymer caused by exposure to ultraviolet radiation and/or other extreme sources of light (Encyclopedia, 1984). Oxidative degradation is the degradation caused by the reaction oxygen and ozone with a polymer structure (Encyclopedia, 1984). It is common to have one type of degradation initiate another type of degradation, or they may occur simultaneously.

Degradation can be the loss of desired properties and/or the destruction of the molecular structure of the polymer. According to Hardy (1983b), polypropylene degrades through a radical chain process. In 1984, Hawkins concluded that the photo-oxidative degradation mechanism occurring in polyolefins can be Norrish Type I or Norrish Type II. Contaminants, additives, pollutants, photostabilizers, temperature, light source, and the season of year, can all influence degradation. To measure and analyze the effect of photo-oxidative degradation, several tests methods are available.

### **Photo-Oxidative Degradation Mechanism**

Ultraviolet light (290-400nm), visible light (400-760nm) and infrared light (above 760nm), combine to form the electromagnetic energy from sunlight.

The major factor responsible for photo-oxidative degradation is ultraviolet radiation. Wavelengths in the ultraviolet region vary in their effectiveness in causing degradation. Generally, the shorter ultraviolet wavelengths tend to cause more degradation. This is largely because of their higher energies and greater tendency for being absorbed by materials (Searle, 1984). Ultraviolet radiation is largely responsible for the generation of free radicals, while it has little to no effect on the propagation steps of the reaction (Grassie, 1985).

"When polymers are exposed to sunlight, bond cleavage and destructive oxidation occur, leading to reduction in molecular weight and consequently a diminished service life for the polymer" (Hardy, 1983a).

McTigue and Blumberg (1967) investigated the factors affecting light resistance of polypropylene, concluding that the photo-oxidative degradation of polypropylene proceeds from the exposed surface inward. This leads to the conclusion that thicker samples may not degrade as rapidly as thinner samples.

Morphology of a polymer may also impact degradation. Oxygen permeates readily through the amorphous regions of polypropylene, however not as readily through the crystalline regions (Grassie, 1985). Thus one can expect that a more crystalline polymer will not degrade as readily as an amorphous polymer. This assumption does not hold true for all cases, because



a small amount of oxygen permeation can cause considerable degradation of crystalline structures. Oxygen can penetrate into the amorphous region and weaken the 'adhesives' that hold together the crystalline region, sometimes causing as much degradation as if the structure were not crystalline (Grassie, 1985).

Ultraviolet radiation can be absorbed into polymers through groups in their normal structure, but quite often it is the presence of structural irregularities or associated impurities that are primary ultraviolet absorbers (Hawkins, 1984). "Polypropylene's aliphatic structure suggests it should not absorb ultraviolet light, the presence of impurities can cause enough absorption to initiate degradation" (Hardy, 1983a). Polyethylene, polyvinyl chloride, and polystyrene are all more resistant to photo-oxidative degradation than unstabilized polypropylene (Seppala et al, 1991).

Degradation generally begins at the weakest available bond. Unsaturated bonds (double bonds) tend to enhance degradation of a polymer. Chromophores in polymers cause degradation by readily absorbing energy so that it can be available for cleaving bonds. Chromophores tend to absorb only at certain wavelengths. Hydroperoxide groups, aromatic compounds and ketones are examples of chromophores. "The energy content of absorbed ultraviolet light can be sufficient to rupture carbon-carbon, carbon-oxygen and carbon-hydrogen bonds near the surface of polymers" (Tobin and Vigeant, 1981).

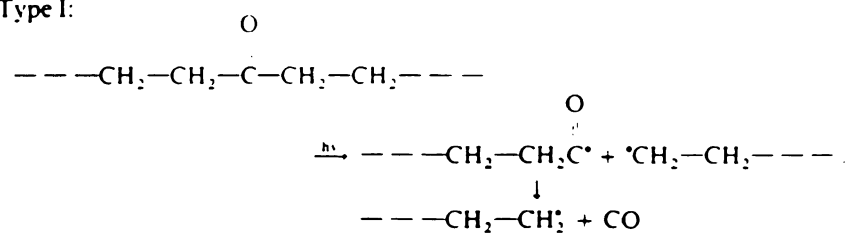
Some uncertainty surrounds the initial reaction in photo-oxidation. Guillet, suggests hydroperoxide or carbonyl groups are responsible for initiation of degradation, while Carlson and Wiles, emphasize the role of hydroperoxides (Hawkins, 1984). More research is needed to be conclusive.

As stated earlier, Norrish Type I and Norrish Type II reactions are common mechanisms for photo-oxidation of polypropylene. The same mechanisms also can occur for the photo-oxidation of polyethylene (Hawkins, 1984). (See Figure 1.) The type I reaction involves the production of a free radical, which promotes chain scission and thus further reaction of free radicals. The Norrish Type II reaction does not directly produce free radicals; however, it does directly produce main-chain cleavage, and thus a decreased molecular weight. Cross-linking can take place in both types of reactions. In 1970, Cicchetti proposed a mechanism for the photo-oxidative degradation of polypropylene. (See Figure 2.)

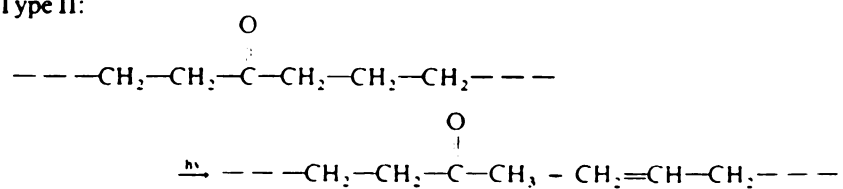
### **Activation Spectrum**

An activation spectrum identifies in a polymer the wavelengths that are most damaging to that material (Searle, 1986). The spectrographic and filter techniques are two techniques used to obtain an activation spectrum. With the spectrographic technique, individual regions of the spectrum are isolated and

Norrish Type I:

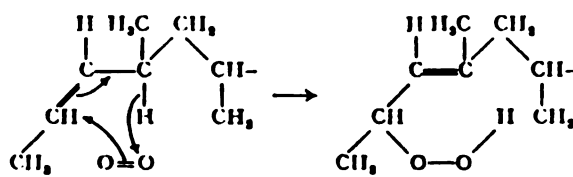
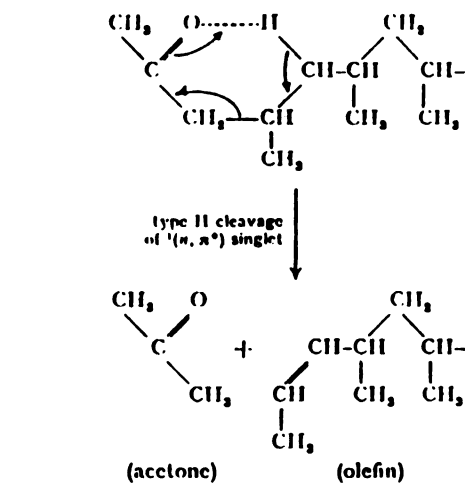


Norrish Type II:



**Fig. 1: Norrish Type I & II Reactions (Hawkins, 1984)**

## 1st Phase (initiation)



## 2nd Phase (degradation)

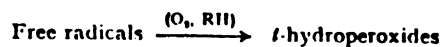
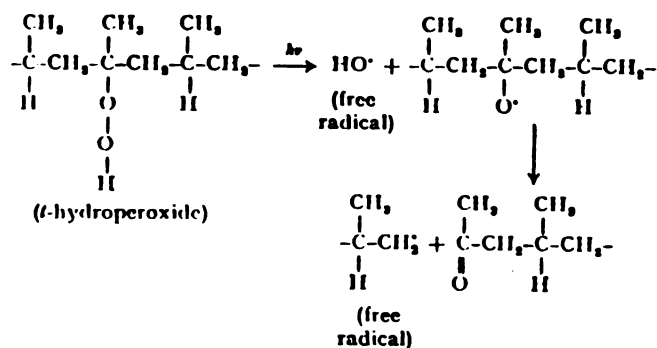


Fig. 2: Oxidative Photodegradation of Polypropylene (Cicchetti, 1970)

are incident on adjacent areas of the same sample (Searle, 1984). A plot of the measured degradation versus wavelength of irradiation is used to obtain an activation spectrum (Searle, 1986). The filter technique uses a separate sample for the radiation transmitted by each filter (Searle, 1984). "In contrast to the spectrographic technique, the filter technique provides a larger size sample which allows physical property as well as optical measurements of degradation to be made" (Searle, 1986).

There are four main factors that are used in determining an activation spectra: 1) emission characteristics of the radiation source: energy and intensity; 2) absorption properties of material: characteristic absorption, effect of thickness, and effect of impurities; 3) criteria of degradation; and 4) stability of the polymer to absorbed radiation (Searle, 1986).

It is important to note that each activation spectrum is based on measurement of a specific type of degradation. Therefore, activation spectrums may vary. Activation spectrums can be useful in selecting ultraviolet screeners and absorbers. "Since the effectiveness of an ultraviolet absorber depends on its ability to screen the actinic wavelengths from the polymer, the relative effectiveness of several absorbers can be estimated from the match of their spectral characteristics to the activation spectrum" (Searle, 1986). Activation spectrums can also be useful when selecting which accelerated weathering test to use.

**Additives**

Some of the uses of degradable polymers include stretch tape, rope, food bags, seed bags, artificial turf, and beverage ring connectors. A major concern when using degradable plastics is their susceptibility to premature failure when exposed to sunlight. The effects of photo-oxidative degradation include both physical and mechanical property loss. Physical property losses include yellowing, discoloration, chalking, brittleness, and flaking. Mechanical property losses include a decrease in impact strength, tensile strength and elongation at break. The combination of physical and mechanical property losses lead to a less desirable and a less reliable polymer. There has been considerable research in this area directed toward making polymers more stable when exposed to sunlight, stabilizing or reducing the rate of reaction of the polymer.

Premature failure of polymers used in outdoor applications can be prevented by using a photostabilizer and/or an antioxidant. There are five general types of photostabilizers: (1) ultraviolet screeners, (2) ultraviolet absorbers, (3) excited state quenchers, (4) hydroperoxide decomposers, and (5) free radical scavengers (Hardy, 1983a).

Ultraviolet screeners can be opaque additives or pigments which reflect or absorb ultraviolet radiation before it penetrates into the interior of the material (Kelen, 1983). However, screeners sometimes have adverse effects on other additives (Kelen, 1983). Carbon black, zinc oxide, titanium dioxide and iron

oxide are all commonly used as screeners (Hardy, 1983a).

Ultraviolet absorbers absorb and dissipate the energy of ultraviolet radiation which has penetrated into the interior of the polymer (Kelen, 1983). Commonly used absorbers are 2-hydroxybenzophenones and hydroxyphenylbenzotriazoles (Hardy, 1983a). Ultraviolet absorbers perform well with thicker samples.

"Quenchers relieve the excited polymer molecules of their excess energy, returning them to ground state; the excited quencher then releases its newly acquired energy as harmless heat" (Tobin et al, 1981).

Hydroperoxide decomposers destroy hydroperoxide groups before light absorption takes place (Hardy, 1983a). Nickel dibutyldithiocarbamate and nickel di-isopropyldithiophosphate are common hydroperoxide decomposers.

Hindered amine light stabilizers (HALS) are free radical scavengers which terminate free radical photo-oxidation reactions (Tobin et al, 1981). "HALS are most effective in the stabilization of polymers which undergo a free-radical chain oxidation after photo-initiation" (Carlsson et al, 1984). Quinones, aromatic amines and conjugated molecules are examples of scavengers.

In addition to photostabilizers, antioxidants are sometimes needed to help impede degradation. "The antioxidant may be a free-radical scavenger that interrupts the degradation or it may be a peroxide decomposer" (Tobin et al, 1981). BHT is an example of an antioxidant. When combining a photostabilizer and antioxidant, it is generally the goal to obtain a synergistic combination.

However, it is possible to obtain an antagonistic combination. For example, "carbon black can inhibit oxidation and also function as a light stabilizer; however, its combination with phenolic and amine compounds is disadvantageous because it catalyzes their oxidation" (Kelen, 1983).

Photostabilizers and antioxidants last only until they are used up by chemical reactions. Using monomers of high purity and proper selection of processing to avoid initiator or catalyst residues are both additional ways to achieve polymer stabilization.

### **Test Methods**

Accelerated laboratory tests and outdoor exposure tests are both common methods used to measure and analyze photo-oxidative degradation.

Accelerated tests were developed as an approach to better control exposure conditions and to permit continuous exposure to the radiation (Schweitzer, 1987). There are two main purposes of using accelerated indoor test methods: (1) the determination of relative photochemical stability and weather resistance of different materials, and (2) the prediction of the life expectancy of samples from relatively short-term exposure testing (McTigue and Blumberg, 1967).

There are four light sources commonly used to produce artificial sunshine: (1) carbon arc, (2) fluorescent lamps, (3) xenon arc, and (4) mercury arc (Hirt and Searle, 1967). The carbon arc weather-ometers have been used as the standard for laboratory weathering since 1933 (Q-Panel, 1988). Carbon



arc light sources give a closer approximation to sunlight at the short wavelength end of the spectrum (Hirt and Searle, 1967). However, "carbon arc has very strong emission peaks in the ultraviolet region, which are not present in sunlight" (Hardy, 1983b). Fluorescent lamps are generally expected to have a harsher effect on clear plastics than either sunlight or the carbon arc (Hirt and Searle, 1967). "Xenon arc emissions bear the closest relationship to the solar spectrum in the ultraviolet region" (Hirt and Searle, 1967). Preference is usually given to a xenon arc light over carbon arc (Hardy, 1983b). "There is probably as much short wavelength energy below 3200Å in the mercury arcs as in the fluorescent sunlamp" (Hirt and Searle, 1967). However, "in the longer wavelength region the background is weaker and the mercury emission lines are stronger than in the fluorescent sunlamp" (Hirt and Searle, 1967).

The overall best light source to use depends largely on the test method and the purpose of the test. In general it is best to match the light source being used as closely as possible to actual sunlight (Fischer, 1984). Although this may lengthen the duration of test time, it will give more reliable results for most materials (Fischer, 1984).

The arc type of weather-ometers try to reproduce all of the sunlight spectrum, while fluorescent weather-ometers just reproduce the damaging effects (Brennan and Fedor, undated). UVA-340 fluorescent lamps may be best used to simulate the short wavelength portion of sunlight, while UV-B fluorescent lamps allow for faster testing (Brennan and Fedor, undated). As the

speed of a test is increased, the accuracy decreases, the reverse also holds true (Fischer, 1984). Xenon Arc lamps with quartz/borosilicate filters are often used in automotive tests. The Carbon Arc is best used when trying to determine the effect of the entire spectrum of sunlight on the polymer.

Common instruments used in accelerated testing include weather-ometers, infrared spectrophotometers and Instron machines. The QUV, S3000 Xenon, UVCON and Sunshine Carbon Arc are all weather-ometers that provide an artificial light source for accelerated testing. Weather-ometers often have special features that range from condensation or spraying moisture on samples to simulate humidity, to having light and dark cycles to simulate day and night. Instron machines are used for performing tensile tests, thus measuring mechanical properties.

The infrared spectrophotometers are used to measure carbonyl content. As photo-oxidation continues, the carbonyl group content increases (Hawkins, 1984). Degradation of polypropylene can easily be measured by its carbonyl content (Hardy, 1983a). Gel permeation chromatography can also be used in future tests to measure molecular weight distribution before and after exposure, thus analyzing and measuring degradation.

Outdoor exposure involves photo-oxidation, thermal degradation and atmospheric contaminants. Thermal degradation is the effect of infrared radiation being absorbed into the polymer and ultraviolet radiation and is responsible for photo-oxidation (Hawkins, 1984). Atmospheric contaminants

(nitrogen oxides and sulfur dioxide) can actually increase the rate of reaction. Outdoor tests are usually conducted in either southern Florida, where material are exposed to sunlight and high humidity, or in Arizona, where materials are exposed to sunlight and low humidity. With an increase in temperature and humidity there is generally an increase in degradation. "Ideally, the exposure site selected should approximate the conditions to which the polymer will be subjected in the intended application" (Schweitzer, 1987).

Latitude, season, pollution and cloud cover are just some of the geographic influences that affect how much ultraviolet radiation reaches the earth. Variation in the level of ultraviolet radiation is also influenced by different ozone concentrations and the intensity of sky radiation (Hawkins, 1984). The summer months are the best time for outdoor testing, because of higher temperatures, increased ultraviolet intensity and longer days, thus more sunlight. The major problem with outdoor testing is the time required to obtain results. Nonetheless, outdoor testing is used extensively since it does reflect the actual conditions of use (Schweitzer, 1987).

### **Correlation**

Correlation of accelerated weathering to outdoor testing is often complex and difficult. As stated earlier, there are many factors that influence photo-oxidative degradation outdoors; some are not reproduced in accelerated laboratory tests conditions, thus variation in results may occur. Sample

preparation and storage, test conditions and test equipment may all contribute to variation in results. In 1987, Simms investigated the variability between replicate samples and found that both accelerated and outdoor exposure results of duplicate samples were greatly variable (Fischer and Ketola, 1993).

To adjust for variations, accelerated shift factors, statistical correlations, models and correlation coefficients have been developed. "There are two types of statistics that are commonly used to measure correlation, Pearson's  $r$ , which is a parametric measure, and Spearman's Rho which is non-parametric" (Crewdson, 1993). Pearson's linear correlation works under the assumption that the degradation can be measured on an interval scale (Grossman, 1977). However, Spearman's rank correlation uses visual ranking like physical degradation or color loss (Grossman, 1977). To help reduce the need for the correlation coefficients, continuous monitoring and stringent controls of tests methods may be helpful. The best correlation method to use depends largely on the tests being conducted. According to Crewdson (1993), the best use for correlation results between outdoor and laboratory accelerated tests is as a guideline rather than a rule.

## **MATERIALS**

Three woven polypropylene fabrics differing in proprietary additives were donated by bag manufacturers. These fabrics are typical of those used by the USDA. The resins are formulated by the manufacturers to have adequate UV stabilizers to meet the 200 hour carbon arc test. All three fabric are circular woven.

Sample A had an average thickness of .01208 inches and had 10 (warp) by 11 (fill) yarns per inch. Sample B had an average thickness of .00924 inches and had 9 (warp) by 9 (fill) yarns per inch. Sample C had an average thickness of .00724 inches and had 11 (warp) by 7 (fill) yarns per inch. All three samples had a white color. Fabric weights:

Sample A: 2.65 oz/yd<sup>2</sup>    Sample B: 2.68 oz/yd<sup>2</sup>    Sample C: 2.38 oz/yd<sup>2</sup>

## **METHODS**

### **Outdoor Testing**

The specimens were mounted on a plywood backing and exposed to direct weathering in south Florida at 45 degrees South, following ASTM-G7-89. The specimens were tested at 1, 2, 3, 4, and 5 months of exposure, beginning on

August 24, 1993. Outdoor weather conditions were recorded by South Florida Test Service in Miami, Florida. Sample size was 4" by 12".

### **QUV Testing**

The specimens were exposed in a QUV/SE Accelerated Weathering Tester, in accordance with ASTM G53. QUV/SE is manufactured by the Q-Panel Company, in Cleveland, Ohio. The specimens were tested for 100, 200, 250, 300, 350, 400, 450, 500, 550, 600, 700, 800, 900, and 1000 hours. The QUV machine was located in a temperature controlled (72 degrees F and 50% RH) room. Samples were rotated every other day. (See Figures 3, 4 & 5.) Test conditions were as follows:

Light Source:	UVA-340, fluorescent bulbs
Temperature:	UV cycle 70 degrees C, Condensation cycle 40 degrees C
Irradiance Level:	$1.35 \pm .05 \text{ W/m}^2/\text{nm}$ @ 340nm
Test Cycle:	8 hours UV/4 hours condensation
Sample Size:	4.5" by 7.5"
Water Type:	Regular drinking water



Fig.3: QUV WEATHER-OMETER

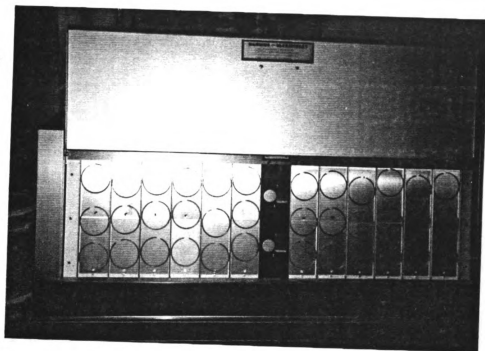


Fig. 4: INSIDE QUV



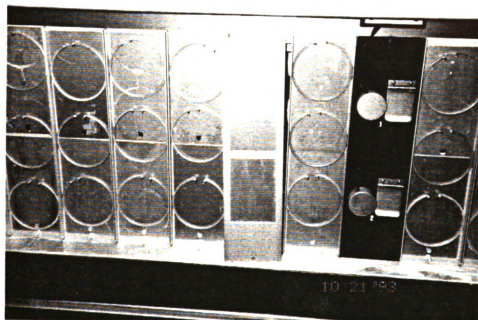


Fig. 5: QUV SAMPLE HOLDERS

**Sunshine Carbon Arc Accelerated Testing**

The specimens were exposed in a CXW #1 Sunshine Carbon Arc Weather-Ometer, in accordance with ASTM 5804. The specimens were tested at 100, 200, 300, and 400 hours intervals. (See Figure 6.) Test conditions were as follows:

RH:	55 $\pm$ 5%
Spray Nozzle:	F-80
Black Panel Temperature:	63 $\pm$ 2 degrees C
Test Cycle:	102 minutes light, 18 minutes dark and spray
Filter Type:	Corex D
Sample Size:	2 5/8" by 8"
Light Source:	Sunshine Carbon Arc
Water Type:	Deionized Water

**Instron Testing**

Nonexposed, conditioned (72 degrees F and 50% RH) samples of all three fabrics, in both fill and warp direction, were tested using an Instron machine, in accordance with ASTM D5035 (ravel test). Once specimens were exposed to one of the three testing methods, they were tested for a decrease in tensile strength using the Instron machine. Exposed specimens too brittle to be

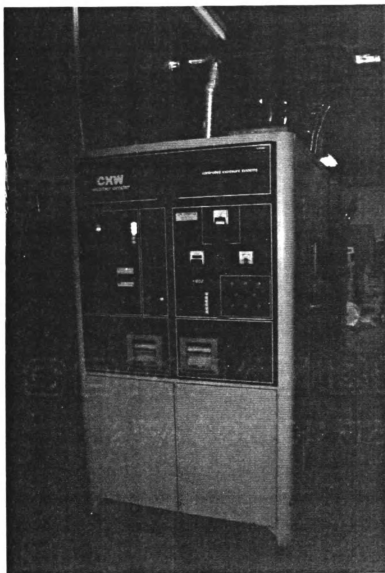


Fig. 6: SUNSHINE CARBON ARC APPARTUS

handled or having any visible hole through the sample were not tested in the Instron. Their tensile strength was considered to be zero. Testing conditions were as follows:

Load Cell Weight:	5Kn
Gage Length:	3"
Speed:	12 in/sec
Sample Size:	10 yarns
Jaw Pressure:	90 psi

## **RESULTS & DISCUSSION**

### **CARBON ARC EXPOSED**

Samples exposed in the Sunshine Carbon Arc Weather-ometer showed no signs of physical degradation, but they did show a decrease in load strength when tested using the Instron. (See Table 1.)

Sample A showed an unexplained increase in load strength between 100 hour and 200 hour samples in both the warp and fill direction. In the fill direction there was some increase between 300 hour and 400 hour samples.

Sample B in the warp direction showed some fluctuation (decrease then increase in strength) in the 200 hour and 300 hour samples. However, in the fill direction there was a steady decrease in load strength.

Sample C showed a steady decrease in load strength in the warp direction. However, in the fill direction there was a little fluctuation between the 100 hour and 200 hour samples and between the 300 hour and 400 hour samples.

Sample B showed the highest average percent reduction for load in the warp and fill direction, followed by Sample A and Sample C, respectively.

Table 1: Carbon Arc Exposed Averages

	WARP			FILL		
			% REDCT			% REDCT
HOURS	LOAD	EXTN	LOAD	LOAD	EXTN	LOAD
<b>A</b>						
0	106.24	0.7138		73.11	0.6515	
100	55.17	0.3141	48.07	44.51	0.3322	39.12
200	103.88	0.6412	2.22	65.55	0.5443	10.35
300	96.35	0.6575	9.31	8.09	0.1398	88.93
400	64.04	0.3783	39.72	46.99	0.3689	35.73
		AVG=	24.83			43.53
<b>B</b>						
0	96.55	0.7348		105.86	0.7756	
100	79.59	0.6224	17.57	42.32	0.5326	60.02
200	60.70	0.4654	37.13	34.86	0.2270	67.07
300	76.16	0.5493	21.11	11.49	0.2136	89.15
400	67.03	0.4969	30.58	4.63	0.2050	95.63
		AVG=	26.60			77.97
<b>C</b>						
0	98.31	0.7384		80.46	0.6636	
100	88.62	0.7267	9.86	71.08	0.6004	11.66
200	83.66	0.5352	14.90	78.55	0.5838	2.38
300	78.01	0.4986	20.65	59.20	0.4541	26.42
400	65.82	0.4440	33.05	63.26	0.4674	21.37
		AVG=	19.6131		AVG=	15.4587

**OUTDOOR EXPOSED SAMPLES**

The only fabric to exhibit visible physical degradation after being exposed outdoors in Florida was Sample B. In both the fill and warp direction, samples exposed for 5 months were extremely brittle. The samples actually broke apart when handled and therefore, were unable to be tested in the Instron.

All three fabrics showed a decrease in load strength when tested in the Instron. (See Table 2.) Sample A showed a steady decrease in load strength in both the warp and fill direction. Sample B showed a very small initial increase in load strength, in both the warp and fill direction. This may be due to the brittleness that occurred. Some fluctuation between the 4 and 5 month samples was shown in the warp direction for Sample B. Sample C showed a consistent decrease in both the warp and fill direction.

In the warp direction, Sample A had the highest average percent reduction for load, followed by Sample B and Sample C, respectively. However, in the fill direction Sample B had the highest average percent reduction for load followed by Sample A and Sample C, respectively. It is important to note however, that at 5 months Sample A was tested using the Instron, but Sample B was too brittle to be tested.

Table 2: Outdoor Exposed Averages

	WARP			FILL		
			% REDCT			% REDCT
MONTHS	LOAD	EXTN	LOAD	LOAD	EXTN	LOAD
<b>A</b>						
0	106.24	0.7138		73.11	0.6515	
1	81.06	0.5289	23.70	62.92	0.4619	13.94
2	73.58	0.4692	30.74	51.52	0.3775	29.53
3	65.43	0.4191	38.41	45.00	0.3399	38.45
4	54.71	0.3589	48.51	37.71	0.3380	48.42
5	47.72	0.3225	55.08	32.68	0.2799	55.29
		AVG=	39.29			37.12
<b>B</b>						
0	96.55	0.7348		105.86	0.7756	
1	97.26	0.6161	-0.74	107.30	0.6377	-1.36
2	79.36	0.4726	17.80	53.23	0.2440	49.72
3	57.17	0.4627	40.79	9.17	0.2824	91.34
4	62.75	0.4278	35.01	4.44	0.2529	95.80
5	0	0	100	0	0	100
		AVG=	38.57			67.10
<b>C</b>						
0	98.31	0.7384		80.46	0.6636	
1	80.38	0.5101	18.24	64.29	0.5146	20.10
2	80.99	0.4801	17.62	62.20	0.4407	22.69
3	64.13	0.4147	34.76	56.21	0.4137	30.14
4	52.58	0.3581	46.51	45.13	0.3837	43.91
5	40.40	0.2699	58.90	37.45	0.3180	53.46



**QUV EXPOSED SAMPLES**

All three samples showed some physical degradation at various time intervals. At 600 hours Sample A began to show the first signs of flaking and brittleness. (See Figures 7-16.) At 700 hours the brittleness increased and a visible hole was present. (See Figure 17.) At 800, 900 and 1000 hours the brittleness continued to increase and so did the size of the holes. (See Figures 18 - 20.) From 700 to 1000 hours Sample A was not tested on the Instron.

Sample B began to show signs of flaking and brittleness at 300 hours. (See Figure 10.) At 350, 400 and 450 hours the flaking and brittleness increased to a point where the samples could not be tested using the Instron. (See Figures 11 - 13.) The first visible hole appeared at 500 hours. (See Figure 14.) The brittleness and hole size increased for the duration of the test times. (See Figures 15 - 20.)

Sample C did not exhibit signs of flaking, but at 800 hours there was a noticeable amount of brittleness. (See Figure 18.) At 900 and 1000 hour test intervals the brittleness increased to a point where tensile testing was not possible. (See Figures 19 & 20.) No visible holes were ever present.

All three samples showed a decrease in load strength when tested using the Instron. (See Table 3.) Sample A and B showed a steady decrease in load strength in both the warp and fill direction. Sample C had a slight increase between the 400 and 500 hour samples in the warp direction. There was a small fluctuation between the 550 and 600 hour samples in both the warp and

A(4 on left)

B(4 in middle)

C(4 on right)

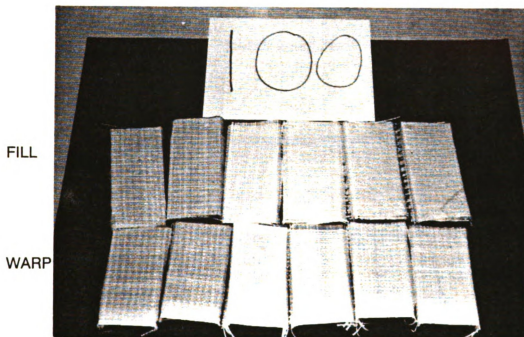


Fig. 7: 100 HOUR SAMPLES, QUV EXPOSED

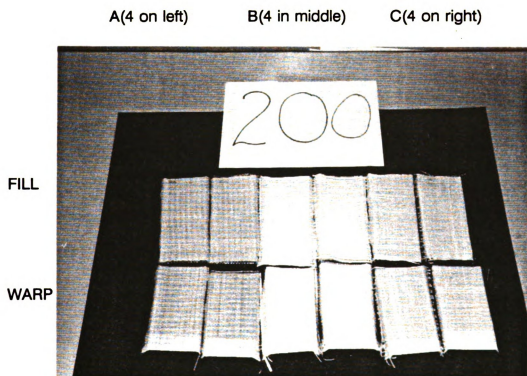


Fig 8 : 200 HOUR SAMPLES, QUV EXPOSED

A(4 on left)

B(4 in middle)

C(4 on right)

FILL

WARP

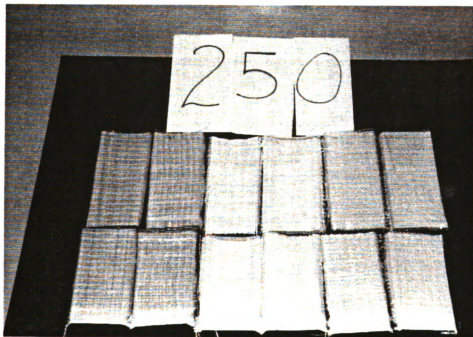


Fig. 9: 250 HOUR SAMPLES, QUV EXPOSED

A(4 on left)

B(4 in middle)

C(4 on right)

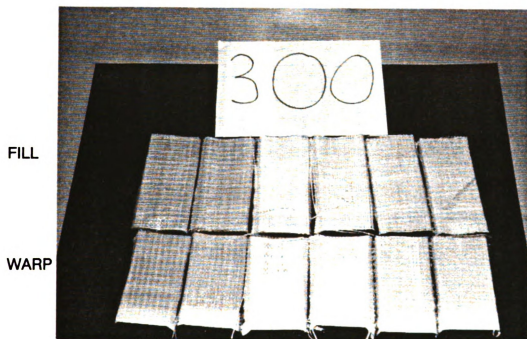


Fig. 10: 300 HOUR SAMPLES, QUV EXPOSED

A(4 on left)

B(4 in middle)

C(4 on right)

FILL

WARP

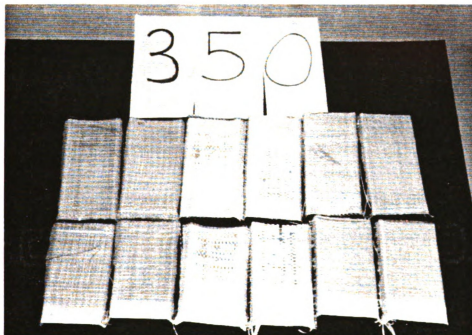


Fig. 11: 350 HOUR SAMPLES, QUV EXPOSED

A(4 on left)

B(4 in middle)

C(4 on right)



Fig. 12: 400 HOUR SAMPLES, QUV EXPOSED

A(4 on left)

B(4 in middle)

C(4 on right)

FILL

WARP

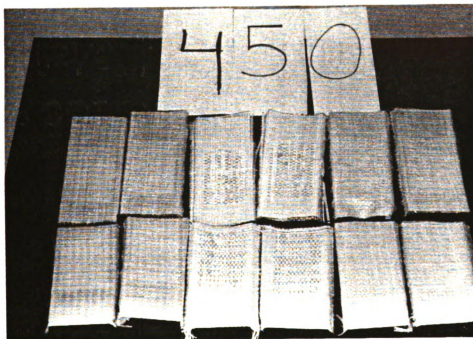


Fig. 13: 450 HOUR SAMPLES, QUV EXPOSED



A(4 on left)

B(4 in middle)

C(4 on right)

FILL

WARP



Fig. 14: 500 HOUR SAMPLES, QUV EXPOSED

A(4 on left)

B(4 in middle)

C(4 on right)

FILL

WARP



Fig. 15: 550 HOUR SAMPLES, QUV EXPOSED

A(4 on left)

B(4 in middle)

C(4 on right)

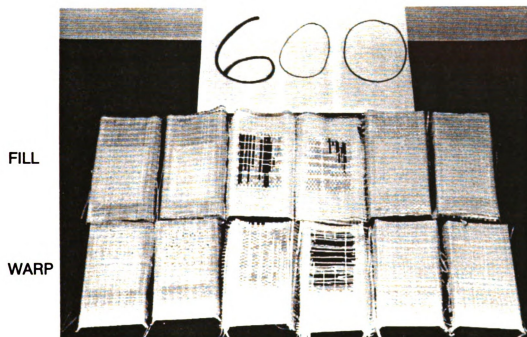


Fig. 16: 600 HOUR SAMPLES, QUV EXPOSED

A(4 on left)

B(4 in middle)

C(4 on right)

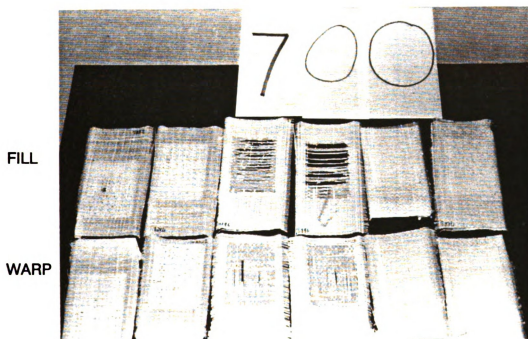


Fig. 17: 700 HOUR SAMPLES, QUV EXPOSED

A(4 on left)

B(4 in middle)

C(4 on right)

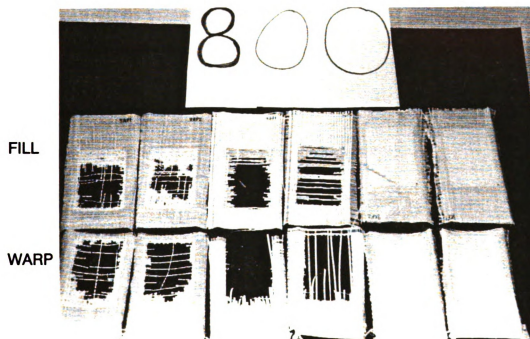


Fig. 18: 800 HOUR SAMPLES, QUV EXPOSED

A(4 on left)

B(4 in middle)

C(4 on right)



Fig. 19: 900 HOUR SAMPLES, QUV EXPOSED

A(4 on left)

B(4 in middle)

C(4 on right)

FILL

WARP

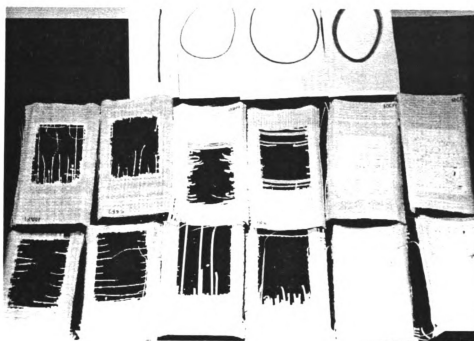


Fig. 20: 1000 HOUR SAMPLES, QUV EXPOSED

Table 3: QUV Exposed Averages

	WARP		FILL			
			% REDCT			% REDCT
HOURS	LOAD	EXTN	LOAD	LOAD	EXTN	LOAD
A						
0	106.24	0.7138		73.11	0.6515	
100	102.40	0.6108	3.61	69.71	0.5058	4.65
200	89.01	0.6103	16.22	67.84	0.4723	7.21
250	90.09	0.5185	15.20	61.50	0.4252	15.88
300	64.01	0.3830	39.75	55.58	0.3510	23.98
350	60.63	0.3340	42.93	44.73	0.3190	38.62
400	49.94	0.2962	52.99	44.56	0.2962	39.05
450	44.14	0.2698	58.45	24.19	0.2005	66.91
500	22.79	0.1600	78.55	22.20	0.1945	69.63
550	12.94	0.1532	87.82	8.70	0.1270	88.10
600	5.70	0.2062	94.63	4.37	0.1010	94.02
700	0	0	100	0	0	100
800	0	0	100	0	0	100
900	0	0	100	0	0	100
1000	0	0	100	0	0	100
	AVG=		63.5829			60.5898
B						
0	96.55	0.7348		105.86	0.7756	
100	96.30	0.6070	0.26	102.90	0.6698	2.80
200	83.58	0.5115	13.44	32.91	0.2953	68.91
250	79.90	0.4290	17.25	12.45	0.3193	88.24
300	45.64	0.2975	52.73	12.67	0.4653	88.04
350	0	0	100	0	0	100
400	0	0	100	0	0	100
450	0	0	100	0	0	100
500	0	0	100	0	0	100
550	0	0	100	0	0	100
600	0	0	100	0	0	100
700	0	0	100	0	0	100
800	0	0	100	0	0	100
900	0	0	100	0	0	100
1000	0	0	100	0	0	100
	AVG=		77.4053			89.1415
C						
0	98.31	0.7384		80.46	0.6636	
100	91.66	0.6688	6.76	75.73	0.4820	5.88
200	65.27	0.4203	33.61	63.34	0.4745	21.28
250	68.70	0.4480	30.12	60.24	0.4335	25.13
300	59.40	0.3635	39.58	53.77	0.4713	33.17
350	59.28	0.3293	39.70	51.07	0.3690	36.53
400	41.42	0.2845	57.87	45.93	0.3658	42.92
450	51.42	0.3435	47.70	45.99	0.3053	42.84
500	32.30	0.1933	67.14	38.03	0.3185	52.73
550	29.63	0.2093	69.86	28.90	0.2455	64.08
600	33.11	0.1980	66.32	33.81	0.2700	57.98
700	12.85	0.1240	86.93	15.87	0.1402	80.28
800	2.84	0.1213	97.11	2.83	0.1035	96.48
900	0	0	100	0	0	100
1000	0	0	100	0	0	100
	AVG=		60.193	AVG=		54.2355



fill direction.

Sample B had the highest average percent reduction for load in both the warp and fill direction, followed by Sample A and Sample C respectively.

## **CORRELATION**

Correlation of the three test methods and three fabrics was obtained using linear regression. First, the load averages versus time (original graphs) were graphed using a best fit line. (Percent elongation was not used in determining correlation between test methods.) Secondly, from the original graphs the equation of a line (for each graph) was used and 50%, 60%, 70%, 80%, and 90% of the initial load strength was used as Y, and an X (time) was calculated. (See Table 4.) Thirdly, the X's (time) calculated for each test method and each material were plotted against one another, again using a best fit line. Finally, from this last set of graphs X was set equal to 200 hours (USDA standard for carbon arc) and a Y (time) correlation was calculated for the QUV and outdoors.

## **CARBON ARC EXPOSED SAMPLES**

The load averages for the three carbon arc fabrics were plotted versus time (hours). In the warp direction: Sample C had a 97% correlation; Sample B had a 52% correlation; while Sample A had only a 8% correlation.

Table 4: Load as a Function of X (time)

	INITIAL LOAD	WARP	Y 0.5	Y 0.6	Y 0.7	Y 0.8	Y 0.9
A		106.24	53.12	63.744	74.368	84.992	95.616
B		96.55	48.275	57.93	67.585	77.24	86.895
C		96.31	49.155	58.986	69.817	76.648	88.479
		FILL					
A		73.11	36.555	43.866	51.177	58.488	65.799
B		105.86	52.93	63.516	74.102	84.688	95.274
C		80.46	40.23	48.276	56.322	64.368	72.414
Y=LOAD			Y=Mx+B X=(Y-B)/M				
OUTDOOR (MONTHS)			WARP				
	B	M	X	X	X	X	X
A	98.585	-10.851	4.189936	3.210856	2.231776	1.252696	0.273615
B	108.98	-17.385	3.491803	2.936439	2.381076	1.825712	1.270348
C	97.309	-11.137	4.323786	3.441052	2.558319	1.675586	0.792853
		FILL					
	B	M	X	X	X	X	X
A	70.797	-8.1229	4.21549	3.315442	2.415394	1.515346	0.615297
B	109.66	-25.198	2.251369	1.831256	1.411144	0.991031	0.570918
C	77.518	-7.9577	4.685776	3.67468	2.663584	1.652488	0.641391
QUV (HOURS)			WARP				
	B	M	X	X	X	X	X
A	104.97	-0.13051	397.2876	315.8838	234.4801	153.0764	71.67267
B	79.076	-0.11045	278.8683	191.4531	104.038	16.62291	-70.7922
C	93.094	-0.10566	415.8527	322.809	229.7653	136.7216	43.67783
		FILL					
	B	M	X	X	X	X	X
A	75.514	-0.09271	420.238	341.3766	262.5152	183.6539	104.7925
B	58.923	-0.08691	68.95719	-52.8484	-174.654	-296.46	-418.265
C	81.934	-0.08916	467.7434	377.5011	287.2589	197.0166	106.7743
CARBON ARC (HOURS)			WARP				
	B	M	X	X	X	X	X
A	93.78	-0.04322	940.7682	694.956	449.1439	203.3318	-42.4803
B	88.5	-0.06247	643.9091	489.3549	334.8007	180.2465	25.69233
C	98.002	-0.07559	646.2098	516.1529	386.096	256.0392	125.9823
		FILL					
	B	M	X	X	X	X	X
A	65.382	-0.08866	325.141	242.6799	160.2188	77.75773	-4.70336
B	86.49	-0.23329	143.8553	98.47829	53.10129	7.724292	-37.6527
C	79.765	-0.04628	854.2567	680.4019	506.5471	332.6923	158.8375

(See Figures 21 - 23.) In the fill direction: Sample B had a 84% correlation; Sample C had a 62% correlation; and Sample A had a 30% correlation. (See Figures 24-26.)

### **OUTDOOR EXPOSED SAMPLES**

Graphs of load averages versus time (months) in the warp direction for the three outdoor samples showed: Sample C had a 96% correlation; Sample A had a 94% correlation; and Sample B had a 81% correlation. (See Figures 27 - 29.) In the fill direction Sample A had a 98% correlation; Sample C had a 96% correlation; and Sample B had a correlation of 88%. (See Figures 30 - 32.)

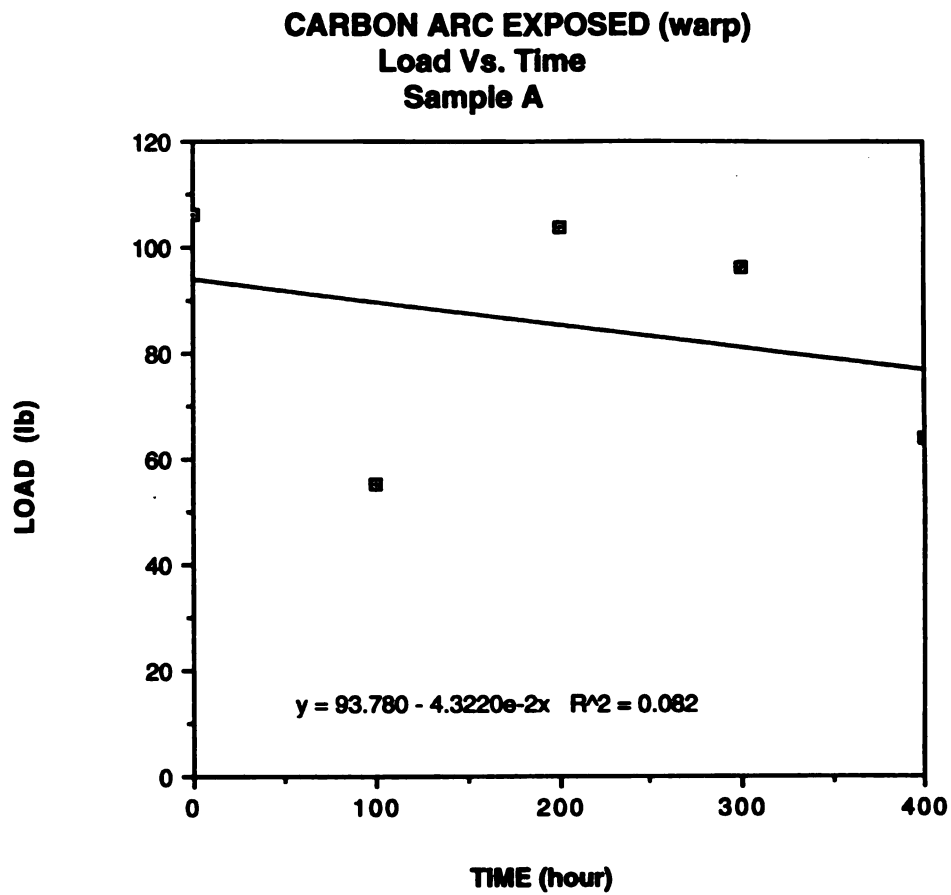
### **QUV EXPOSED SAMPLES**

Load averages for the three fabrics exposed in the QUV were plotted versus time (hours), using a best fit line. The graphs for the warp direction showed: Sample C had a correlation of 95%; Sample A had a correlation of 88%; and Sample B had a 61% correlation. (See Figures 33 - 35.) In the fill direction the graphs showed; Sample C had a 97% correlation; Sample A had a 87% correlation; and Sample B had a 48% correlation. (See Figures 36 - 38.)

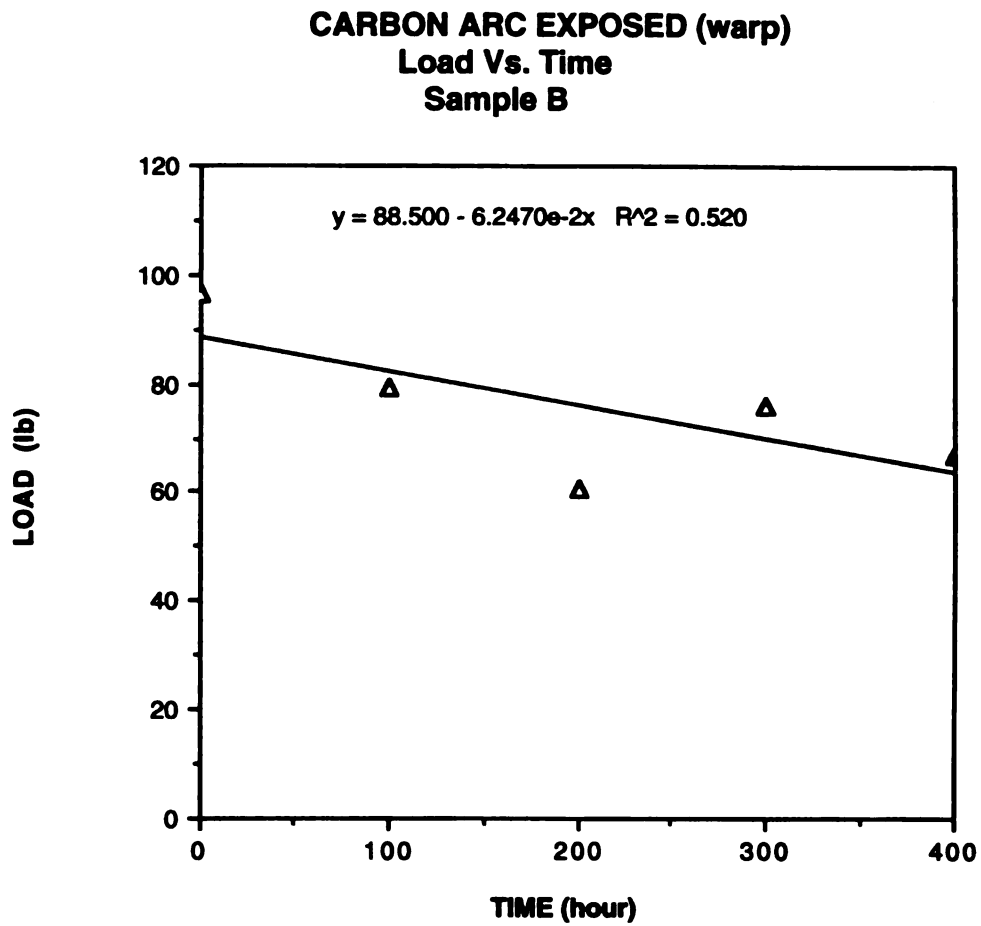
**DISCUSSION**

In the warp direction correlation between carbon arc and outdoor test methods yielded 85% correlation; carbon arc and QUV yielded 80% correlation; and outdoor and QUV yielded 78% correlation. (See Figures 39-41.) In the fill direction correlation between carbon arc and outdoor yielded 31% correlation; carbon arc and QUV yielded 54% correlation; and outdoor and QUV yielded 59% correlation. (See Figures 42-44.)

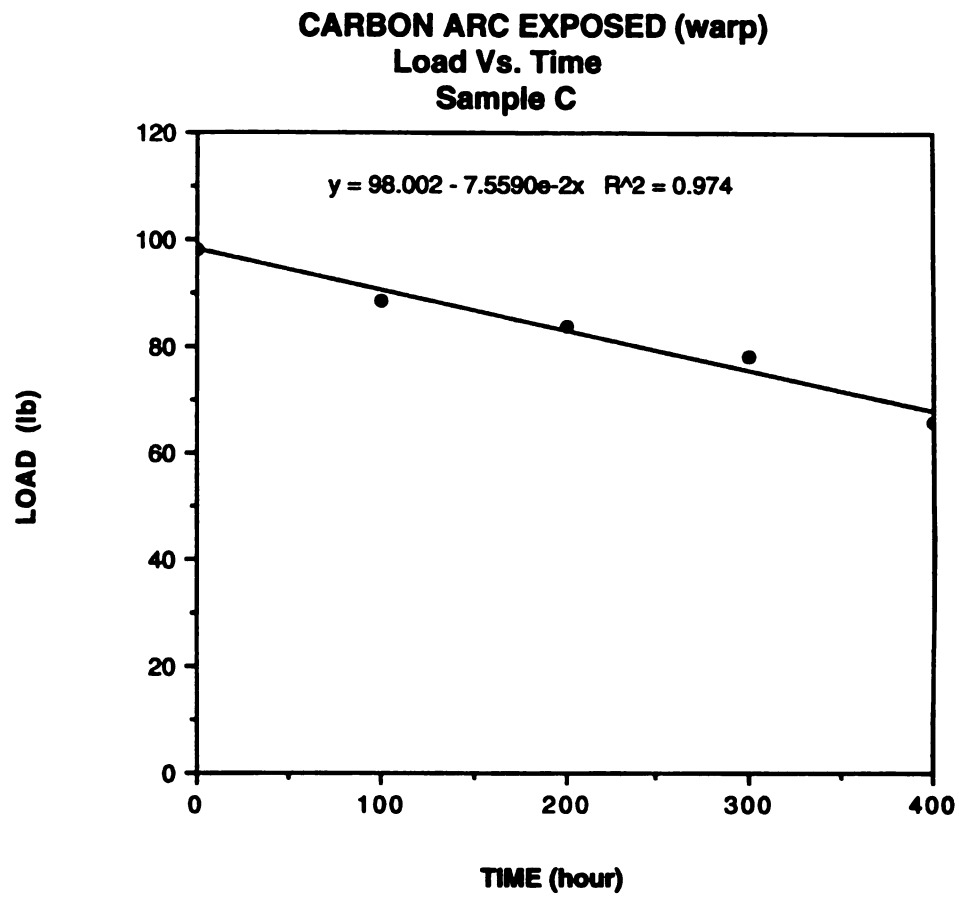
Since the warp direction gave the best correlation, it was used to calculate equivalent test times. Using the equation of the line from Figures 39 and 40 and the USDA standard: 200 hours (X) in the carbon arc was calculated to be equivalent to 1.65 months outdoors and 98.3 hours in the QUV. Using 98.3 hours in the QUV as X and the equation of the line from Figure 41, and equivalence of 1.54 months outdoors was calculated.



**Fig. 21: Carbon Arc Exposed, Load Vs. Time, Sample A (warp)**



**Fig. 22: Carbon Arc Exposed, Load Vs. Time, Sample B (warp)**



**Fig. 23: Carbon Arc Exposed, Load Vs. Time, Sample C (warp)**

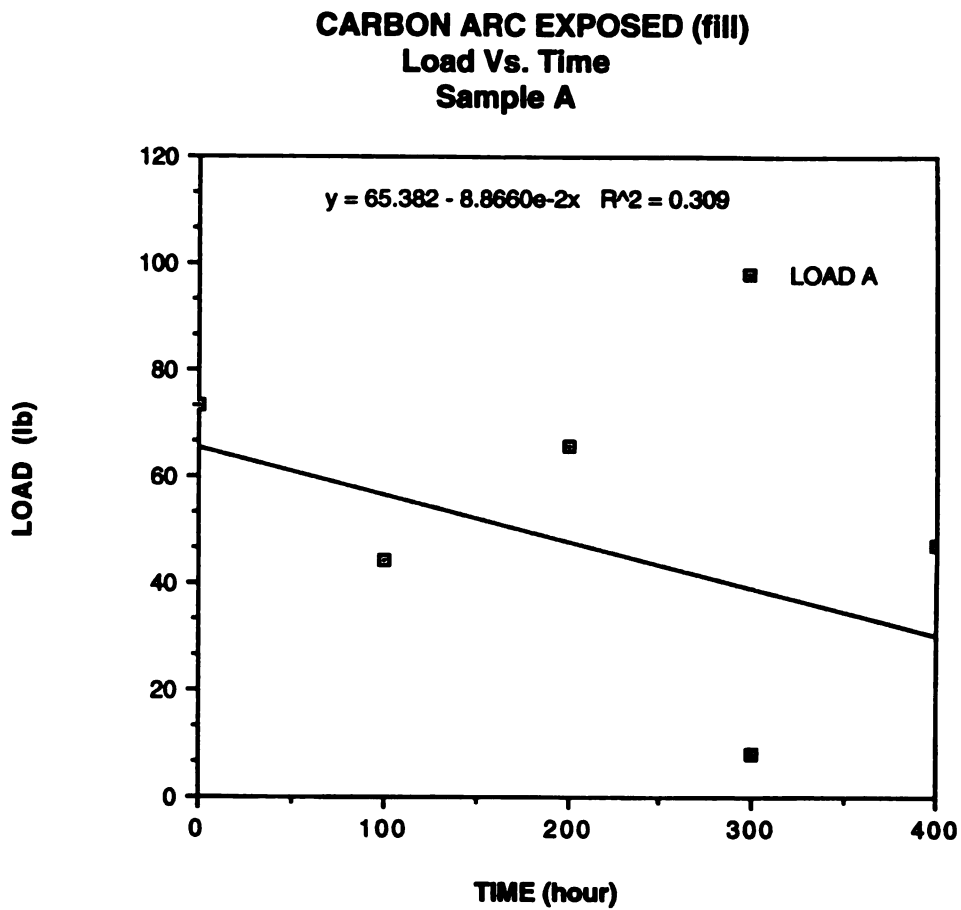


Fig. 24: Carbon Arc Exposed, Load Vs. Time, Sample A (fill)



**CARBON ARC EXPOSED (fill)**  
**Load Vs. Time**  
**Sample B**

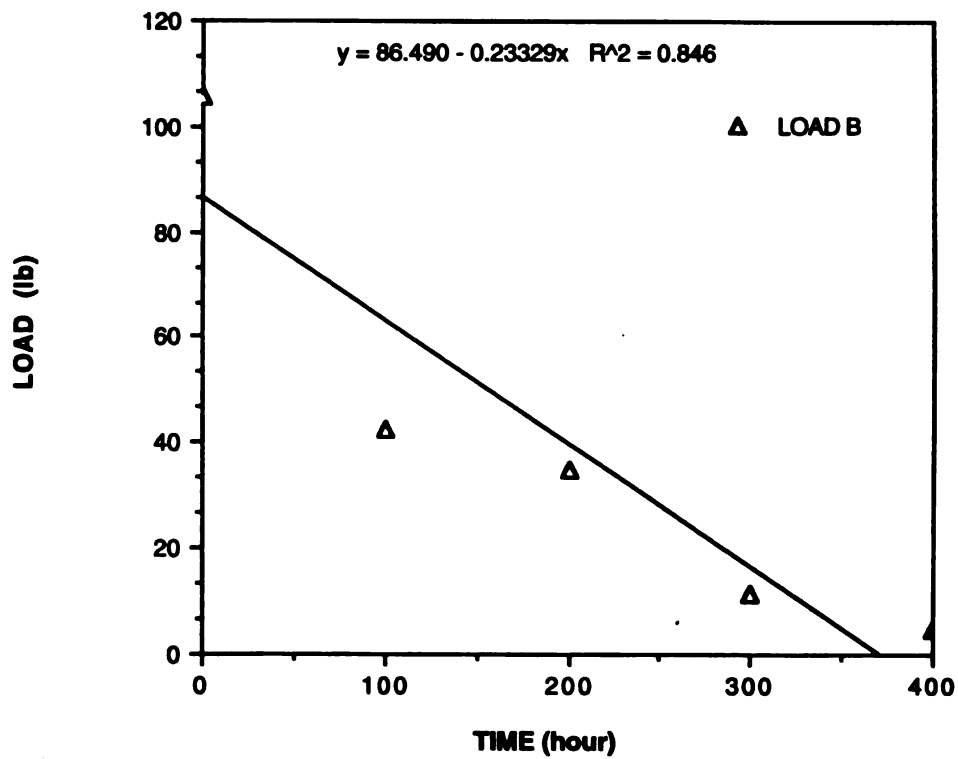
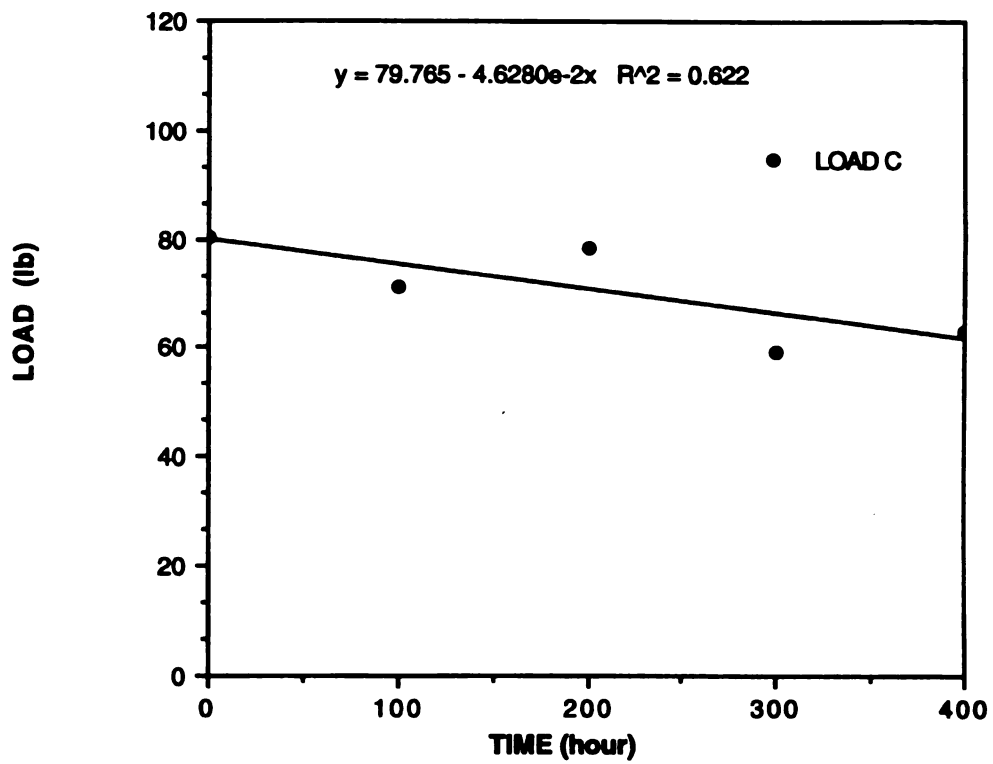


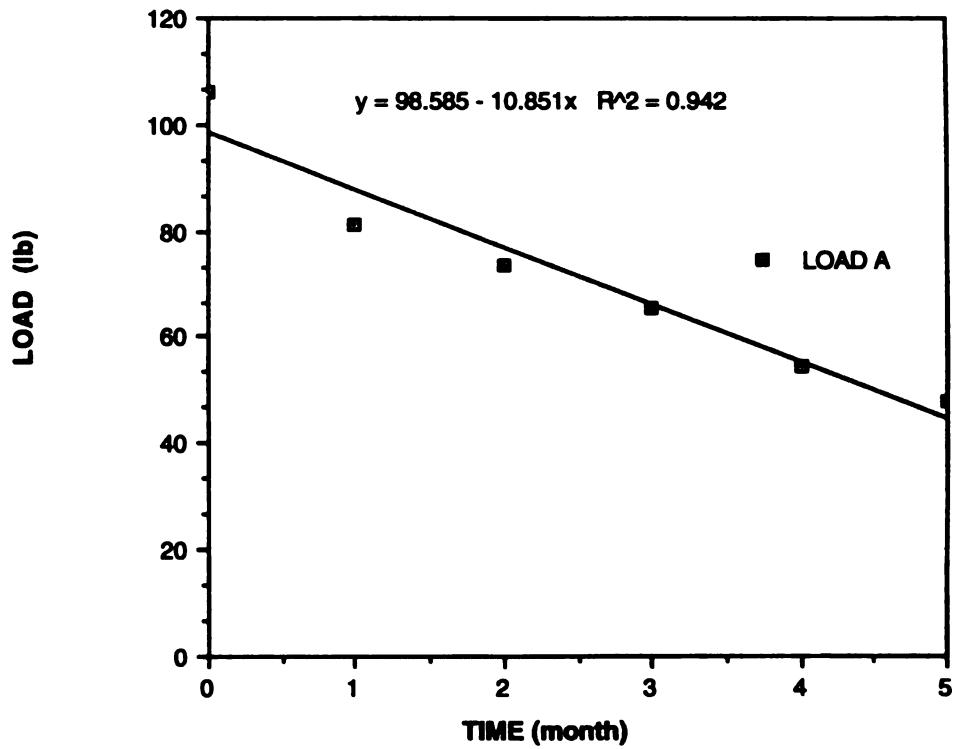
Fig. 25 : Carbon Arc Exposed, Load Vs. Time, Sample B (fill)

**CARBON ARC EXPOSED (fill)**  
**Load Vs. Time**  
**Sample C**



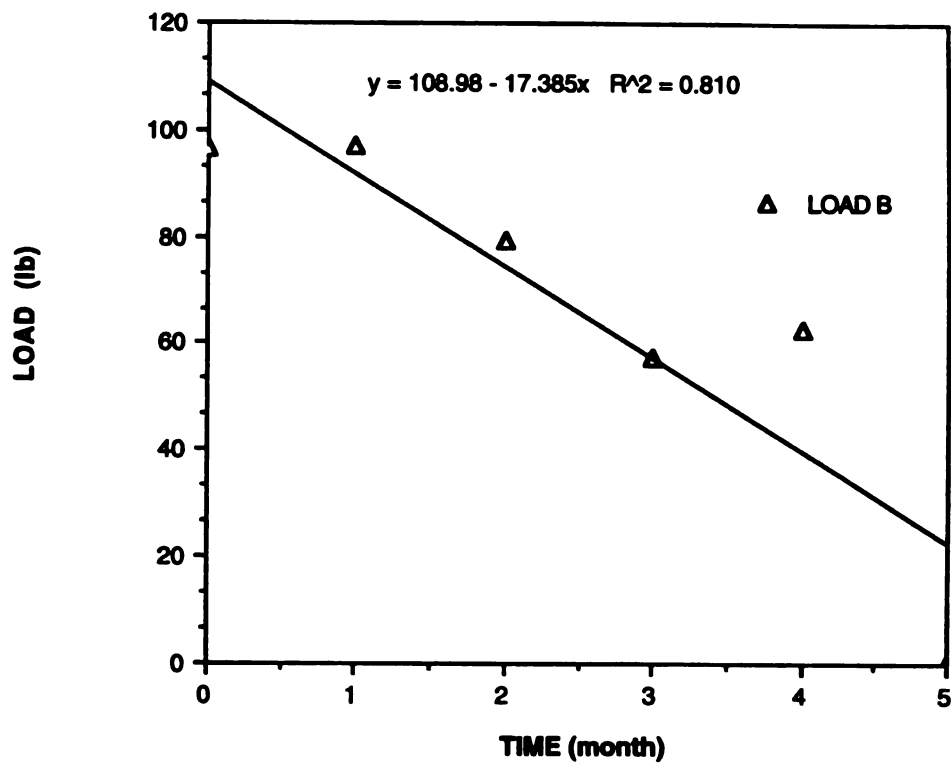
**Fig. 26: Carbon Arc Exposed, Load Vs. Time, Sample C (fill)**

**OUTDOOR EXPOSED (warp)**  
**Load Vs. Time**  
**Sample A**

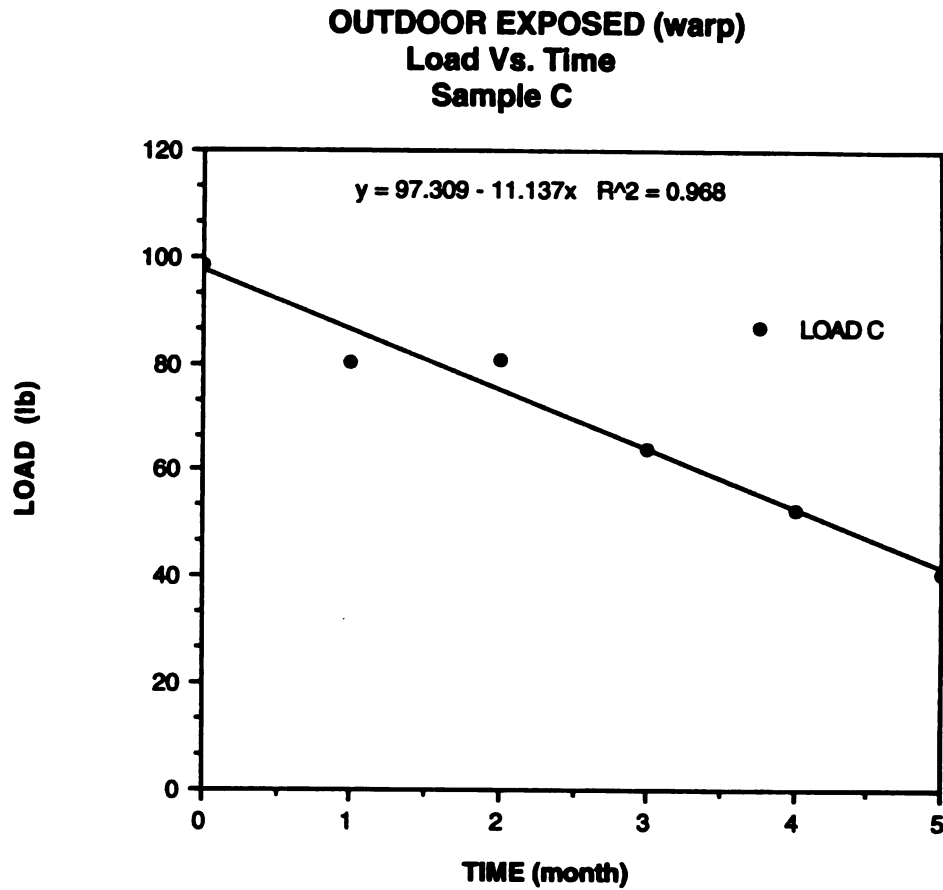


**Fig. 27: Outdoor Exposed, Load Vs. Time, Sample A (warp)**

**OUTDOOR EXPOSED (warp)**  
**Load Vs. Time**  
**Sample B**



**Fig. 28: Outdoor Exposed, Load Vs. Time, Sample B (warp)**



**Fig.29 : Outdoor Exposed, Load Vs. Time, Sample C (warp)**

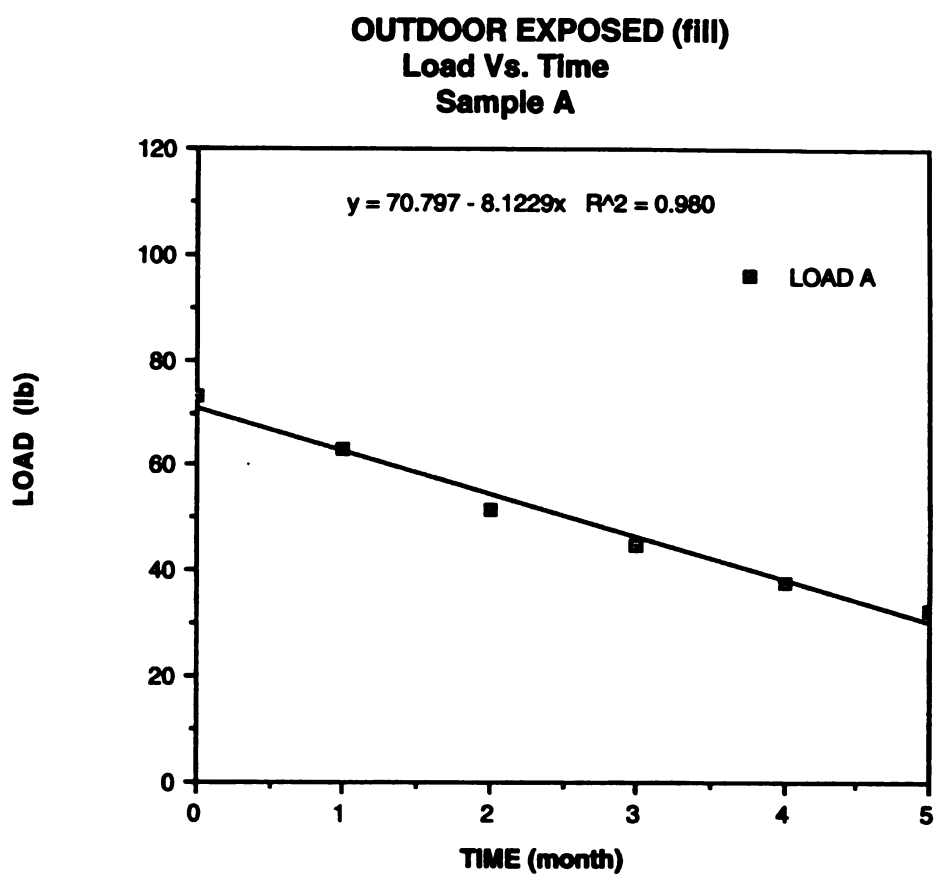
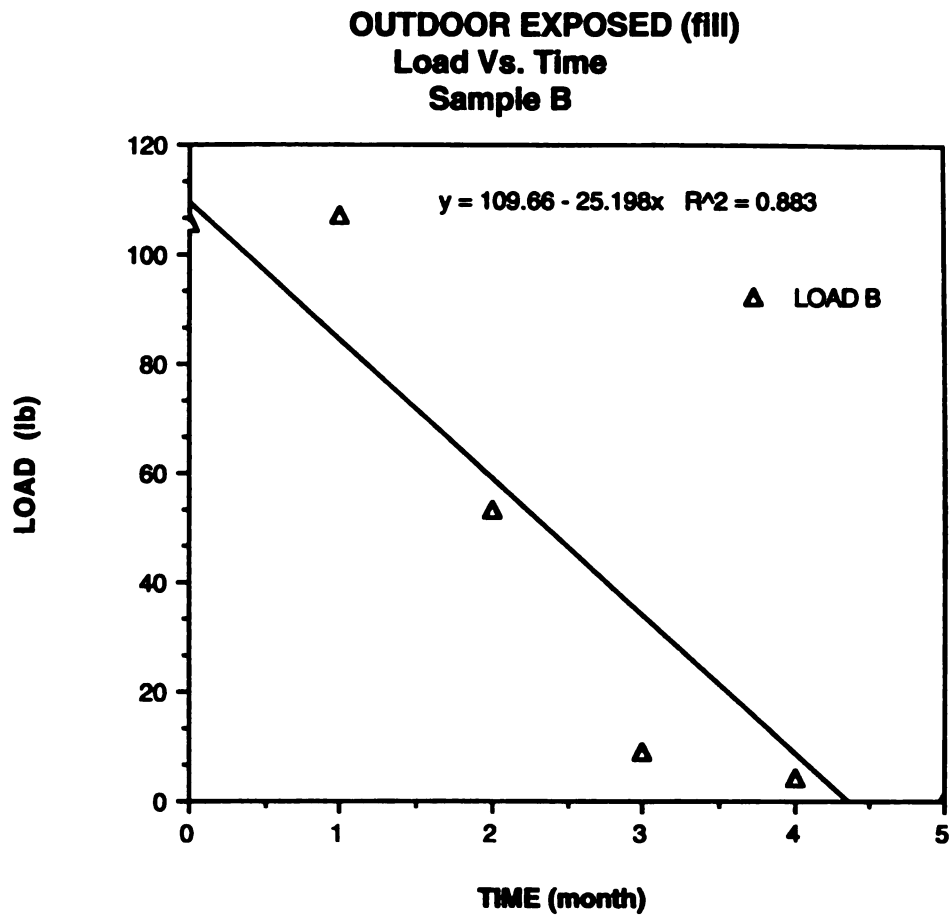
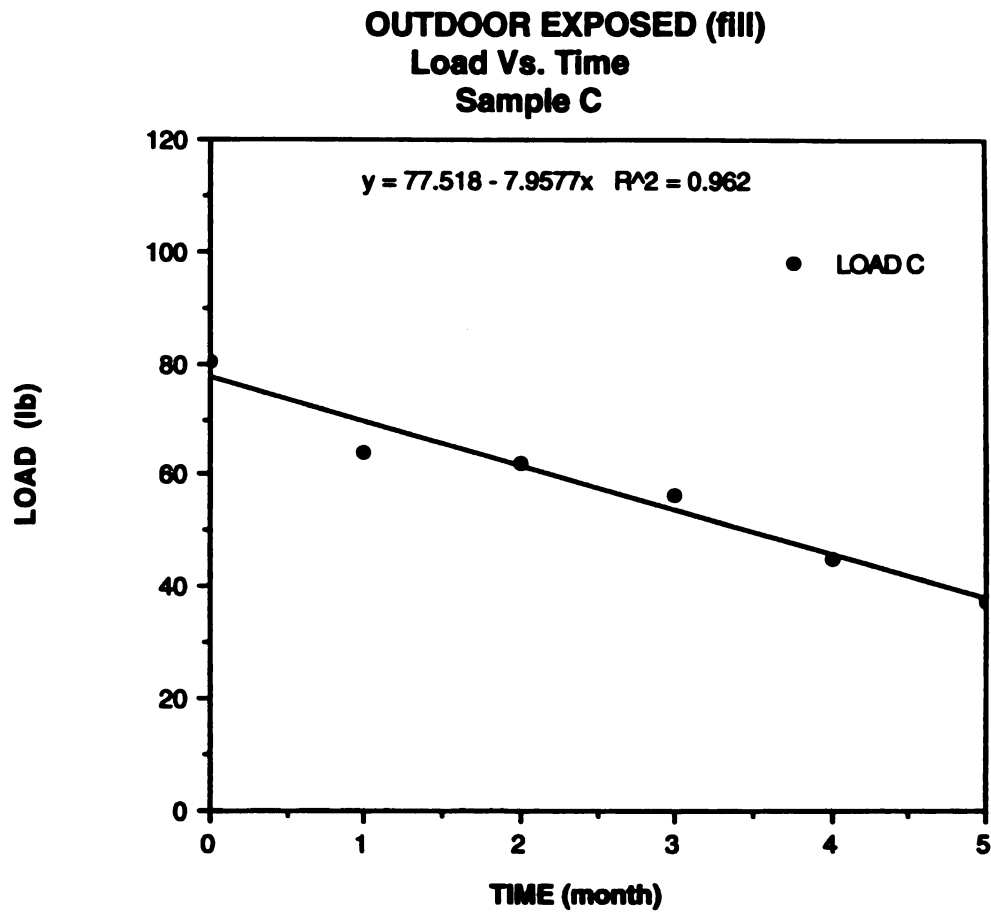


Fig. 30: Outdoor Exposed, Load Vs. Time, Sample A (fill)



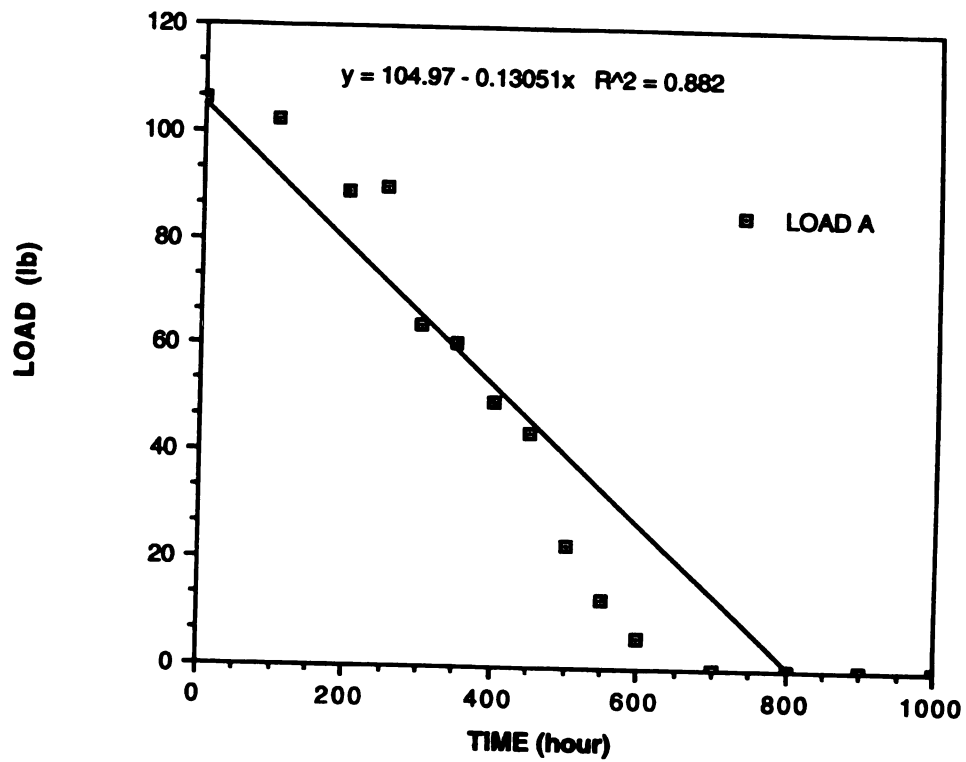
**Fig. 31: Outdoor Exposed, Load Vs. Time, Sample B (fill)**



**Fig. 32: Outdoor Exposed, Load Vs. Time, Sample C (fill)**



**QUV EXPOSED (warp)**  
**Load Vs. Time**  
**Sample A**



**Fig. 33: QUV Exposed, Load Vs. Time, Sample A (warp)**

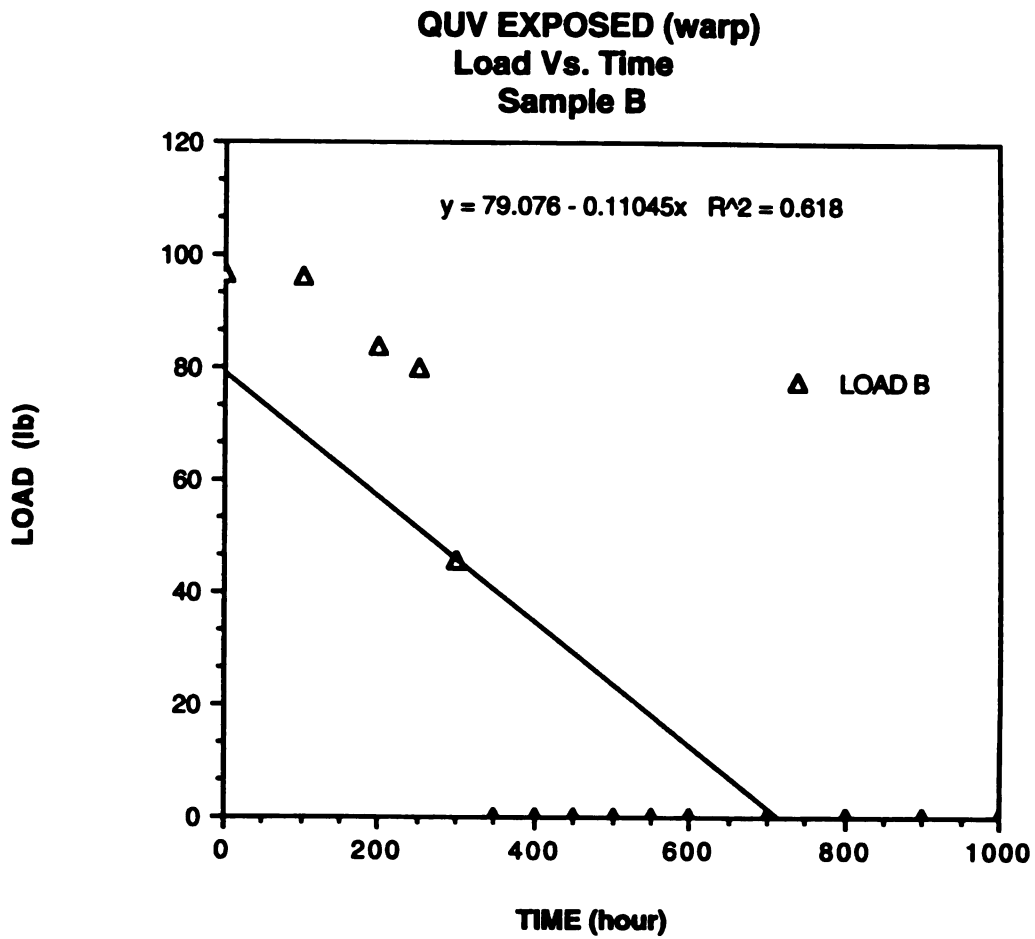
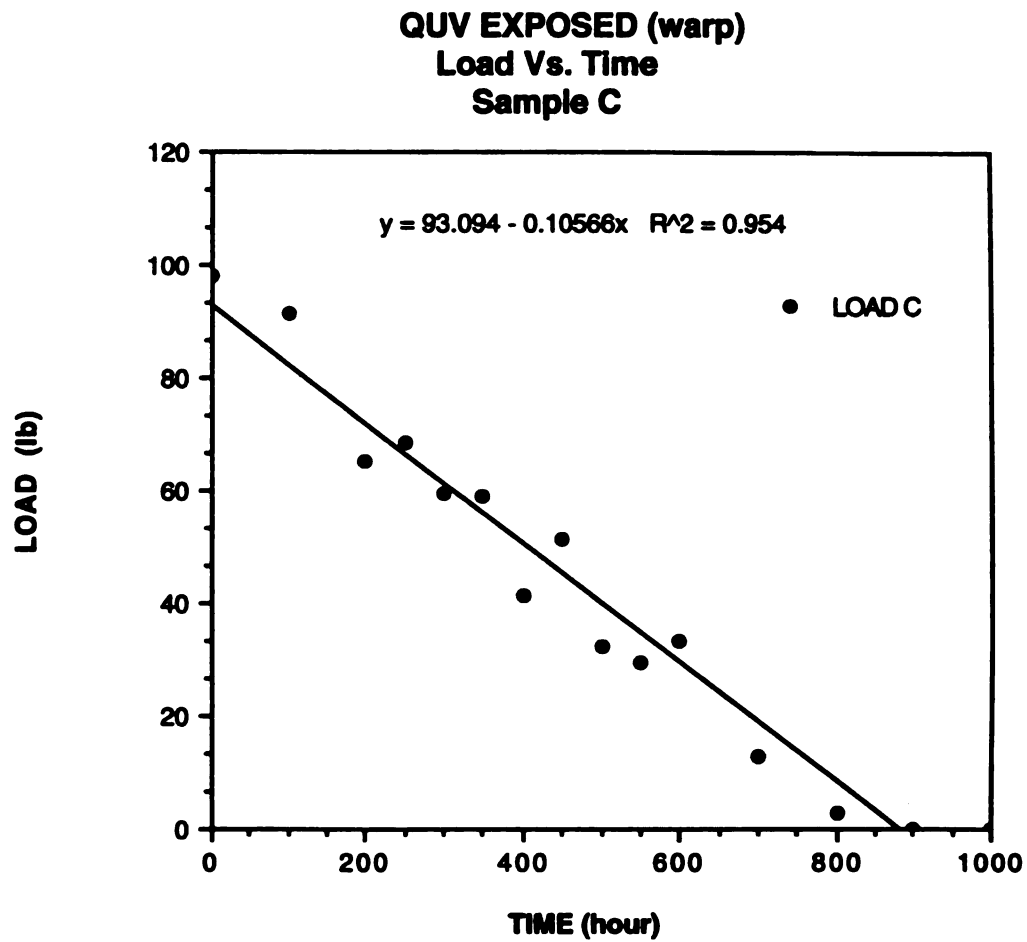
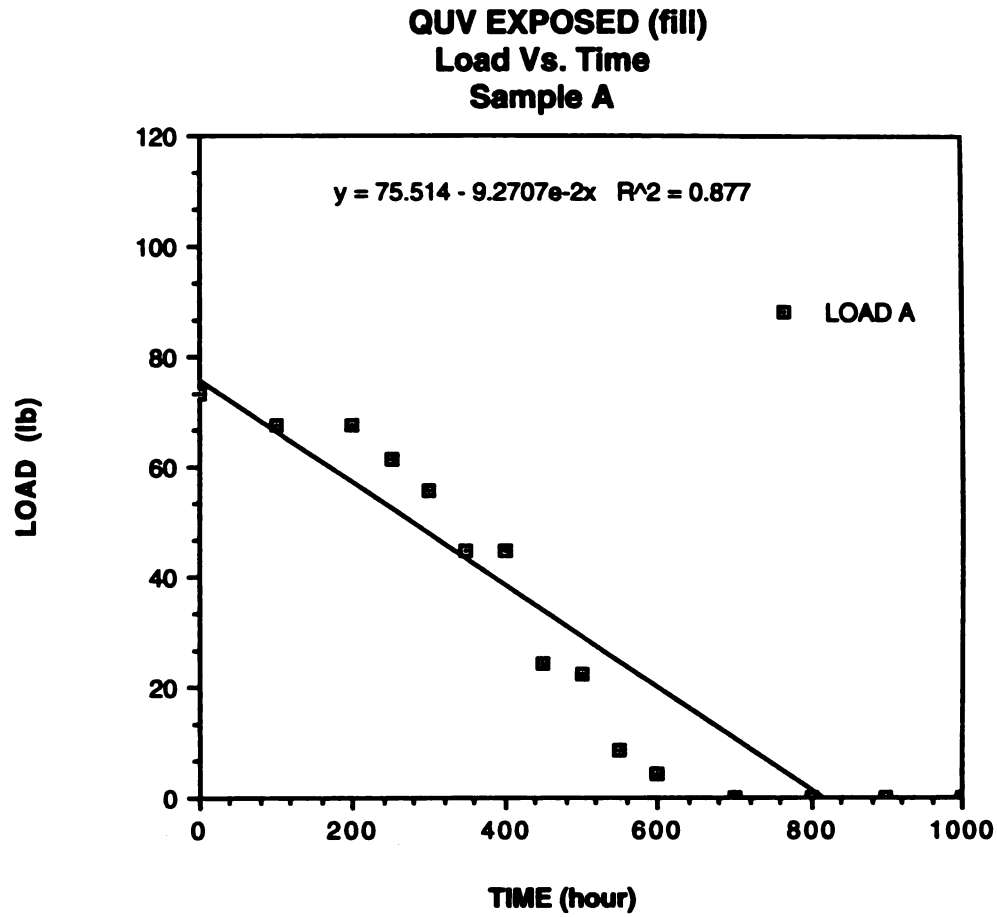


Fig. 34: QUV Exposed, Load Vs. Time, Sample B (warp)

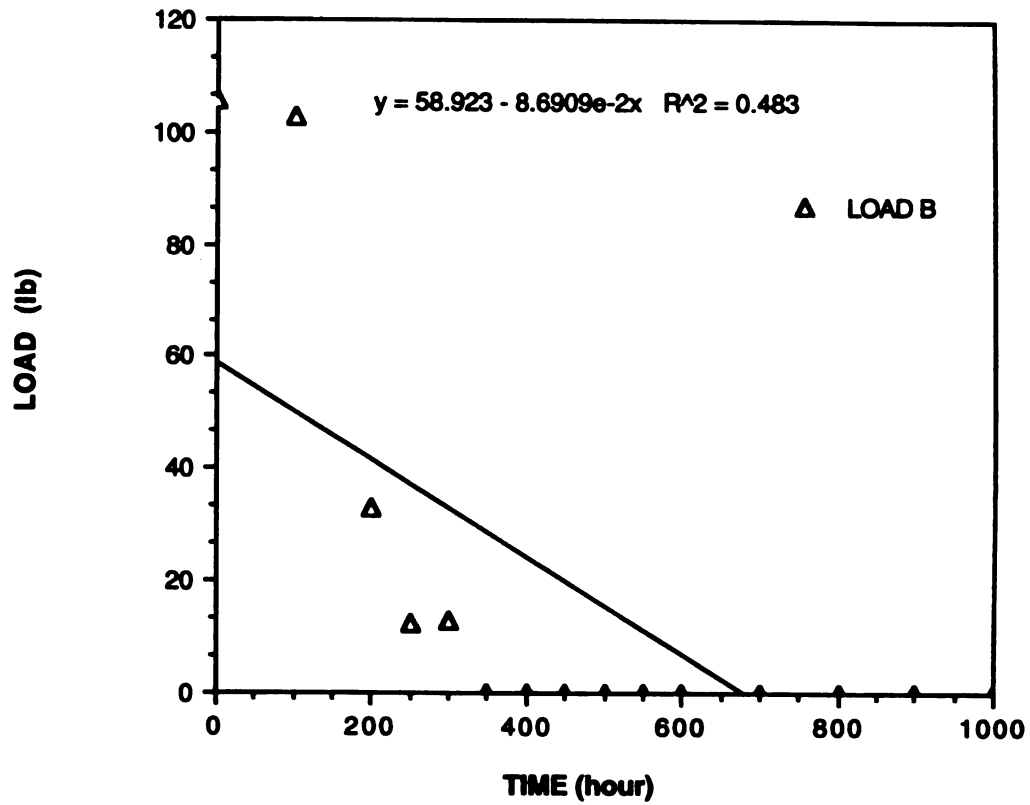


**Fig. 35: QUV Exposed, Load Vs. Time, Sample C (warp)**



**Fig. 36: QUV Exposed, Load Vs. Time Sample A (fill)**

**QUV EXPOSED (fill)  
Load Vs. Time  
Sample B**



**Fig. 37: QUV Exposed, Load Vs. Time Sample B (fill)**

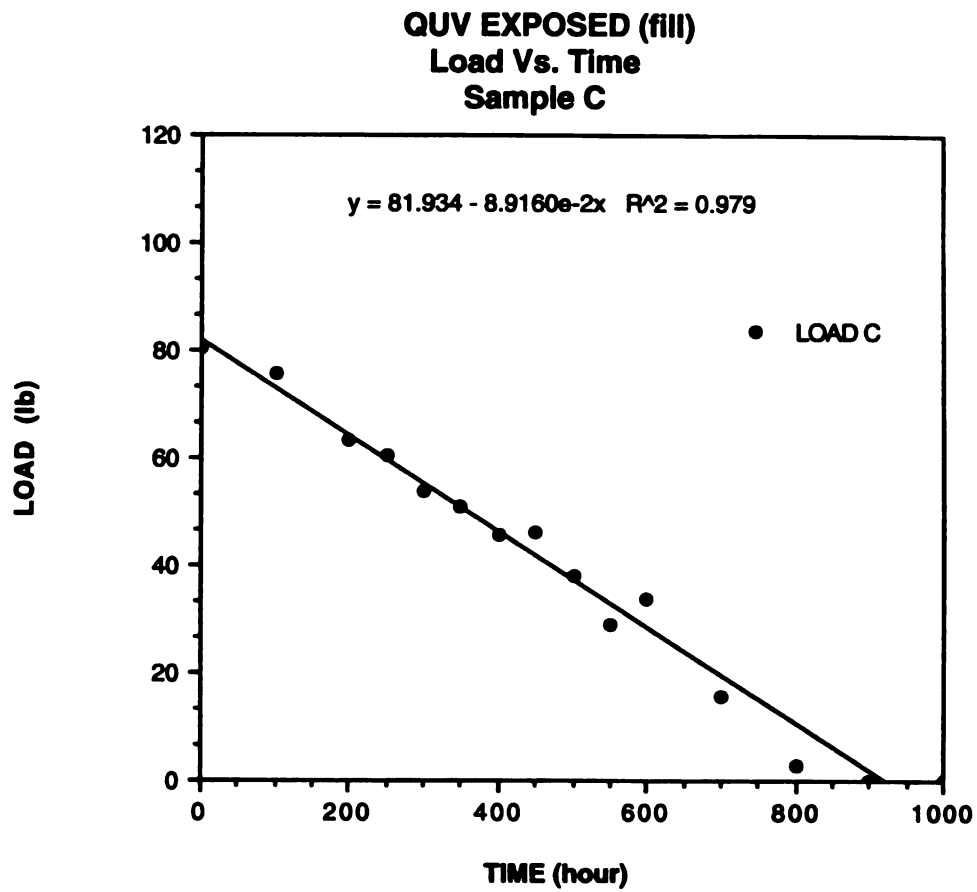


Fig. 38: QUV Exposed, Load Vs. Time Sample C (fill)

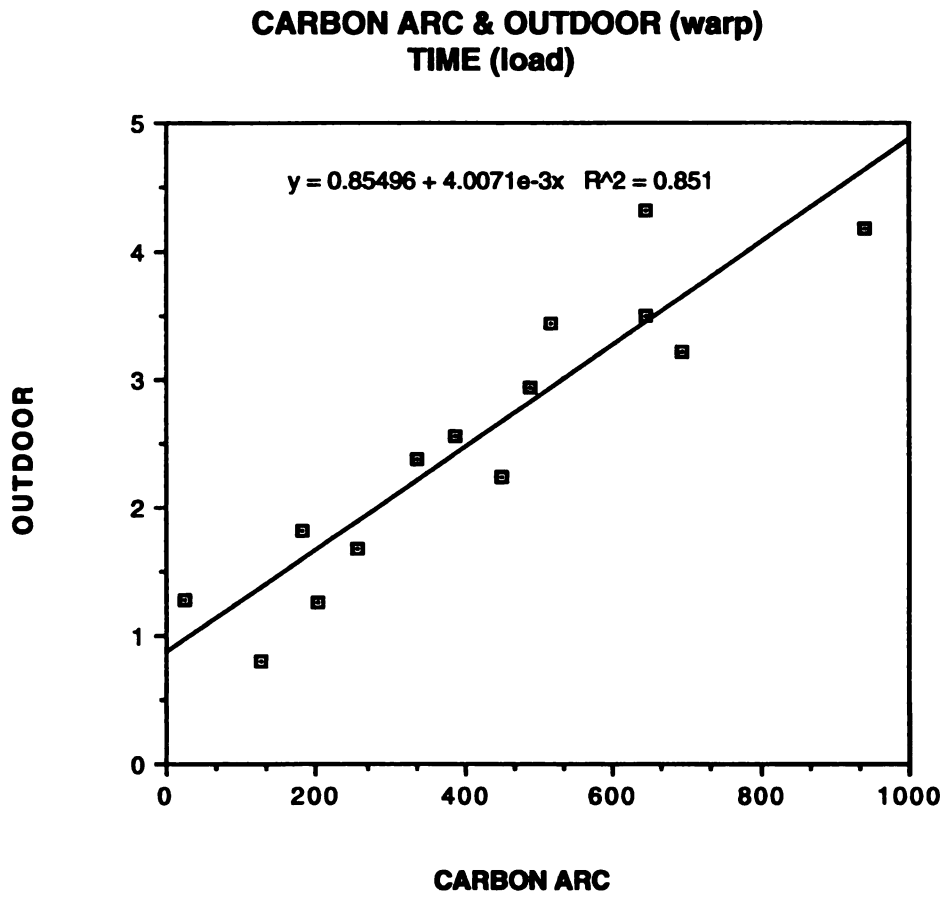


Fig.39: Carbon Arc & Outdoor (warp)

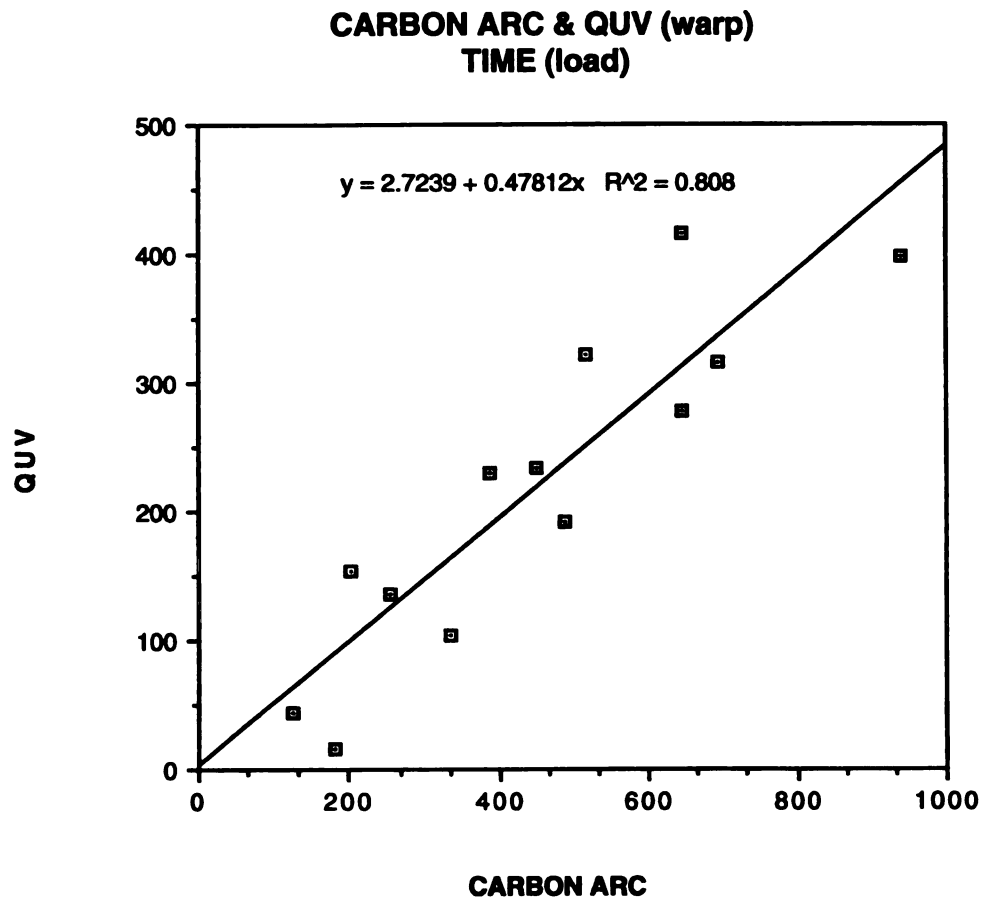


Fig. 40: Carbon Arc & QUV (warp)



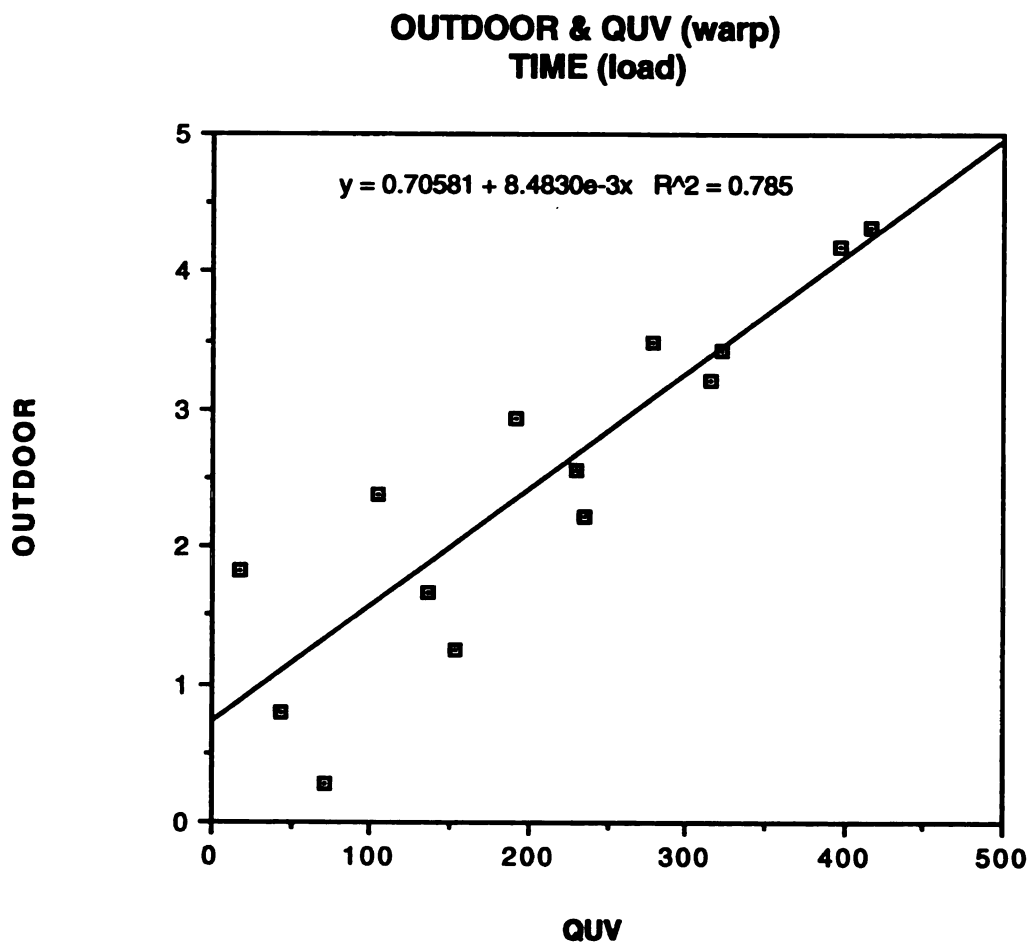


Fig. 41: Outdoor & QUV (warp)

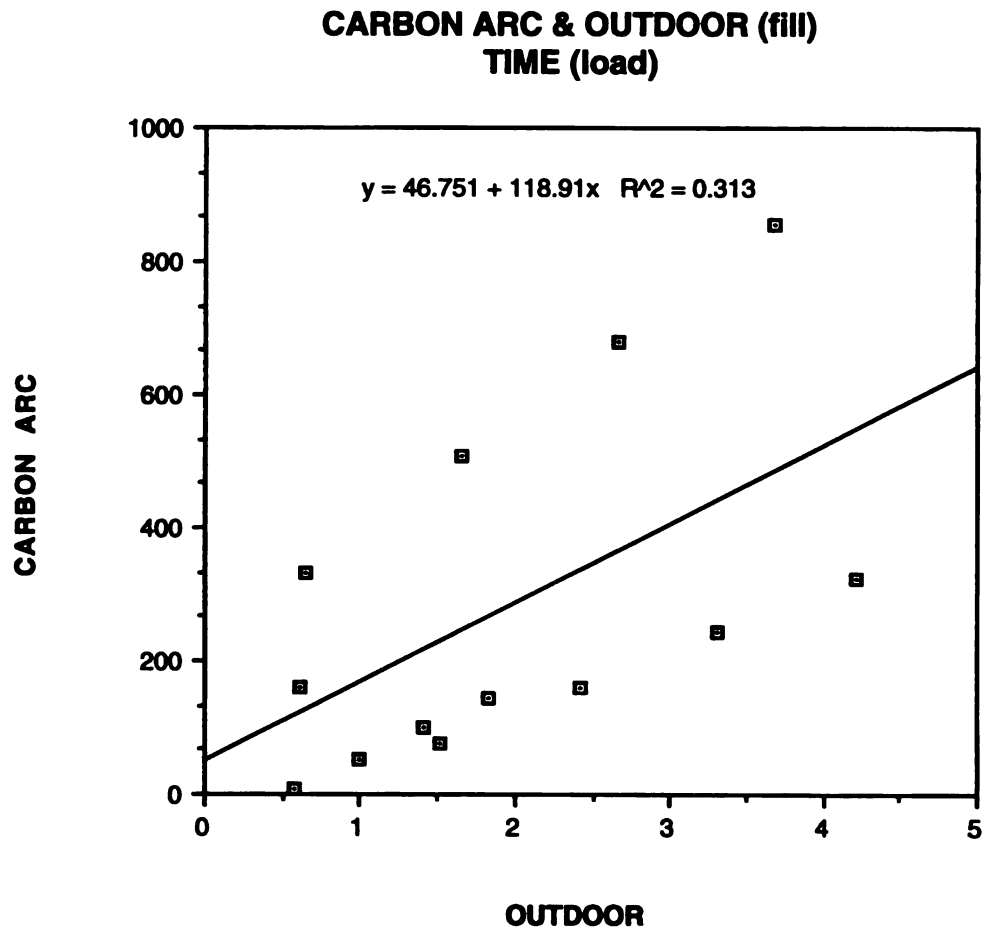


Fig. 42: Carbon Arc & Outdoor (fill)

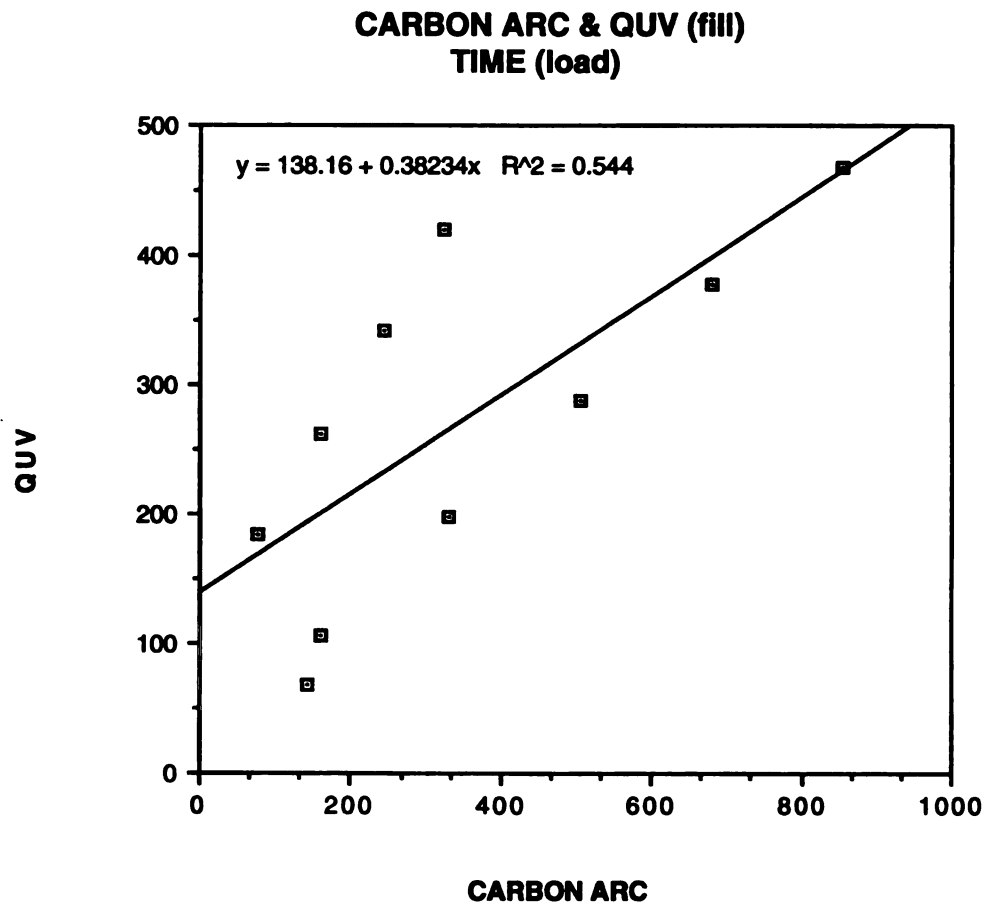


Fig. 43: Carbon Arc & QUV (fill)

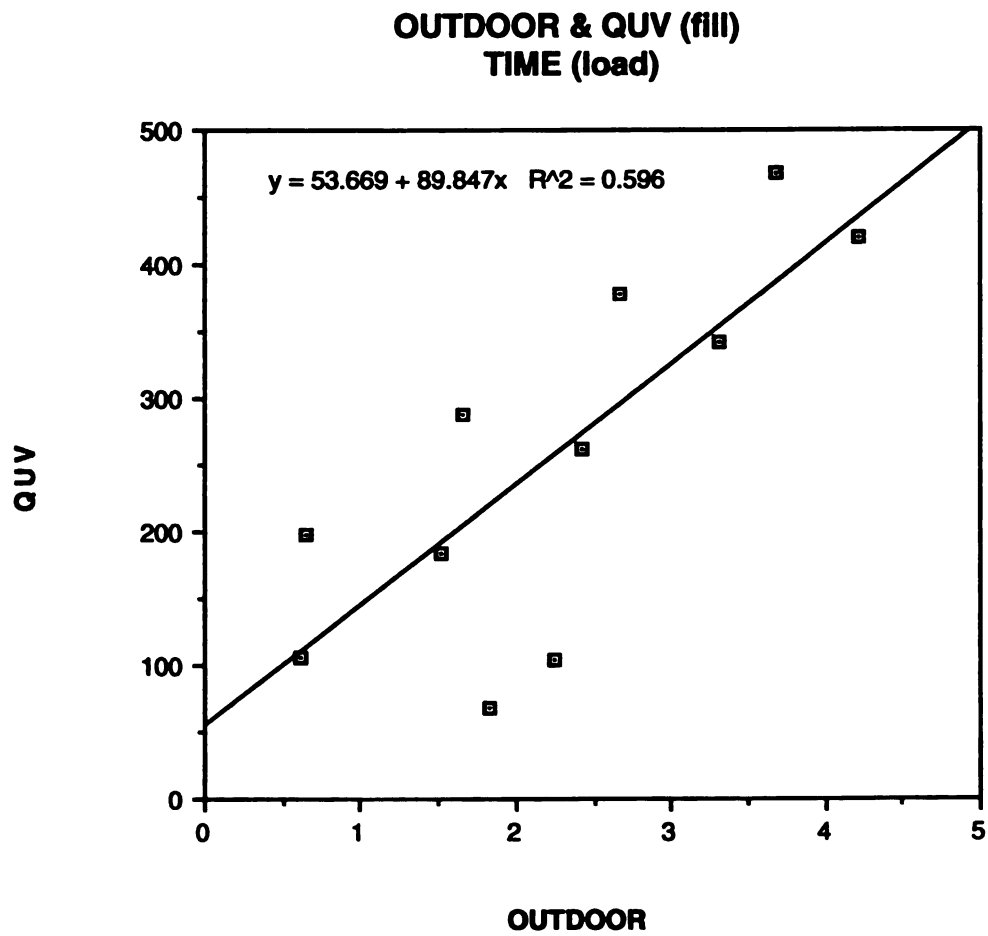


Fig. 44: Outdoor & QUV (fill)

## **SUMMARY AND CONCLUSIONS**

There are numerous factors (internal and external) which can influence the rate of photo-oxidative degradation many of which were not taken into account during this study. Polypropylene degrades by a free-radical process, however the initial site for degradation is still ambiguous to researchers. To help retard or slow down the degradation ultraviolet absorbers, ultraviolet screeners, free radical scavengers and excited state quenchers are frequently added to materials. There are several techniques commonly used to measure degradation such as infrared spectrophotometer, Instron and weather-ometers.

In this study the Instron was used to measure tensile strength, thus measuring degradation. Generally, the tensile strength should decrease as time increases (linear relationship). However, there was a small increase in tensile strength for some fabrics. This increase may be due to some initial brittleness that can occur in the fabric or due to crosslinking that can also occur.

Chemistry and kinetics may also affect the rate of degradation.

Generally, the original correlations (load vs. time) showed good correlation between the test methods and fabrics. However, fabric A in the warp and fill directions had very poor correlation in the carbon arc test method. This poor correlation may have skewed overall results. Original correlations

were also calculated using extension vs. time. (See Appendix.) These correlations were generally good, however when graphed using percent elongation, correlation between test methods were very poor. (See Appendix.) Therefore, correlations using % elongation were not used.

Overall, Sample B had the largest amount of degradation (in all three test methods) followed by A and C. Although the rate of degradation varied between test methods, the order in which the fabrics degraded generally stayed the same. Data reveals that sample B did not maintain 70% of its initial load strength after 200 hours of exposure in the Sunshine Carbon Arc. This study shows that there is a better correlation between the carbon arc and outdoor test methods than the QUV and outdoor test method. However, this does not imply that the QUV is not a viable test method, more research may be needed.

The QUV is an appropriate quality control test, however stringent control of test conditions is needed. The QUV must be kept in a temperature controlled room and monitored closely. Samples must also be rotated consistently to assure even exposure.

If adopted, the hours required for the test should fall in a range of approximately 98-200 hours in the QUV, until more research can be conducted. Data collected from samples exposed in the QUV show that all three fabrics maintained a minimum of 70% initial load strength after 200 hours of exposure in the QUV. As stated earlier, 200 hours in the Sunshine Carbon Arc was calculated to be equivalent to 98.3 hours in the QUV.

## **RECOMMENDATIONS**

Further research may be needed to reinforce these findings. The following recommendations may be considered:

1. Modification of QUV test method may help to give a better correlation with outdoor testing (eg. irradiance level or light source). Another fluorescent test apparatus (eg. Atlas UVCON) should be compared.
2. Use gel permeation chromatography to determine composition of fabrics. This may help to better understand how the composition of a material influences degradation.
3. Use of infrared spectrophotometer to measure carbonyl content in fabrics. This could be used as a direct measure of degradation.
4. Expand testing to include more time intervals and perhaps comparing different materials (eg. polyethylene & polypropylene).

## **APPENDIX**



**Table 5: Not Exposed Averages**

	WARP			FILL	
	LOAD	EXTN		LOAD	EXTN
<b>A</b>	106.24	0.7138		73.11	0.6515
<b>B</b>	96.55	0.7348		105.86	0.7756
<b>C</b>	98.31	0.7384		80.46	0.6636

**Table 6: Not Exposed**

	WARP		FILL	
	LOAD	EXTN	LOAD	EXTN
<b>A</b>	117.30	0.704	75.06	0.647
	105.40	0.695	70.85	0.740
	115.30	0.762	77.18	0.593
	114.10	0.737	52.32	0.579
	109.20	0.704	79.46	0.640
	85.64	0.657	85.42	0.660
	101.30	0.759	65.21	0.550
	104.20	0.755	80.11	0.703
	100.20	0.698	77.29	0.637
	109.80	0.667	68.24	0.766
AVG=	106.24	0.714	73.11	0.652
STD=	8.82	0.036	8.96	0.066
<b>B</b>	77.10	0.678	115.20	0.760
	88.89	0.766	116.50	0.803
	103.90	0.699	102.30	0.745
	101.50	0.680	101.50	0.819
	97.23	0.731	105.20	0.815
	83.19	0.776	101.40	0.841
	121.30	0.843	107.90	0.719
	81.77	0.713	104.10	0.759
	108.20	0.761	88.40	0.777
	102.40	0.701	116.10	0.718
AVG=	96.55	0.735	105.86	0.776
STD=	13.02	0.049	8.18	0.041
<b>C</b>	97.66	0.717	89.21	0.700
	102.50	0.775	74.71	0.630
	105.30	0.757	89.29	0.731
	115.10	0.760	70.25	0.656
	99.01	0.718	81.99	0.700
	93.61	0.710	79.79	0.623
	87.65	0.617	86.31	0.648
	104.70	0.783	86.58	0.596
	80.11	0.767	74.76	0.673
	97.43	0.780	71.73	0.679
AVG=	98.31	0.738	80.46	0.664
STD=	9.26	0.048	6.89	0.039

**Table 7: Carbon Arc Exposed**

	WARP		FILL	
	LOAD	EXTN	LOAD	EXTN
<b>SAMPLE A</b>				
100 HRS	52.00	0.306	36.00	0.269
	43.70	0.240	57.77	0.442
	61.02	0.417	36.40	0.252
	47.76	0.254	27.97	0.230
	51.36	0.266	46.34	0.409
	87.06	0.479	52.32	0.408
	36.99	0.201	34.90	0.285
	49.45	0.283	50.34	0.336
	67.17	0.379	58.52	0.357
AVG=	55.17	0.314	44.51	0.332
STD=	14.87	0.092	0.09	0.077
200 HRS	106.60	0.673	65.72	0.457
	105.70	0.655	75.03	0.530
	107.40	0.677	57.23	0.483
	109.20	0.624	67.19	0.600
	102.30	0.693	47.60	0.474
	111.00	0.658	62.23	0.605
	87.84	0.551	72.91	0.570
	98.09	0.563	70.44	0.625
	106.80	0.677	71.57	0.555
AVG=	103.86	0.641	65.55	0.544
STD=	7.11	0.052	8.73	0.062
300 HRS	103.90	0.724	11.89	0.152
	98.42	0.705	14.50	0.197
	91.95	0.790	4.99	0.155
	97.29	0.604	4.46	0.151
	98.63	0.586	5.45	0.093
	98.63	0.618	6.20	0.111
	85.42	0.587	14.01	0.161
	96.54	0.646	3.22	0.096
AVG=	96.35	0.658	8.09	0.140
STD=	5.50	0.075	4.59	0.036

Table 7 (cont'd)

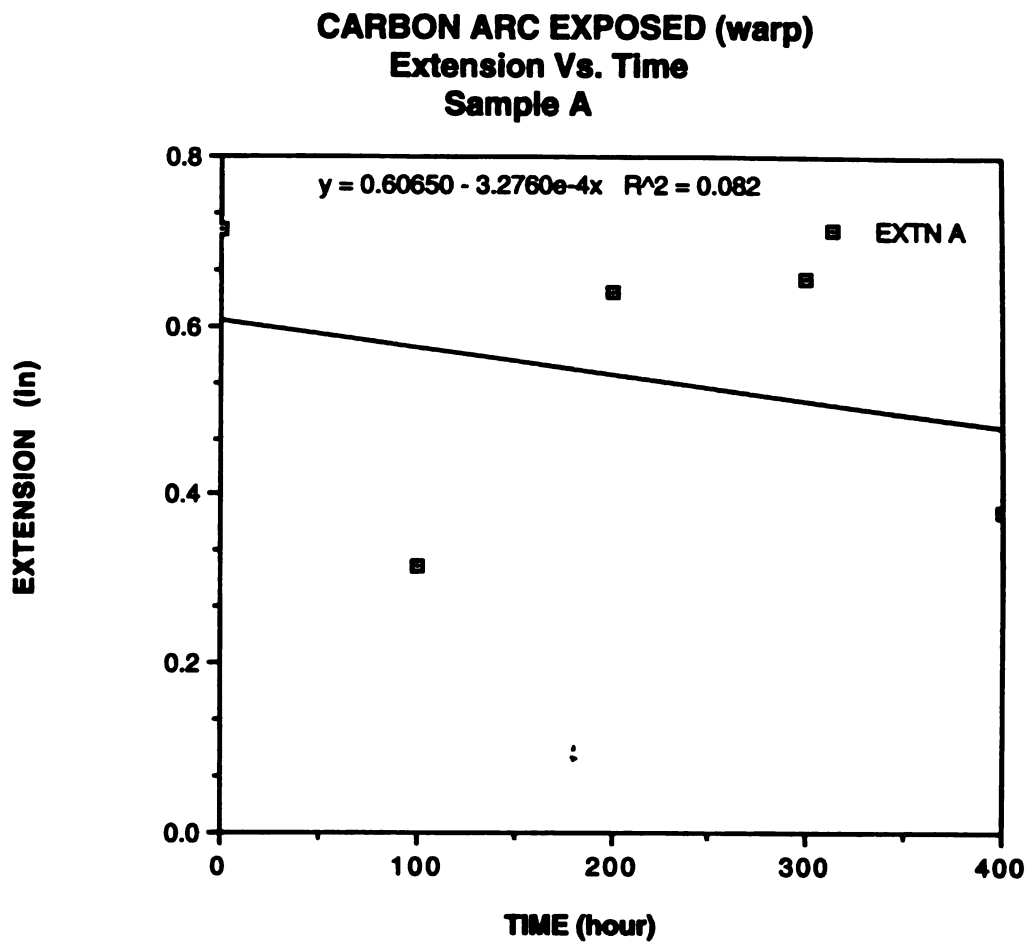
	WARP		FILL	
	LOAD	EXTN	LOAD	EXTN
<b>SAMPLE A</b>				
400 HRS	68.32	0.457	20.13	0.202
	58.95	0.323	52.40	0.398
	53.53	0.357	56.83	0.482
	72.83	0.413	54.50	0.366
	61.40	0.331	62.87	0.497
	70.74	0.380	53.40	0.377
	67.36	0.373	39.38	0.337
	71.38	0.440	23.28	0.198
	51.87	0.331	60.08	0.463
AVG=	64.04	0.378	46.99	0.369
STD=	7.88	0.049	15.77	0.110
<b>SAMPLE B</b>				
100 HRS	65.50	0.451	8.94	0.635
	84.13	0.718	4.51	0.276
	88.13	0.671	101.90	0.649
	69.15	0.537	79.92	1.355
	80.56	0.603	93.29	0.521
	102.60	0.752	4.97	0.068
	67.03	0.625	2.74	0.224
AVG=	79.59	0.622	42.32	0.533
STD=	13.47	0.104	46.67	0.424
200 HRS	49.56	0.379	63.14	0.329
	36.97	0.395	15.11	0.488
	35.09	0.279	31.52	0.158
	47.87	0.472	12.51	0.092
	73.77	0.546	37.74	0.160
	44.19	0.560	27.03	0.119
	100.30	0.586	19.89	0.094
	64.48	0.426	71.92	0.376
	76.13	0.464		
	78.63	0.547		
AVG=	60.70	0.465	34.86	0.227
STD=	21.33	0.097	21.93	0.150

Table 7 (cont'd)

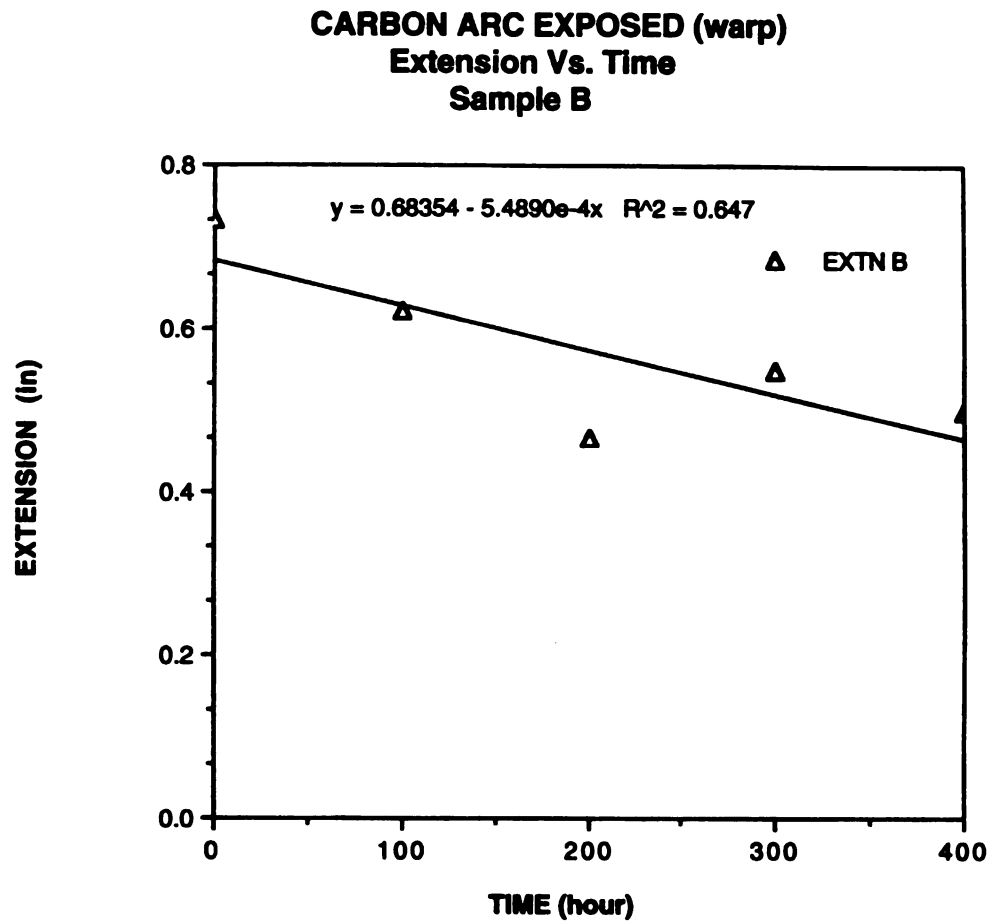
	WARP		FILL	
	LOAD	EXTN	LOAD	EXTN
<b>SAMPLE B</b>				
300 HRS	90.17	0.619	12.59	0.461
	87.84	0.634	1.93	0.085
	97.61	0.697	4.99	0.203
	77.61	0.537	21.91	0.091
	109.40	0.625	32.00	0.187
	78.52	0.586	1.77	0.141
	60.30	0.593	5.21	0.327
	47.03	0.328		
	66.15	0.546		
	47.01	0.328		
AVG =	76.16	0.549	11.49	0.214
STD =	20.96	0.125	11.53	0.136
400 HRS	75.68	0.519	3.33	0.277
	56.16	0.576	5.40	0.347
	63.76	0.450	3.38	0.313
	66.85	0.607	5.21	0.275
	87.11	0.535	8.91	0.096
	99.92	0.535	1.96	0.105
	71.52	0.465	4.86	0.082
	44.89	0.393	4.73	0.223
	37.34	0.392	3.89	0.127
AVG =	67.03	0.497	4.63	0.205
STD =	19.62	0.076	1.94	0.103
<b>SAMPLE C</b>				
100 HRS	91.44	0.737	41.77	0.259
	72.59	0.754	80.51	0.815
	90.85	0.697	79.54	0.727
	81.40	0.694	39.60	0.287
	91.57	0.724	84.32	0.650
	105.60	0.747	86.87	0.698
	98.79	0.733	62.39	0.591
	78.44	0.759	81.15	0.670
	86.90	0.695	83.57	0.707
AVG =	88.62	0.727	71.08	0.600
STD =	10.18	0.026	18.60	0.195

Table 7 (cont'd)

	WARP		FILL	
	LOAD	EXTN	LOAD	EXTN
SAMPLE C				
200 HRS	84.64	0.597	81.50	0.655
	84.64	0.527	85.50	0.574
	83.27	0.513	90.50	0.607
	82.47	0.540	83.46	0.576
	88.89	0.569	47.06	0.595
	84.99	0.510	76.56	0.563
	80.86	0.520	81.34	0.534
	79.27	0.533	82.44	0.566
	83.92	0.508		
AVG=	83.66	0.535	78.55	0.584
STD=	2.73	0.030	13.32	0.036
300 HRS	80.32	0.474	56.75	0.427
	80.81	0.505	45.40	0.453
	66.52	0.465	65.53	0.437
	72.27	0.505	65.05	0.449
	81.74	0.531	68.08	0.470
	78.23	0.538	43.79	0.504
	76.11	0.455	61.53	0.420
	81.96	0.507	66.04	0.448
	84.13	0.487	60.62	0.479
AVG=	78.01	0.499	59.20	0.454
STD=	5.58	0.026	8.95	0.026
400 HRS	77.96	0.478	70.12	0.490
	66.23	0.450	64.24	0.523
	65.58	0.415	62.44	0.460
	61.85	0.451	70.47	0.546
	62.07	0.428	56.13	0.433
	65.96	0.462	66.52	0.451
	64.30	0.483	51.41	0.395
	62.63	0.385	64.78	0.441
AVG=	65.82	0.444	63.26	0.467
STD=	4.87	0.031	6.17	0.046

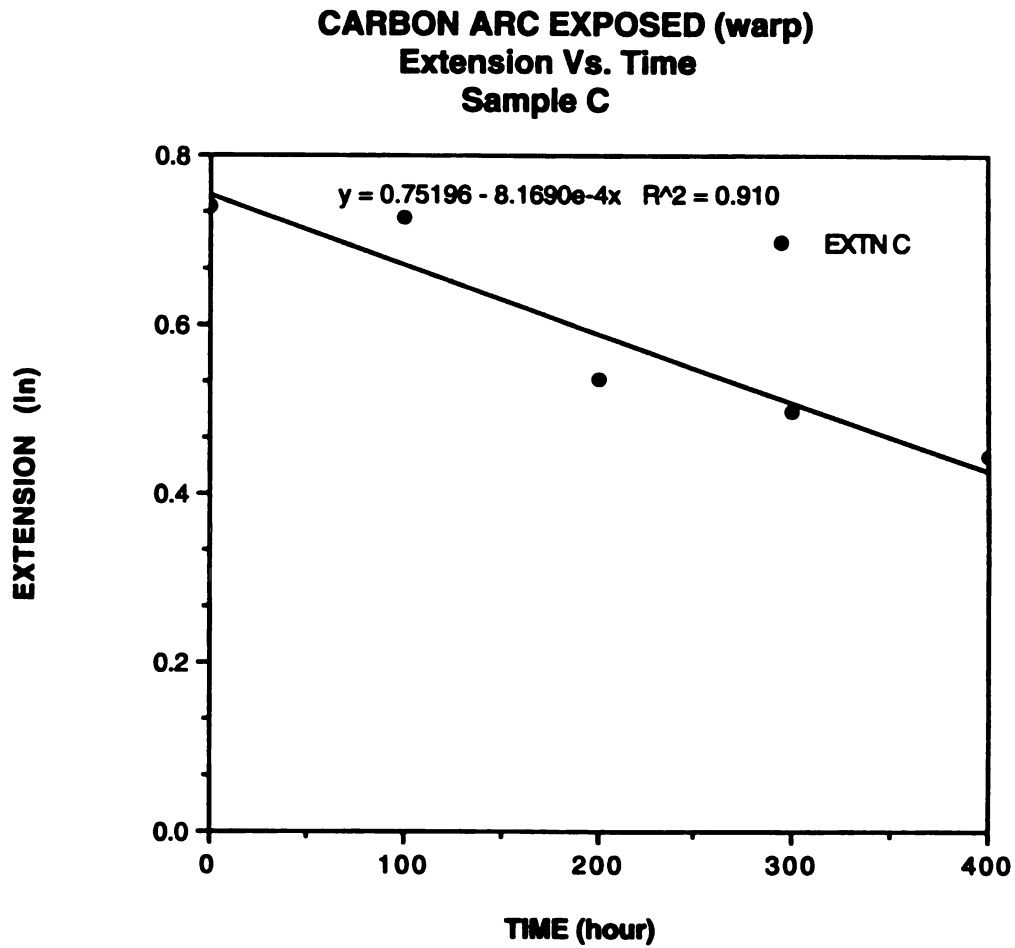


**Fig. 45: Carbon Arc Exposed, Extension Vs. Time, Sample A (warp)**

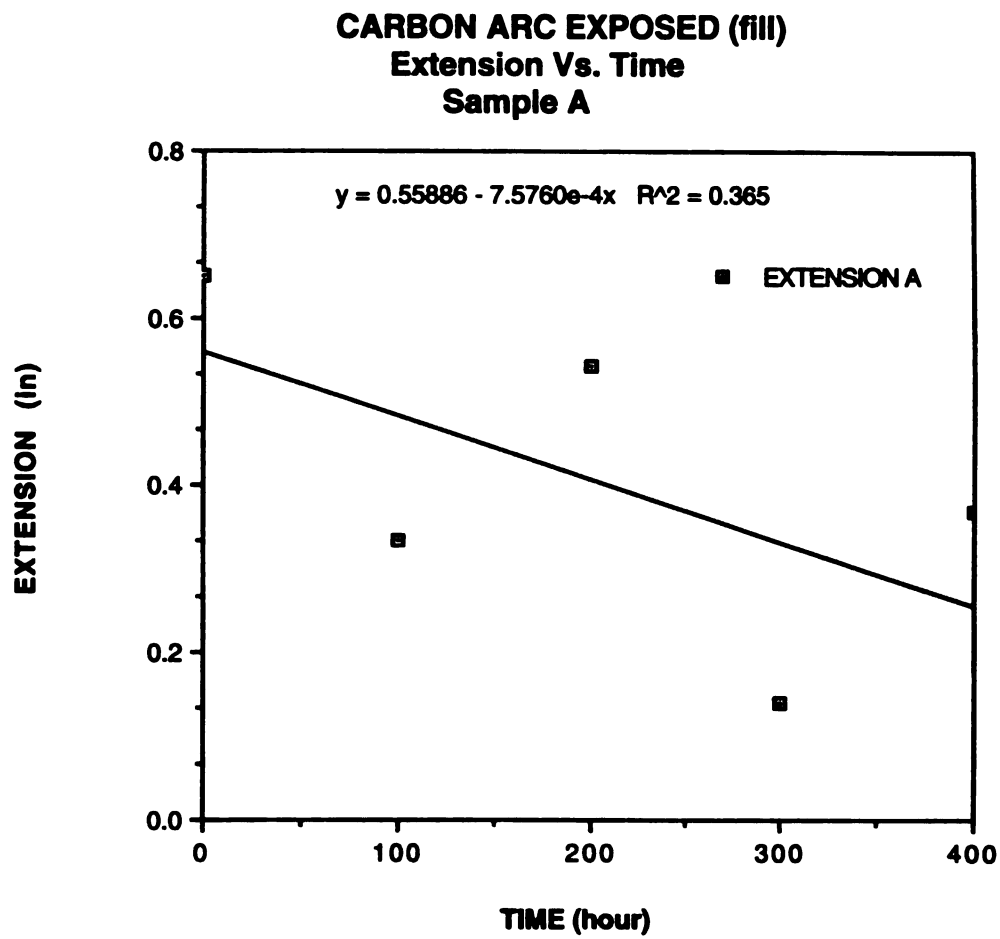


**Fig. 46: Carbon Arc Exposed, Extension Vs. Time, Sample B (warp)**





**Fig. 47: Carbon Arc Exposed, Extension Vs. Time, Sample C (warp)**



**Fig. 48: Carbon Arc Exposed, Extension Vs. Time, Sample A (fill)**

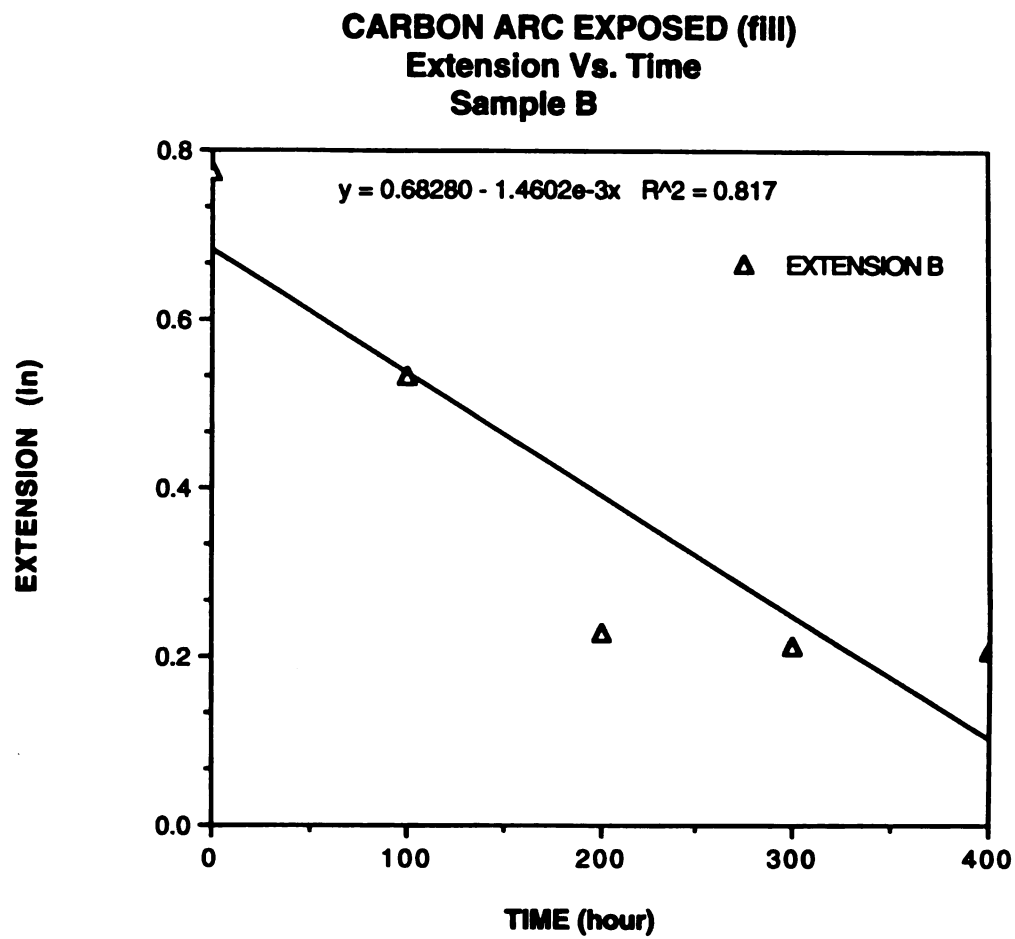
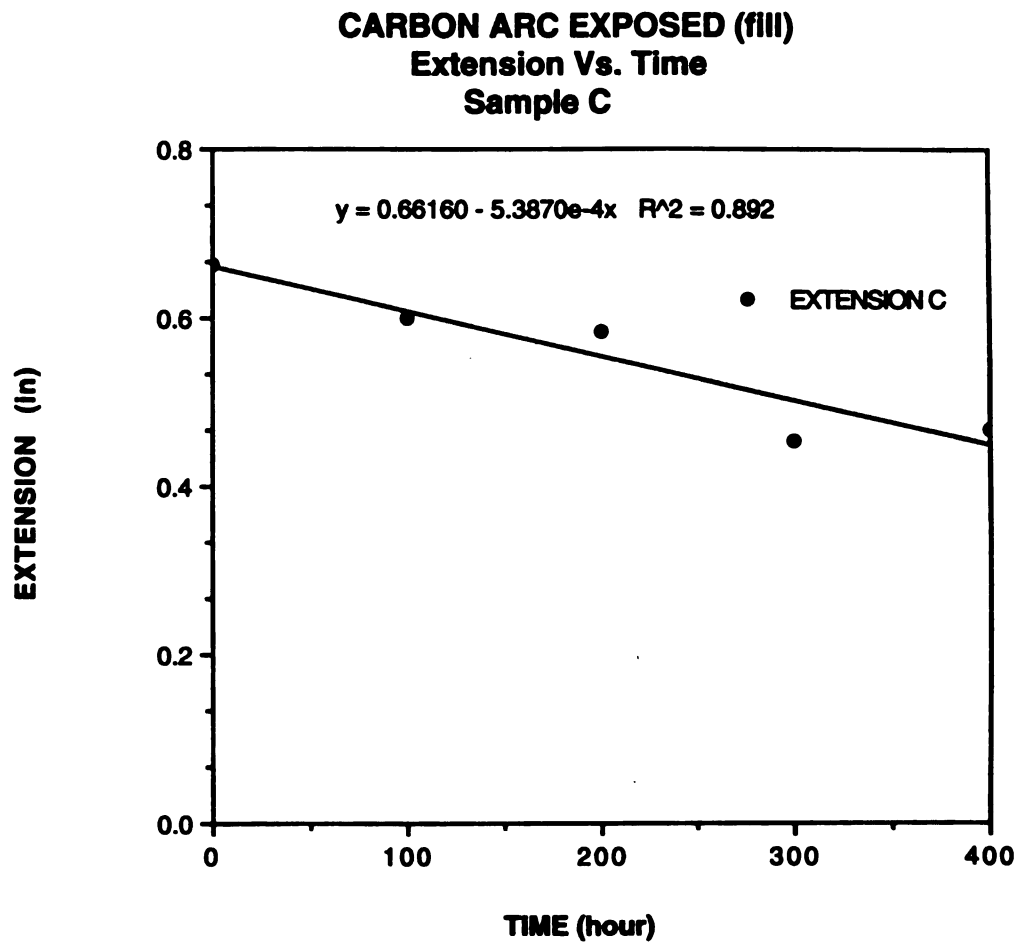


Fig. 49: Carbon Arc Exposed, Extension Vs. Time, Sample B (fill)



**Fig. 50: Carbon Arc Exposed, Extension Vs. Time, Sample C (fIII)**

Table 8: Outdoor Exposed (1 month)

	WARP		FILL	
	LOAD	EXTN	LOAD	EXTN
<b>A</b>	117.60	0.658	65.69	0.543
	79.60	0.454	53.72	0.480
	67.84	0.483	48.16	0.412
	88.62	0.596	62.68	0.476
	92.97	0.633	71.97	0.557
	64.19	0.421	62.87	0.452
	80.40	0.478	61.66	0.416
	65.83	0.568	79.44	0.496
	53.50	0.340	62.76	0.543
	69.99	0.526	67.06	0.454
	81.96	0.482	67.33	0.450
	69.61	0.417	67.76	0.425
	77.37	0.549	69.32	0.463
	98.79	0.613	55.06	0.433
	88.30	0.586	55.92	0.407
	100.40	0.659	55.33	0.384
AVG=	81.06	0.529	62.92	0.462
STD=	16.32	0.094	7.90	0.052
<b>B</b>				
	103.10	0.612	125.20	0.755
	100.60	0.624	122.20	0.582
	101.60	0.592	101.00	0.557
	103.00	0.611	113.00	0.656
	96.75	0.640	91.92	0.461
	86.87	0.482	116.60	0.746
	95.19	0.605	83.25	0.719
	70.44	0.664	111.60	0.606
	72.08	0.470	110.10	0.619
	99.81	0.615	110.20	0.693
	116.10	0.663	96.81	0.680
	116.70	0.705	108.80	0.674
	98.79	0.607	112.40	0.559
	89.23	0.627	114.30	0.666
	109.00	0.652	103.40	0.606
	96.97	0.689	96.00	0.629
AVG=	97.26	0.616	107.30	0.638
STD=	12.93	0.063	11.20	0.077

Table 8 (cont'd)

	WARP		FILL	
	LOAD	EXTN	LOAD	EXTN
C	81.50	0.441	61.21	0.405
	66.09	0.435	47.95	0.403
	59.01	0.332	67.73	0.473
	82.85	0.574	55.95	0.552
	95.19	0.601	71.44	0.389
	84.00	0.542	67.92	0.498
	86.87	0.535	68.56	0.620
	74.31	0.639	67.30	0.530
	67.97	0.540	67.44	0.567
	95.17	0.563	67.27	0.437
	89.56	0.523	67.81	0.549
	68.00	0.409	56.40	0.677
	76.11	0.487	52.00	0.496
	89.18	0.618	70.98	0.647
	76.70	0.563	58.25	0.360
	93.61	0.519	80.40	0.630
AVG=	80.38	0.520	64.29	0.515
STD=	11.18	0.082	8.31	0.099

Table 9: Outdoor Exposed (2 month)

	WARP		FILL	
	LOAD	EXTN	LOAD	EXTN
<b>A</b>	70.34	0.438	45.66	0.387
	73.10	0.492	59.01	0.365
	67.49	0.441	58.47	0.421
	70.95	0.400	44.30	0.334
	86.25	0.560	49.96	0.443
	79.44	0.423	43.76	0.327
	74.93	0.539	54.68	0.414
	85.45	0.470	60.62	0.392
	74.12	0.540	41.23	0.359
	66.28	0.426	54.09	0.370
	76.48	0.487	52.99	0.358
	80.91	0.435	47.19	0.329
	71.70	0.503	53.53	0.385
	58.15	0.466	50.47	0.390
	65.88	0.438	55.76	0.368
	75.87	0.450	52.59	0.398
AVG=	73.58	0.469	51.52	0.378
STD=	7.37	0.047	5.80	0.033
<b>B</b>				
	73.32	0.489	44.51	0.193
	68.38	0.413	55.76	0.249
	101.20	0.529	50.04	0.239
	76.13	0.382	52.94	0.236
	51.41	0.370	43.33	0.200
	97.66	0.560	46.42	0.231
	87.73	0.572	58.63	0.253
	75.25	0.411	60.91	0.297
	67.81	0.386	47.14	0.241
	97.56	0.627	64.46	0.256
	92.05	0.554	58.68	0.273
	73.96	0.419	52.54	0.243
	67.84	0.482	54.93	0.255
	80.78	0.423	54.93	0.250
AVG=	79.36	0.473	53.23	0.244
STD=	14.24	0.083	6.35	0.026

Table 9 (cont'd)

	WARP		FILL	
	LOAD	EXTN	LOAD	EXTN
<b>C</b>	85.91	0.641	57.83	0.465
	82.58	0.411	68.27	0.472
	80.46	0.534	55.76	0.355
	90.47	0.535	55.87	0.343
	93.13	0.469	67.25	0.460
	83.57	0.458	63.33	0.465
	83.62	0.535	63.97	0.409
	55.62	0.486	57.10	0.447
	75.49	0.413	48.89	0.420
	94.28	0.497	65.61	0.525
	77.18	0.423	50.44	0.423
	68.00	0.450	74.58	0.479
	86.15	0.429	67.44	0.388
	87.17	0.497	65.99	0.425
	71.25	0.423	70.66	0.535
AVG=	80.99	0.480	62.20	0.441
STD=	10.25	0.063	7.50	0.055



Table 10: Outdoor Exposed (3 month)

	WARP		FILL	
	LOAD	EXTN	LOAD	EXTN
<b>A</b>	70.82	0.418	45.21	0.337
	58.76	0.467	46.12	0.304
	65.61	0.382	54.04	0.377
	57.85	0.418	52.64	0.367
	74.23	0.485	36.48	0.350
	77.07	0.467	41.42	0.321
	59.33	0.401	37.13	0.333
	54.27	0.490	41.23	0.352
	71.19	0.423	36.99	0.329
	58.47	0.370	38.63	0.324
	81.66	0.448	43.14	0.317
	58.15	0.347	56.78	0.380
	65.21	0.379	52.72	0.373
	65.72	0.390	47.41	0.327
	63.11	0.401	45.10	0.308
AVG=	65.43	0.419	45.00	0.340
STD=	8.06	0.044	6.63	0.025
<b>B</b>				
	57.85	0.535	6.87	0.719
	35.22	0.289	10.01	0.650
	88.89	0.547	8.89	0.136
	68.35	0.471	14.58	0.525
	75.01	0.589	7.09	0.073
	96.05	0.644	9.24	0.506
	42.28	0.487	9.26	0.087
	56.67	0.551	6.85	0.063
	31.01	0.300	6.04	0.094
	27.54	0.250	10.74	0.070
	29.23	0.285	9.88	0.107
	79.19	0.489	8.67	0.445
	43.03	0.496	11.73	0.135
	69.99	0.545	8.54	0.343
AVG=	57.17	0.463	9.17	0.282
STD=	22.97	0.128	2.24	0.240

Table 10 (cont'd)

	WARP		FILL	
	LOAD	EXTN	LOAD	EXTN
<b>C</b>	66.39	0.463	61.05	0.459
	64.38	0.431	57.74	0.493
	60.38	0.475	49.56	0.343
	70.79	0.464	61.88	0.430
	52.89	0.343	56.13	0.358
	46.95	0.302	49.23	0.468
	55.44	0.383	54.36	0.357
	65.48	0.419	62.74	0.368
	71.33	0.491	60.43	0.479
	53.74	0.419	57.96	0.483
	73.15	0.456	60.03	0.487
	76.16	0.448	45.10	0.291
	63.03	0.345	61.88	0.499
	74.93	0.418	52.13	0.360
	66.98	0.363	52.89	0.331
AVG=	64.13	0.415	56.21	0.414
STD=	8.76	0.056	5.45	0.071

Table 11: Outdoor Exposed (4 month)

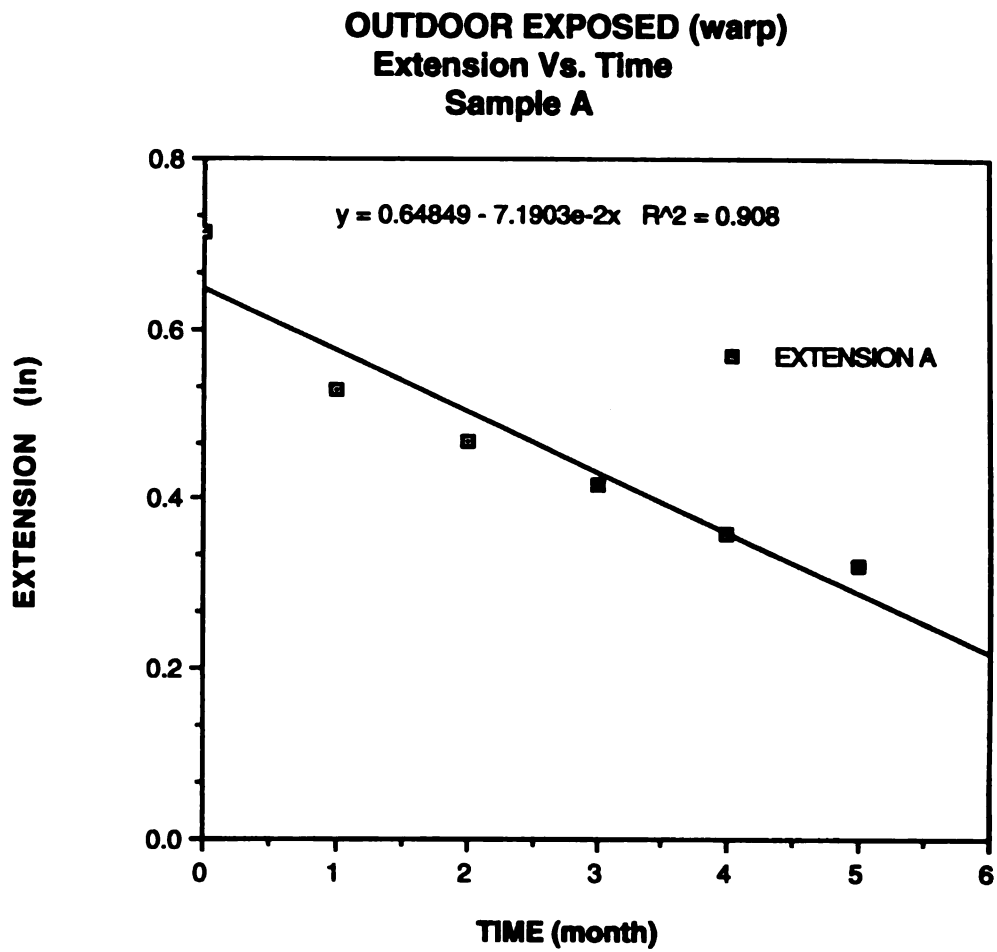
	WARP		FILL	
	LOAD	EXTN	LOAD	EXTN
A	54.20	0.390	32.51	0.315
	65.25	0.395	38.12	0.279
	55.81	0.363	30.50	0.269
	60.16	0.428	33.40	0.307
	62.31	0.360	34.93	0.333
	62.04	0.355	45.56	0.345
	52.51	0.400	35.14	0.520
	56.89	0.391	29.37	0.291
	48.67	0.321	37.69	0.324
	59.46	0.371	39.03	0.389
	52.35	0.322	39.19	0.333
	51.92	0.345	43.22	0.421
	37.85	0.254	35.25	0.347
	49.53	0.401	41.23	0.302
	57.69	0.336	35.60	0.335
	45.91	0.320	41.10	0.327
	54.93	0.407	49.32	0.344
	55.28	0.371	42.42	0.298
	41.18	0.246	36.97	0.303
	70.17	0.401	33.72	0.377
AVG=	54.71	0.359	37.71	0.338
STD=	7.80	0.049	5.05	0.057
B	60.03	0.420	4.78	0.307
	44.54	0.411	7.84	0.300
	74.66	0.411	2.12	0.233
	79.17	0.489	2.55	0.256
	49.69	0.299	6.20	0.370
	84.00	0.443	3.17	0.278
	74.34	0.466	2.09	0.297
	28.70	0.510	3.57	0.341
	85.34	0.457	2.17	0.190
	59.28	0.401	3.49	0.310
	63.70	0.435	9.24	0.162
	60.08	0.431	6.47	0.115
	49.13	0.361	2.12	0.237
	65.66	0.445	6.42	0.145
	55.25	0.344		
	61.10	0.456		
	61.53	0.412		
	73.21	0.509		
AVG=	62.75	0.428	4.44	0.253
STD=	14.47	0.054	2.39	0.076

Table 11 (cont'd)

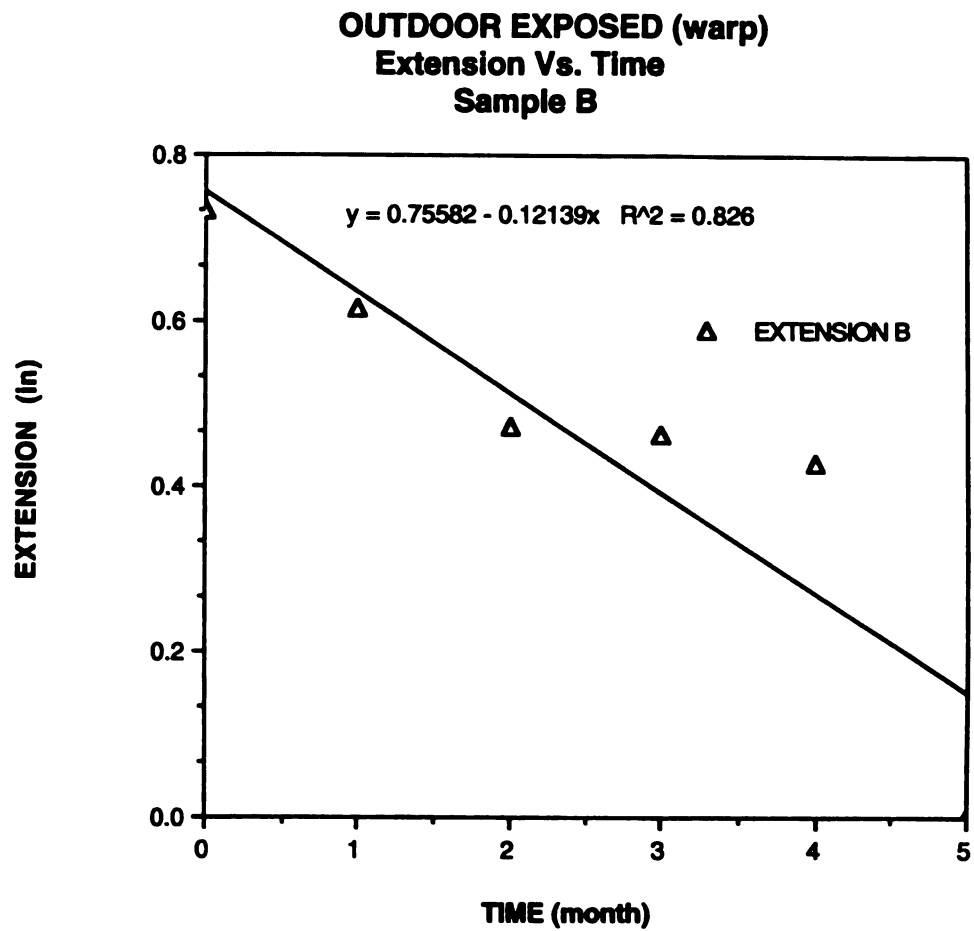
	WARP		FILL	
	LOAD	EXTN	LOAD	EXTN
C	52.82	0.393	45.23	0.397
	56.30	0.377	53.53	0.353
	47.76	0.359	39.33	0.311
	48.86	0.326	44.78	0.396
	43.92	0.361	42.87	0.409
	52.89	0.320	40.43	0.366
	59.22	0.326	43.52	0.438
	54.09	0.474	34.50	0.249
	38.55	0.252	41.69	0.342
	69.74	0.396	37.53	0.445
	45.45	0.396	45.56	0.439
	57.91	0.369	39.65	0.367
	52.05	0.406	52.30	0.379
	59.73	0.414	54.66	0.377
	48.27	0.350	36.40	0.349
	44.56	0.280	54.25	0.412
	54.66	0.315	49.64	0.428
	49.72	0.332	56.46	0.449
AVG=	52.58	0.358	45.13	0.384
STD=	7.65	0.053	6.85	0.052

Table 12: Outdoor Exposed (5 month)

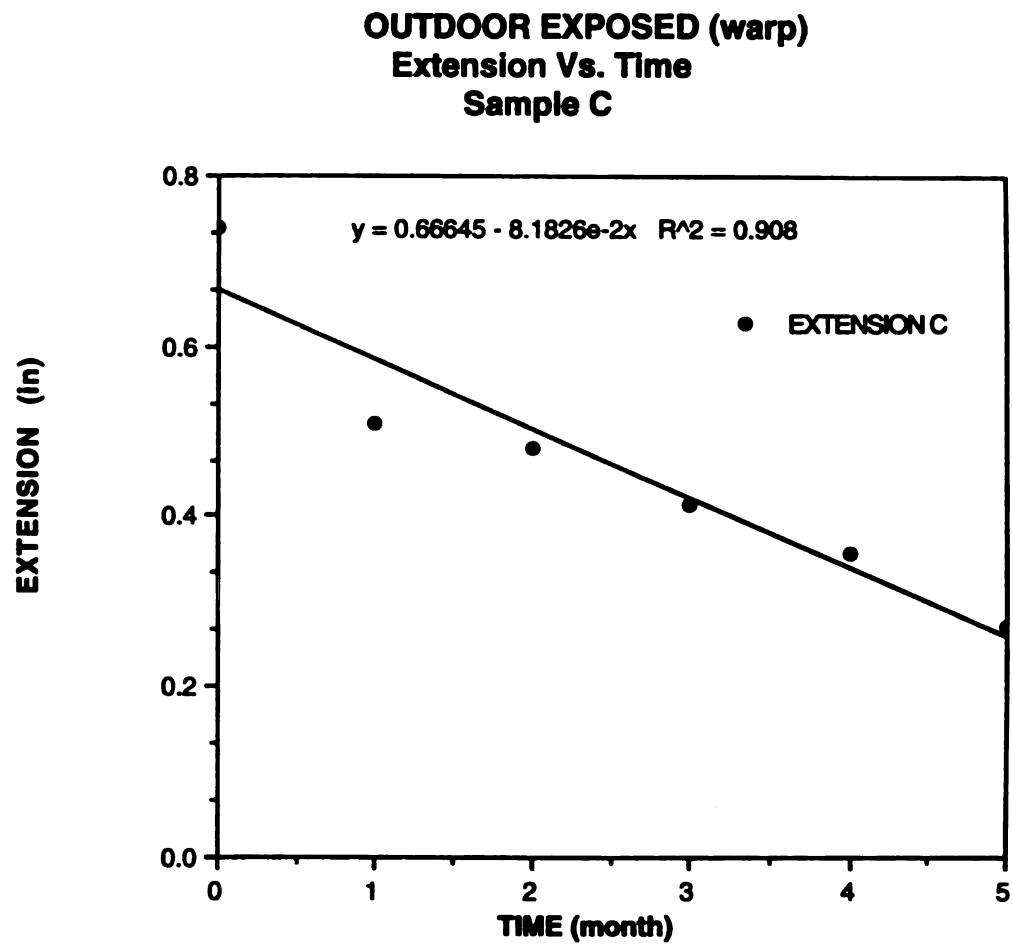
	WARP		FILL	
	LOAD	EXTN	LOAD	EXTN
<b>A</b>	31.22	0.263	37.23	0.297
	53.37	0.303	24.89	0.245
	54.42	0.325	33.69	0.269
	51.33	0.359	39.62	0.289
	44.51	0.321	35.09	0.286
	43.17	0.284	37.23	0.272
	52.00	0.383	39.03	0.328
	54.52	0.355	32.75	0.238
	45.18	0.335	29.93	0.283
	37.29	0.293	26.36	0.320
	55.30	0.389	28.38	0.241
	36.48	0.247	24.11	0.235
	46.60	0.306	27.92	0.285
	59.25	0.357	36.30	0.293
	51.17	0.318	37.74	0.318
AVG=	47.72	0.323	32.68	0.280
STD=	8.03	0.041	5.33	0.030
<b>C</b>				
	36.19	0.260	42.95	0.326
	45.02	0.293	28.94	0.283
	46.39	0.286	31.76	0.331
	43.03	0.232	42.20	0.377
	41.26	0.258	23.60	0.347
	56.86	0.334	55.33	0.390
	40.89	0.315	34.47	0.218
	30.31	0.180	34.82	0.243
	27.46	0.183	37.40	0.285
	43.97	0.289	33.29	0.250
	37.05	0.346	44.32	0.427
	34.36	0.279	38.07	0.350
	42.44	0.254	39.65	0.307
AVG=	40.40	0.270	37.45	0.318
STD=	7.57	0.051	7.93	0.061



**Fig. 51: Outdoor Exposed, Extension Vs. Time, Sample A (warp)**

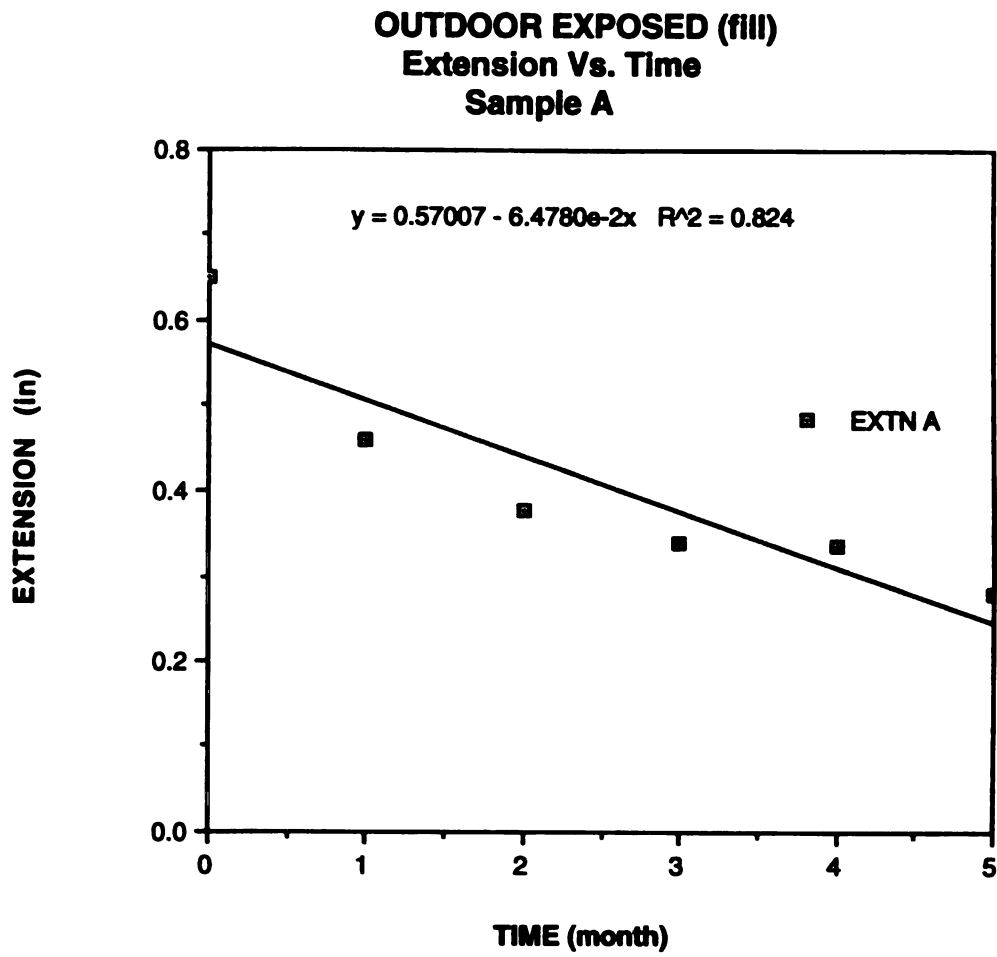


**Fig. 52: Outdoor Exposed, Extension Vs. Time, Sample B (warp)**

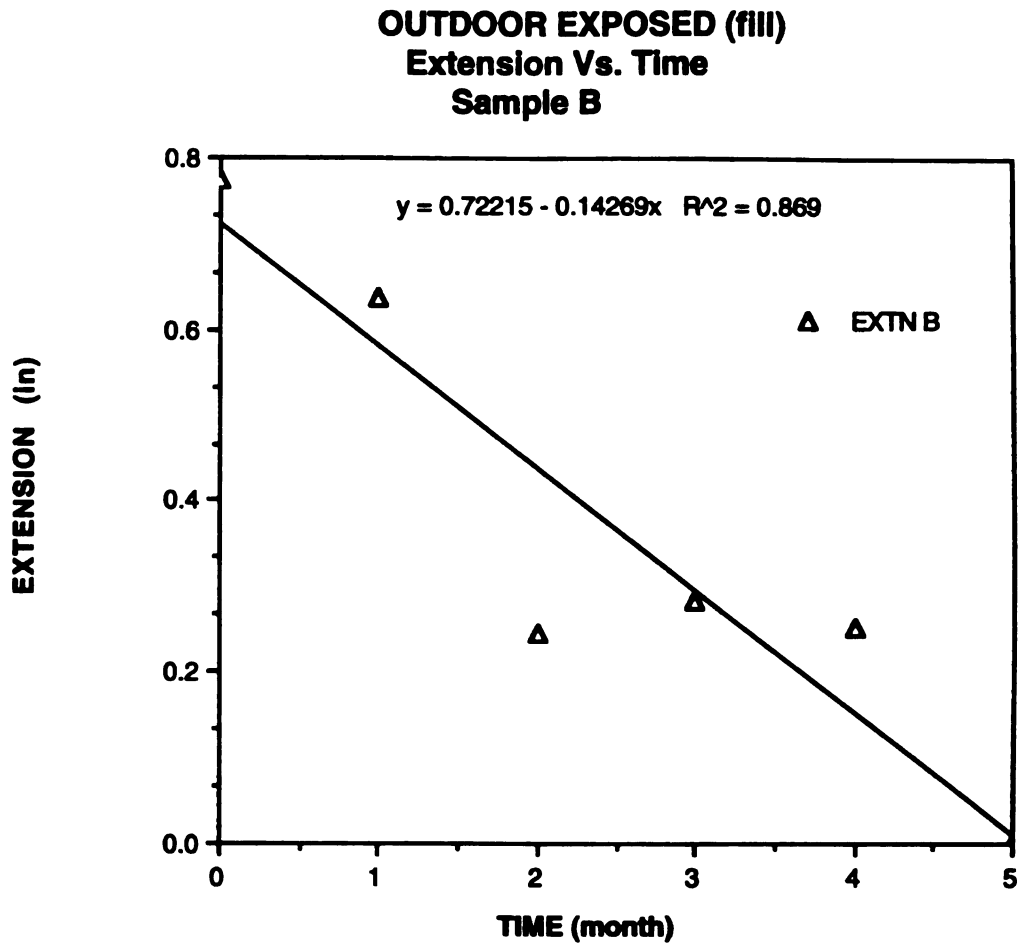


**Fig. 53: Outdoor Exposed, Extension Vs. Time, Sample C (warp)**





**Fig. 54: Outdoor Exposed, Extension Vs. Time, Sample A (fill)**



**Fig. 55: Outdoor Exposed, Extension Vs. Time, Sample B (fill)**

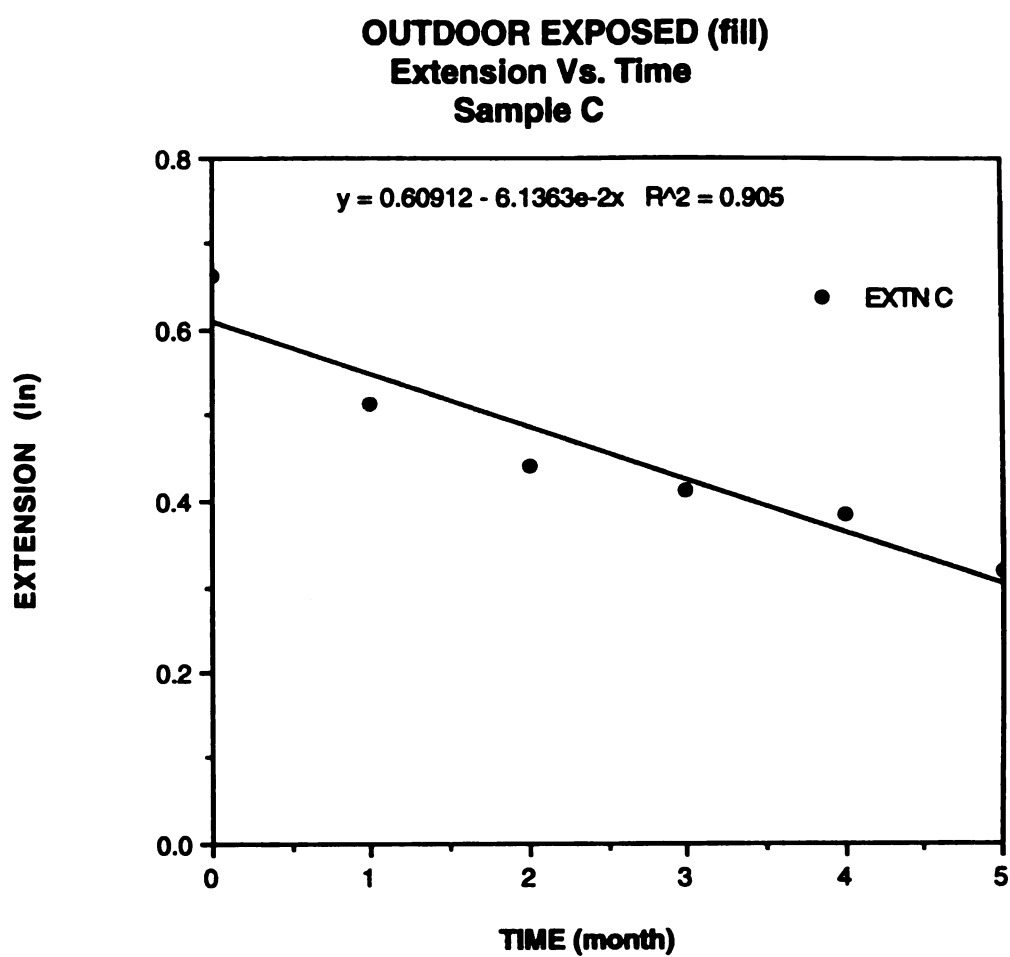


Fig. 56: Outdoor Exposed, Extension Vs. Time, Sample C (fill)

**Table 13: QUV Exposed**

100 HRS	WARP		FILL	
	LOAD	EXTN	LOAD	EXTN
SAMPLE A	104.90	0.571	66.62	0.492
	102.20	0.631	61.58	0.490
	115.70	0.625	73.40	0.510
	86.79	0.516	75.22	0.531
AVG=	102.40	0.611	69.71	0.506
STD=	11.93	0.027	6.09	0.019
SAMPLE B	87.09	0.510	99.76	0.686
	90.82	0.683	97.72	0.561
	96.97	0.544	99.60	0.741
	110.30	0.691	114.50	0.691
AVG=	96.30	0.607	102.90	0.670
STD=	10.19	0.093	7.79	0.077
SAMPLE C	88.99	0.605	78.87	0.446
	90.50	0.683	79.54	0.487
	91.57	0.748	70.74	0.516
	95.57	0.639	73.77	0.479
AVG=	91.66	0.669	75.73	0.482
STD=	2.81	0.062	4.21	0.029
200 HRS				
SAMPLE A	84.78	0.570	61.42	0.472
	79.03	0.642	61.88	0.407
	88.43	0.619	75.14	0.475
	103.80	0.610	72.91	0.535
AVG=	89.01	0.610	67.84	0.472
STD=	10.59	0.030	7.20	0.052
SAMPLE B	93.83	0.504	39.14	0.165
	89.90	0.470	32.70	0.140
	86.66	0.468	30.50	0.169
	95.36	0.591	26.20	0.129
AVG=	91.44	0.508	32.14	0.151
STD=	3.93	0.058	5.39	0.019
SAMPLE C	63.41	0.396	62.15	0.371
	65.21	0.502	67.33	0.521
	61.72	0.320	60.54	0.505
	70.74	0.463	63.33	0.501
AVG=	65.27	0.420	63.34	0.475
STD	3.92	0.080	2.90	0.070

Table 13 (cont'd)

250 HRS	WARP		FILL	
	LOAD	EXTN	LOAD	EXTN
SAMPLE A	94.25	0.509	66.39	0.460
	93.61	0.566	53.05	0.433
	88.70	0.523	54.74	0.404
	83.81	0.476	71.81	0.404
AVG=	90.09	0.519	61.50	0.425
STD=	4.87	0.037	9.08	0.027
SAMPLE B	99.92	0.510	17.32	0.106
	79.54	0.505	13.13	0.112
	90.04	0.493	15.22	0.149
	94.01	0.497	7.81	0.170
AVG=	90.88	0.501	13.37	0.134
STD=	8.58	0.008	4.08	0.030
SAMPLE C	42	0.417	48.05	0.481
	86.79	0.493	68.13	0.474
	49.02	0.427	67.14	0.450
	68.56	0.455	57.64	0.329
AVG=	68.70	0.448	60.24	0.434
STD=	15.47	0.034	9.40	0.071
300 HRS				
SAMPLE A	66.68	0.390	47.22	0.303
	65.34	0.423	45.18	0.264
	57.15	0.348	69.64	0.408
	66.85	0.371	60.27	0.429
AVG=	64.01	0.383	55.58	0.351
STD=	4.62	0.032	11.51	0.080
SAMPLE B	47.11	0.382	10.85	0.368
	65.18	0.353	15.30	0.585
	61.64	0.377	10.07	0.457
	65.07	0.383	14.71	0.418
AVG=	59.75	0.374	12.73	0.457
STD=	8.59	0.014	2.65	0.093
SAMPLE C	64.56	0.416	54.42	0.527
	60.11	0.367	61.29	0.523
	41.85	0.264	47.84	0.454
	71.09	0.407	51.52	0.381
AVG=	59.40	0.364	53.77	0.471
STD=	12.54	0.070	5.69	0.069

Table 13 (cont'd)

350 HRS	WARP		FILL	
	LOAD	EXTN	LOAD	EXTN
SAMPLE A	54.47	0.299	47.54	0.330
	57.34	0.279	45.99	0.338
	63.41	0.386	42.34	0.309
	65.96	0.372	43.03	0.299
AVG=	60.63	0.334	44.73	0.319
STD=	5.31	0.053	2.46	0.018
SAMPLE B	67.11	0.336		
	61.26	0.281		
	65.69	0.343		
	63.65	0.360		
AVG=	64.43	0.330		
STD=	2.54	0.034		
SAMPLE C	61.02	0.363	53.07	0.377
	52.11	0.266	53.74	0.409
	60.08	0.317	53.96	0.340
	63.92	0.371	43.52	0.350
AVG=	59.28	0.329	51.07	0.369
STD=	5.05	0.048	5.05	0.031
400 HRS				
SAMPLE A	57.80	0.336	43.70	0.276
	53.05	0.340	36.89	0.305
	41.58	0.239	49.02	0.319
	47.33	0.278	48.54	0.285
AVG=	49.94	0.298	44.54	0.296
STD=	7.03	0.049	5.64	0.019
SAMPLE C	31.52	0.240	57.26	0.316
	45.26	0.365	47.06	0.345
	46.90	0.297	40.89	0.405
	41.99	0.236	38.52	0.397
AVG=	41.42	0.285	45.93	0.366
STD=	6.91	0.060	8.37	0.043

Table 13 (cont'd)

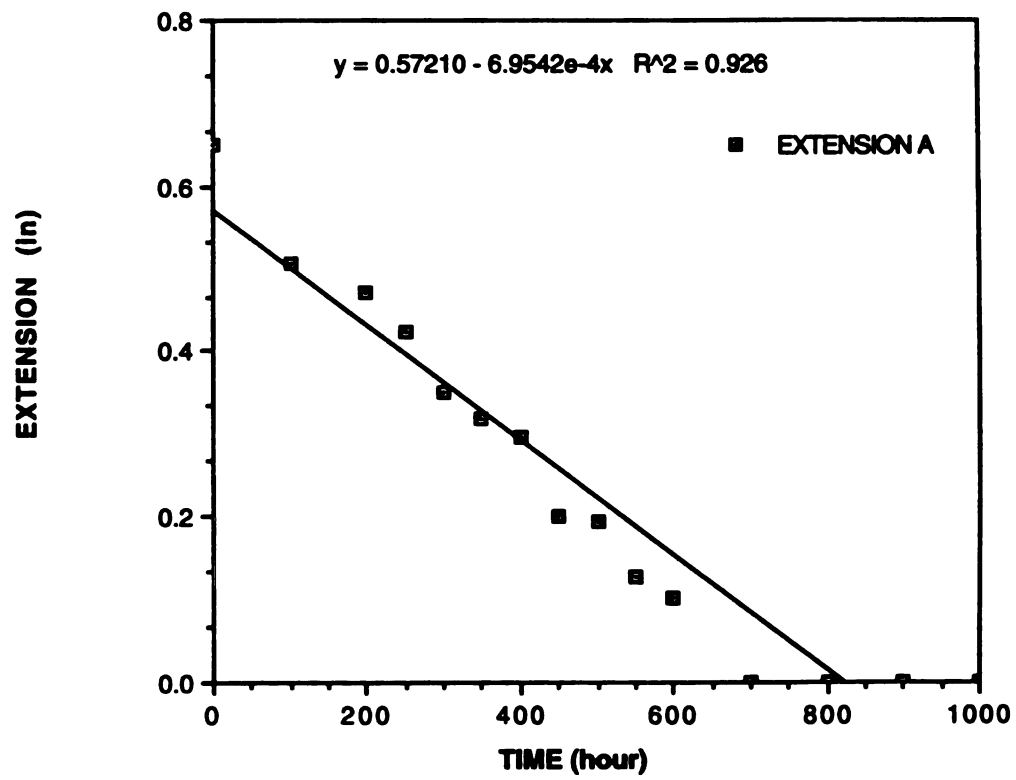
450 HRS	WARP		FILL	
	LOAD	EXTN	LOAD	EXTN
SAMPLE A	49.99	0.275	20.62	0.169
	41.13	0.238	27.87	0.219
	38.74	0.311	21.58	0.188
	46.71	0.255	26.68	0.226
AVG=	44.14	0.270	24.19	0.201
STD=	5.13	0.031	3.62	0.027
SAMPLE C	48.59	0.355	54.15	0.389
	44.16	0.328	40.56	0.290
	57.26	0.362	43.65	0.279
	55.68	0.329	45.58	0.263
AVG=	51.42	0.344	45.99	0.305
STD=	6.14	0.018	5.82	0.057
500 HRS				
SAMPLE A	19.79	0.148	25.64	0.196
	25.69	0.179	19.41	0.180
	22.63	0.155	24.40	0.188
	23.03	0.158	19.33	0.214
AVG=	22.79	0.160	22.20	0.195
STD=	2.41	0.013	3.30	0.015
SAMPLE C	44.00	0.217	44.38	0.266
	27.46	0.174	29.32	0.381
	32.30	0.201	43.06	0.307
	25.45	0.181	35.36	0.320
AVG=	32.30	0.193	38.03	0.319
STD=	8.31	0.020	7.04	0.048
550 HRS				
SAMPLE A	19.46	0.139	3.79	0.095
	10.60	0.172	12.62	0.171
	10.85	0.177	4.86	0.105
	10.85	0.125	13.50	0.137
AVG=	12.94	0.153	8.69	0.127
STD=	4.35	0.025	5.08	0.034
SAMPLE C	23.57	0.222	38.01	0.296
	27.84	0.196	27.60	0.239
	30.74	0.199	25.69	0.269
	36.35	0.220	24.30	0.178
AVG=	29.63	0.209	28.90	0.246
STD=	5.36	0.014	6.22	0.051

Table 13 (cont'd)

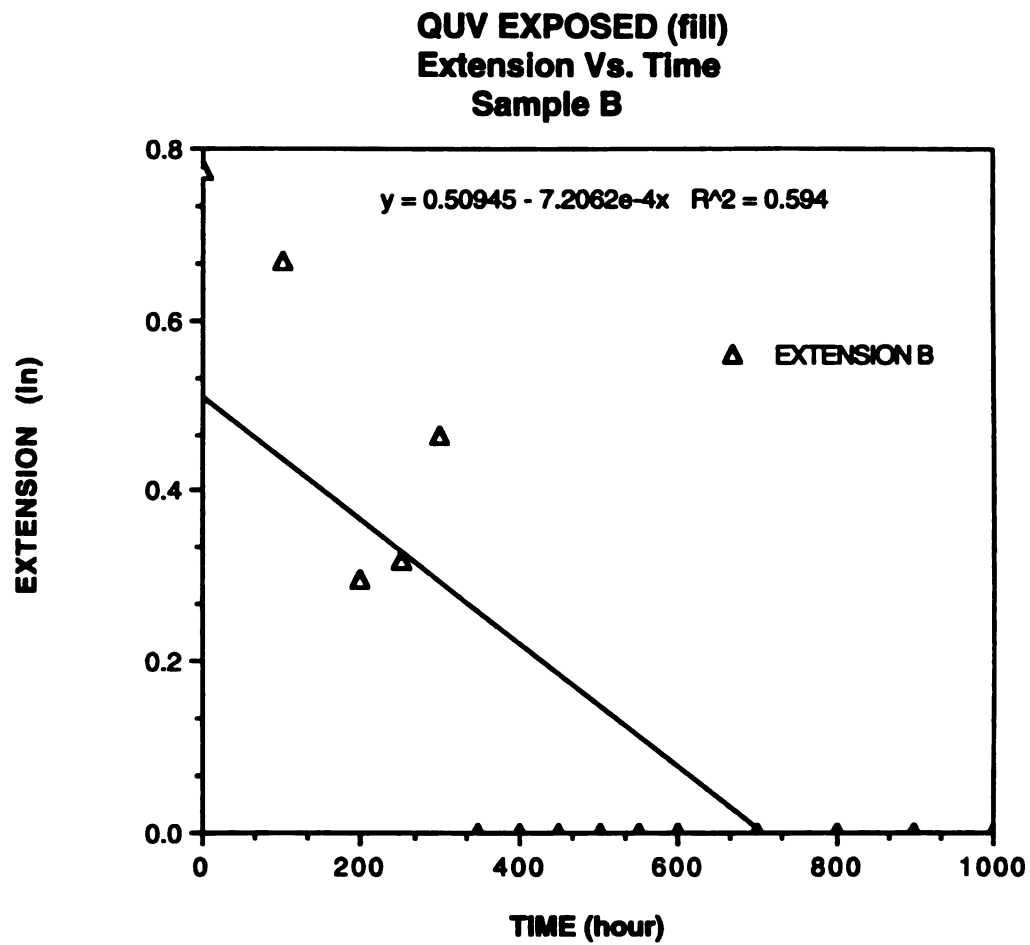
600 HRS	WARP		FILL	
	LOAD	EXTN	LOAD	EXTN
SAMPLE A	5.61	0.091	3.22	0.094
	1.18	0.121	3.38	0.077
	12.91	0.343	4.97	0.111
	3.11	0.270	5.91	0.122
AVG=	5.70	0.206	4.37	0.101
STD=	5.13	0.120	1.29	0.020
SAMPLE C	29.48	0.186	40.69	0.353
	42.36	0.231	31.92	0.227
	27.49	0.177	28.81	0.230
AVG=	33.11	0.198	33.81	0.270
STD=	8.07	0.029	6.16	0.072
700 HRS				
SAMPLE C	13.23	0.111	16.11	0.116
	19.84	0.141	13.48	0.171
	11.60	0.175	22.01	0.157
	6.74	0.069	11.87	0.117
AVG=	12.85	0.124	15.87	0.140
STD=	5.41	0.045	4.45	0.028
800 HRS				
SAMPLE C	3.14	0.095	4.13	0.089
	0.83	0.070	3.92	0.108
	5.99	0.235	1.07	0.089
	1.40	0.085	2.20	0.128
AVG=	2.84	0.121	2.83	0.104
STD=	2.32	0.077	1.46	0.019



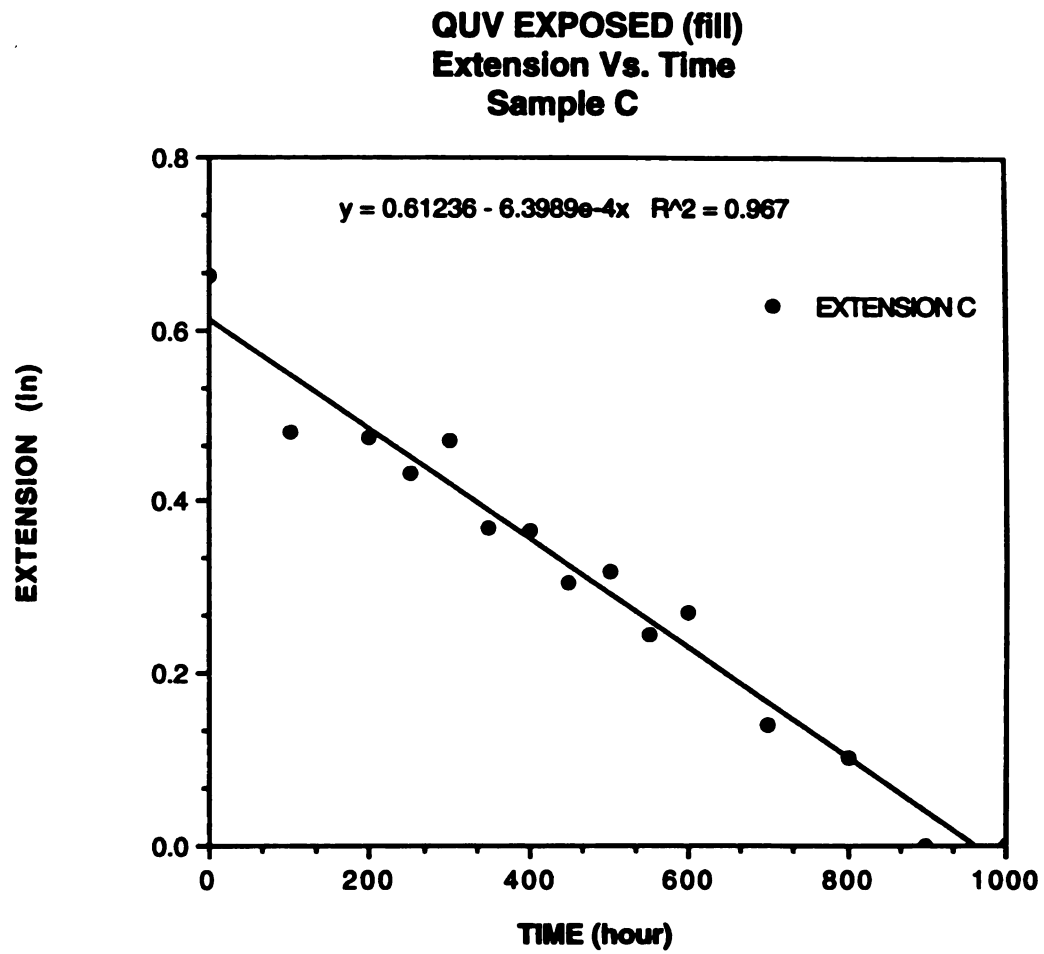
**QUV EXPOSED (fill)  
Extension Vs. Time  
Sample A**



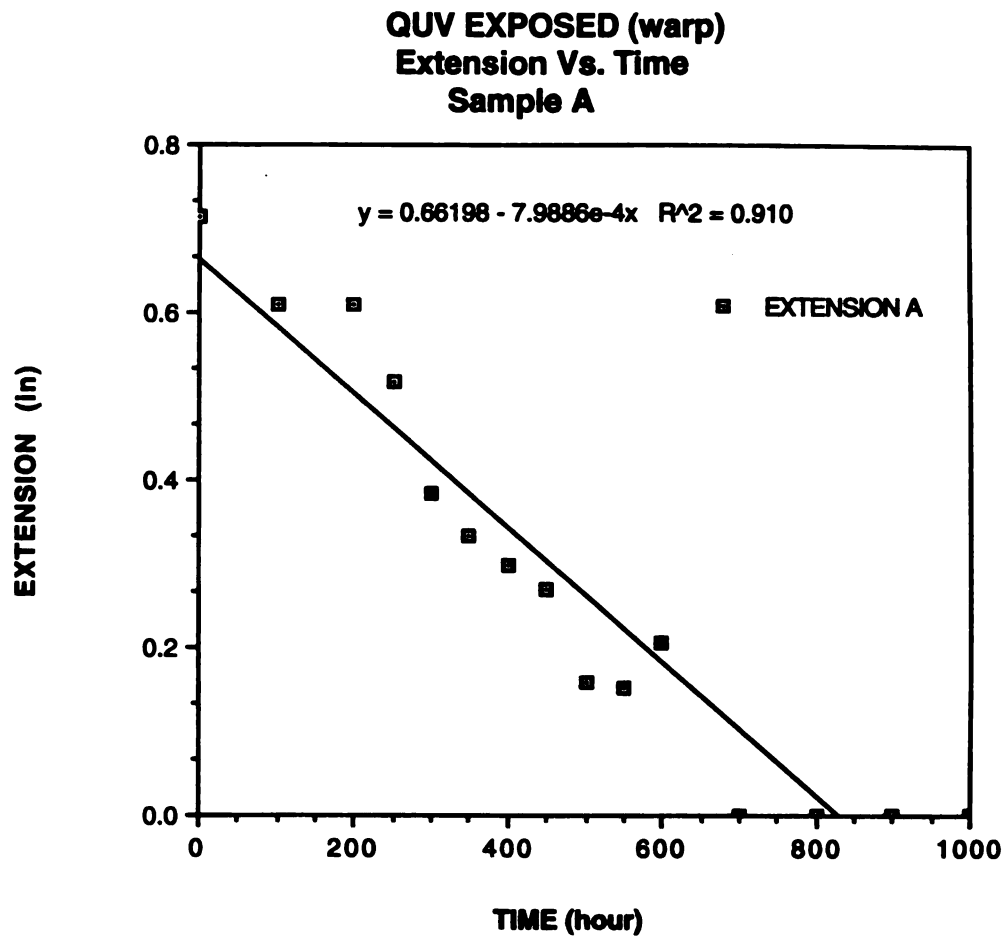
**Fig. 57: QUV Exposed, Extension Vs. Time, Sample A (fill)**



**Fig. 58: QUV Exposed, Extension Vs. Time, Sample B (fill)**



**Fig. 59: QUV Exposed, Extension Vs. Time, Sample C (fill)**



**Fig. 60: QUV Exposed, Extension Vs. Time Sample A (warp)**

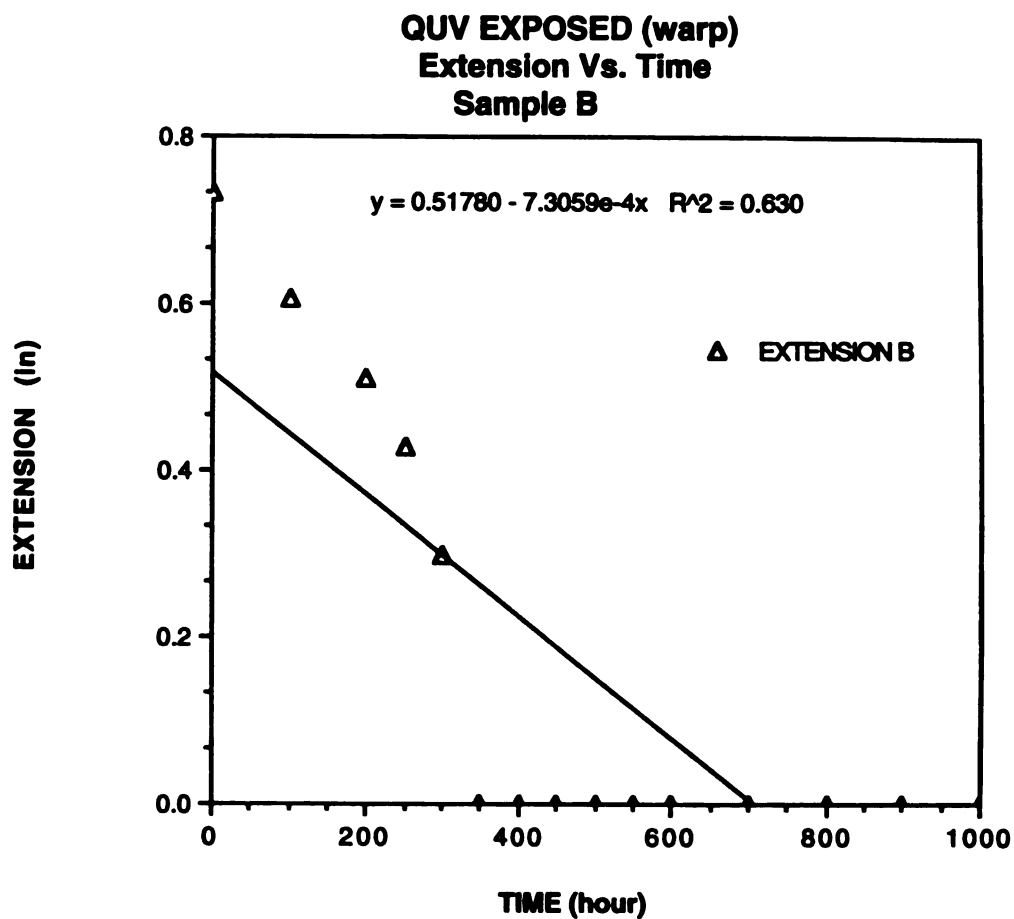
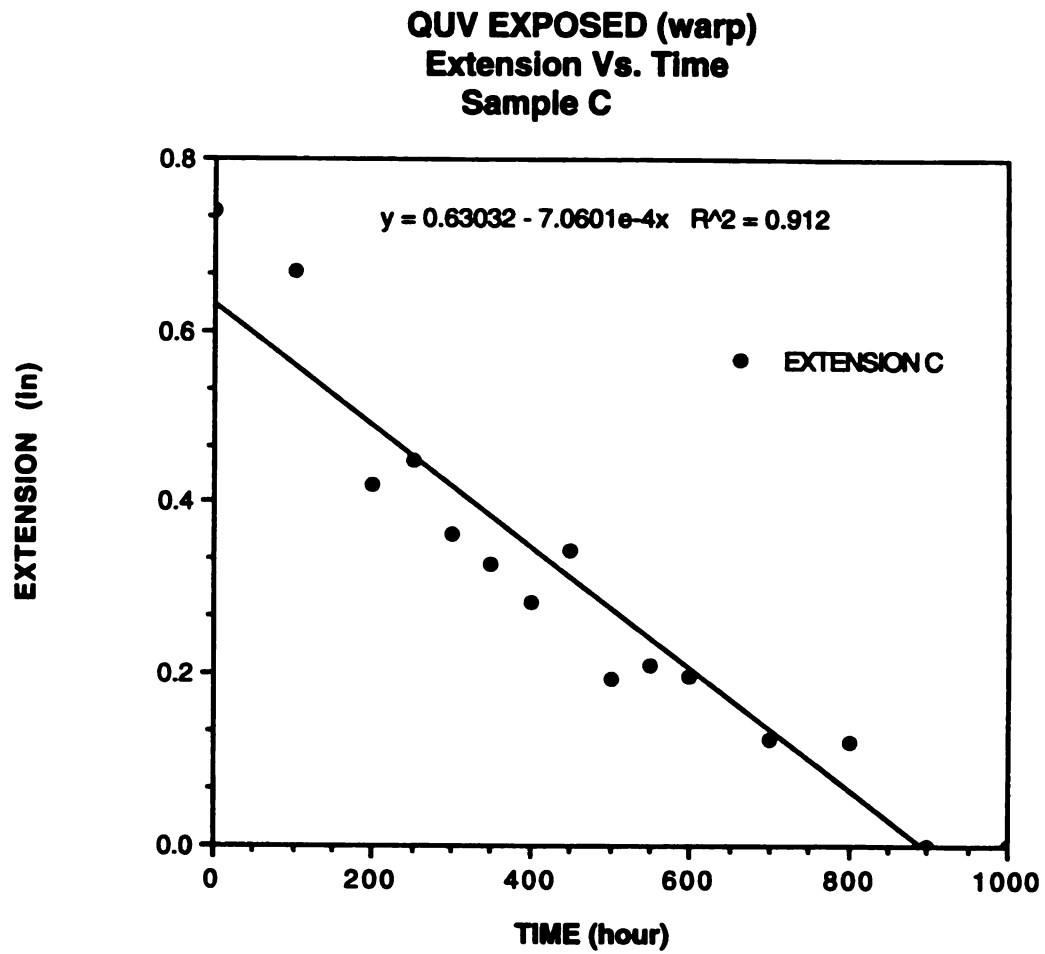


Fig. 61: QUV Exposed, Extension Vs. Time Sample B (warp)



**Fig. 62: QUV Exposed, Extension Vs. Time Sample C (warp)**

**Table 14: % Elongation as Function of X (time)**

	INITIAL %ELONGATION	WARP	Y 0.5	Y 0.6	Y 0.7	Y 0.8	Y 0.9
A		0.237933	0.118967	0.14276	0.166553	0.190347	0.21414
B		0.244933	0.122467	0.14696	0.171453	0.195947	0.22044
C		0.246133	0.123067	0.14768	0.172293	0.196907	0.22152
FILL							
A		0.217167	0.108583	0.1303	0.152017	0.173733	0.19545
B		0.258533	0.129267	0.15512	0.180973	0.206827	0.23268
C		0.2212	0.1106	0.13272	0.15484	0.17696	0.19908
Y=%ELONGATION(in/in)      Y=Mx+B    X=(Y-B)/M							
OUTDOOR (MONTHS)							
	B	M	X	X	X	X	X
A	0.64849	-0.0719	7.364412	7.033503	6.702595	6.371686	6.040777
B	0.75582	-0.12139	5.217508	5.015734	4.813961	4.612187	4.410413
C	0.66645	-0.08183	6.640717	6.339916	6.039116	5.738315	5.437514
FILL							
	B	M	X	X	X	X	X
A	0.57007	-0.06478	7.123907	6.788669	6.453432	6.118195	5.782958
B	0.72215	-0.01427	41.55045	39.73859	37.92674	36.11489	34.30303
C	0.60912	-0.06136	8.124114	7.763636	7.403158	7.04268	6.682203
QUV (HOURS)							
	B	M	X	X	X	X	X
A	0.66198	-0.0008	679.7353	649.9512	620.1671	590.383	560.5989
B	0.5178	-0.00073	541.1152	507.5898	474.0643	440.5389	407.0135
C	0.63032	-0.00071	718.479	683.6164	648.7538	613.8912	579.0286
FILL							
	B	M	X	X	X	X	X
A	0.5721	-0.0007	666.5277	635.2995	604.0714	572.8433	541.6151
B	0.50945	-0.00072	527.5781	491.7016	455.8251	419.9486	384.072
C	0.61236	-0.00064	784.1348	749.5663	714.9979	680.4294	645.861
CARBON ARC (HOURS)							
	B	M	X	X	X	X	X
A	0.6065	-0.00033	1488.197	1415.568	1342.939	1270.309	1197.68
B	0.68354	-0.00055	1022.178	977.5551	932.9325	888.31	843.6874
C	0.75196	-0.00082	769.8535	739.7233	709.5932	679.463	649.3328
FILL							
	B	M	X	X	X	X	X
A	0.55886	-0.00076	594.3462	565.6811	537.016	508.3509	479.6859
B	0.6828	-0.00146	379.0805	361.3752	343.6698	325.9645	308.2591
C	0.6616	-0.00054	1022.833	981.7709	940.7091	899.6473	858.5855

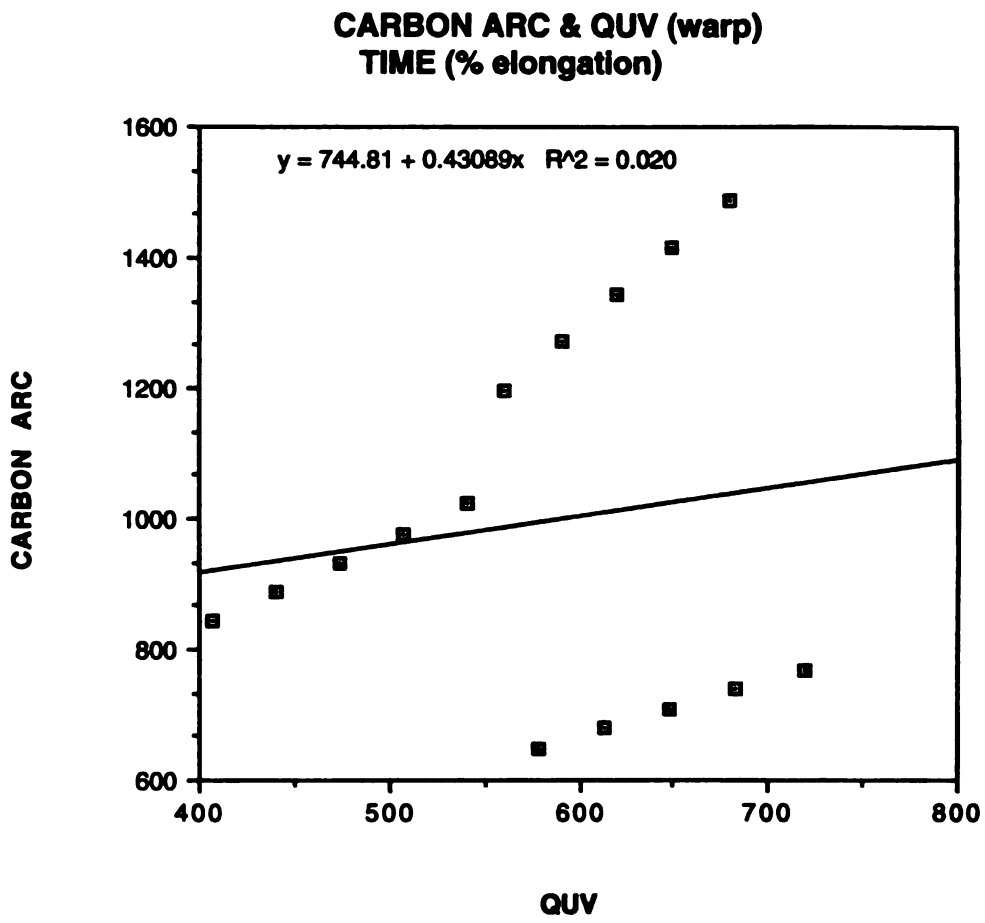
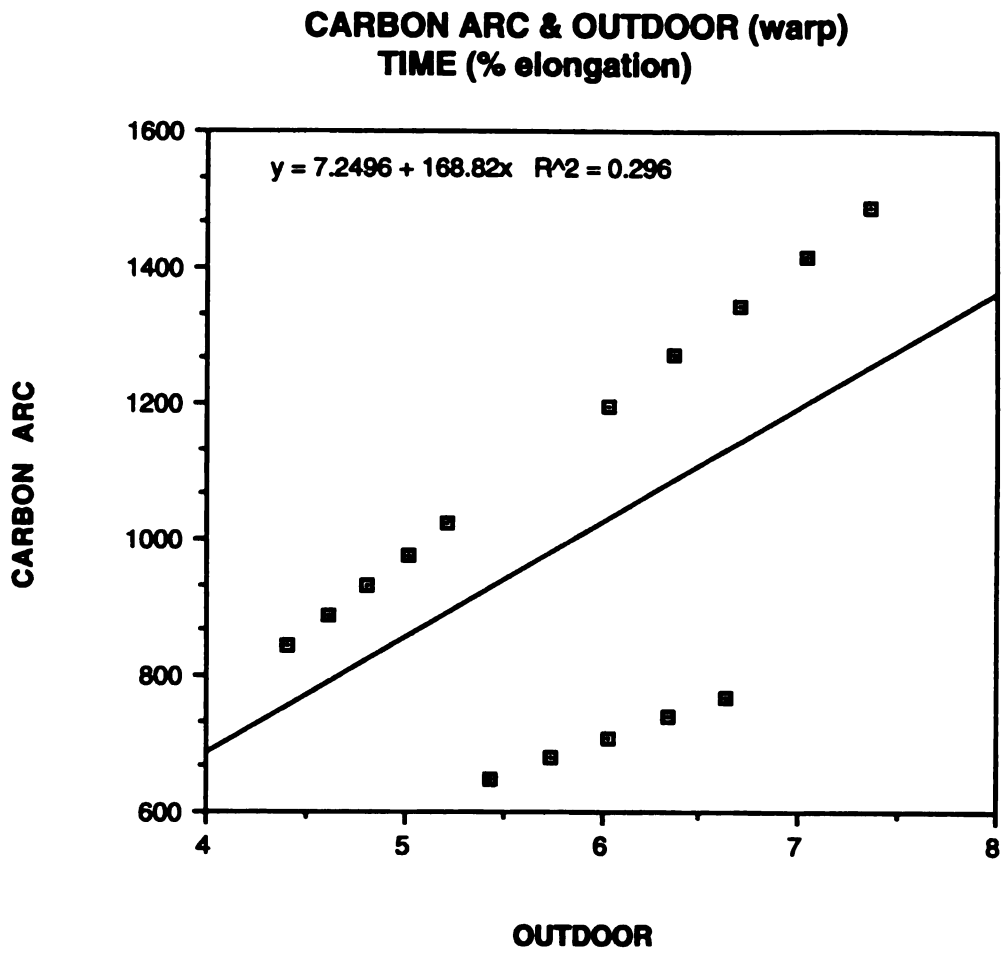


Fig 63 : Carbon Arc & QUV (warp) - % Elongation





**Fig 64 : Carbon Arc & Outdoor (warp) - % Elongation**

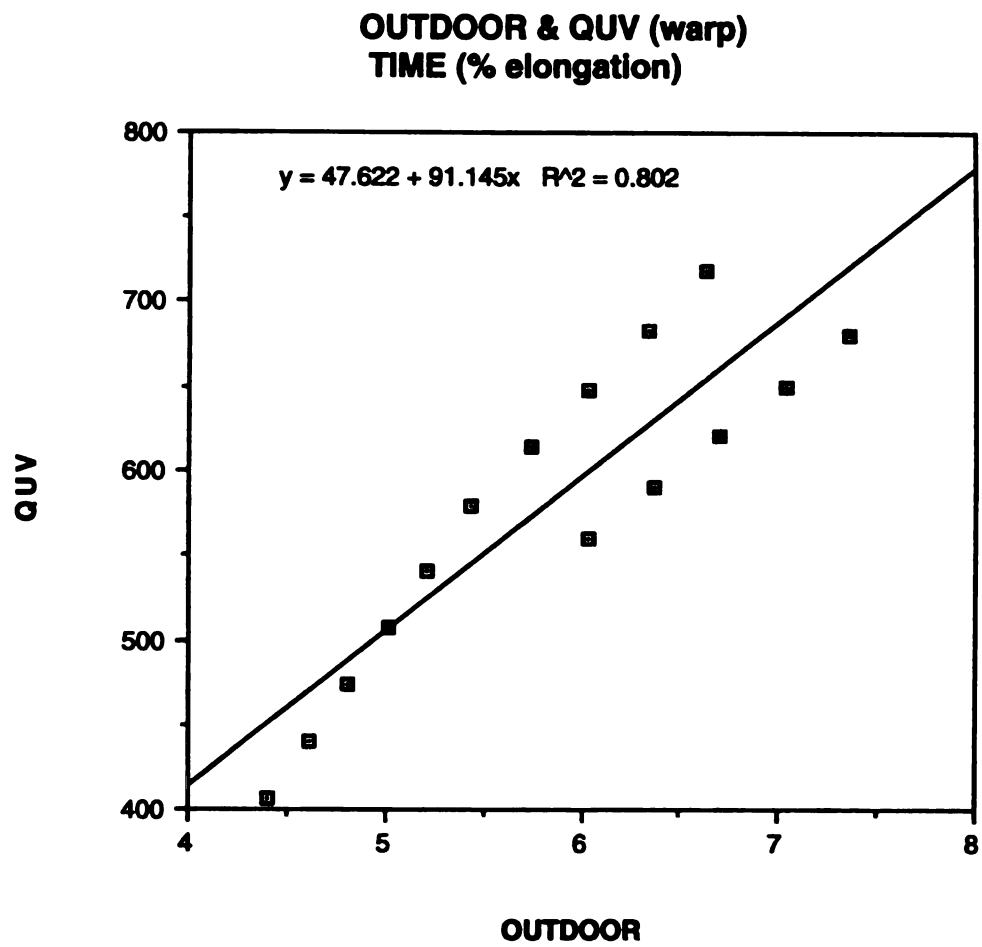
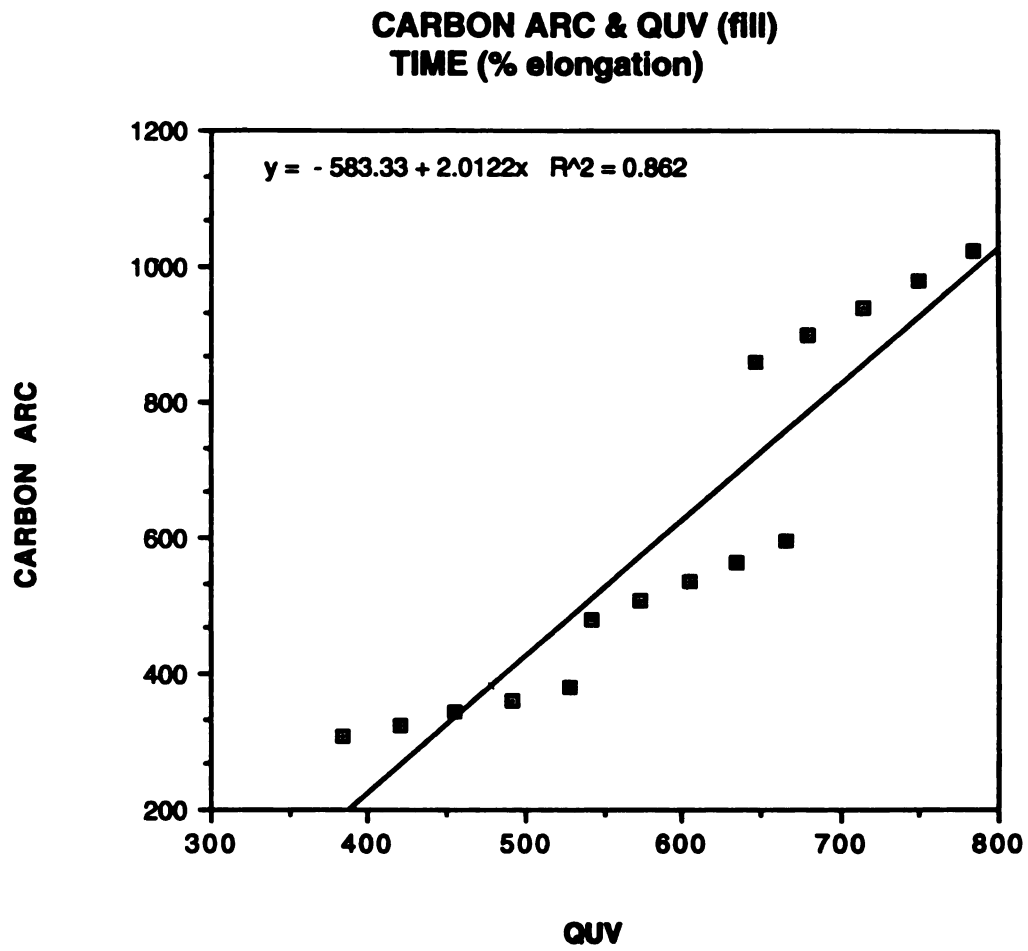
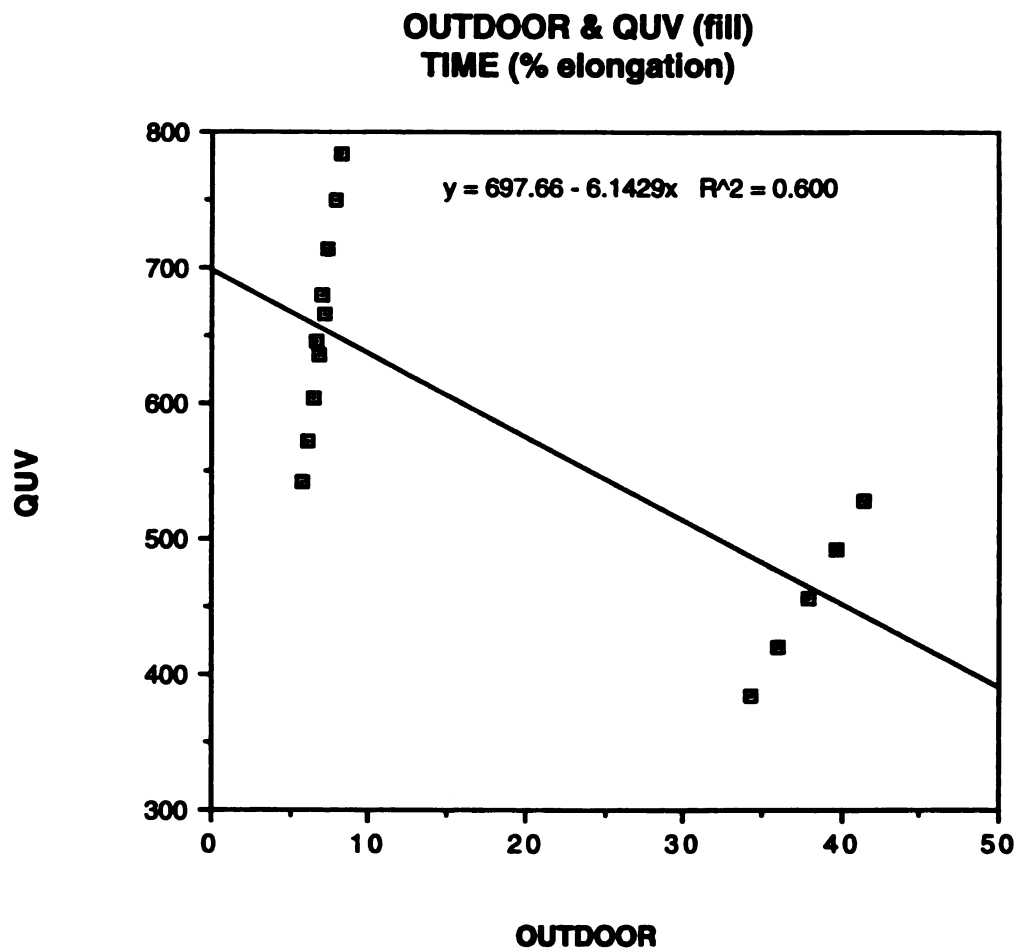


Fig.65: Outdoor & QUV (warp) - % Elongation



**Fig.66 : Carbon Arc & QUV (fiii) - % Elongation**



**Fig. 67: Outdoor & QUV (fill) - % Elongation**

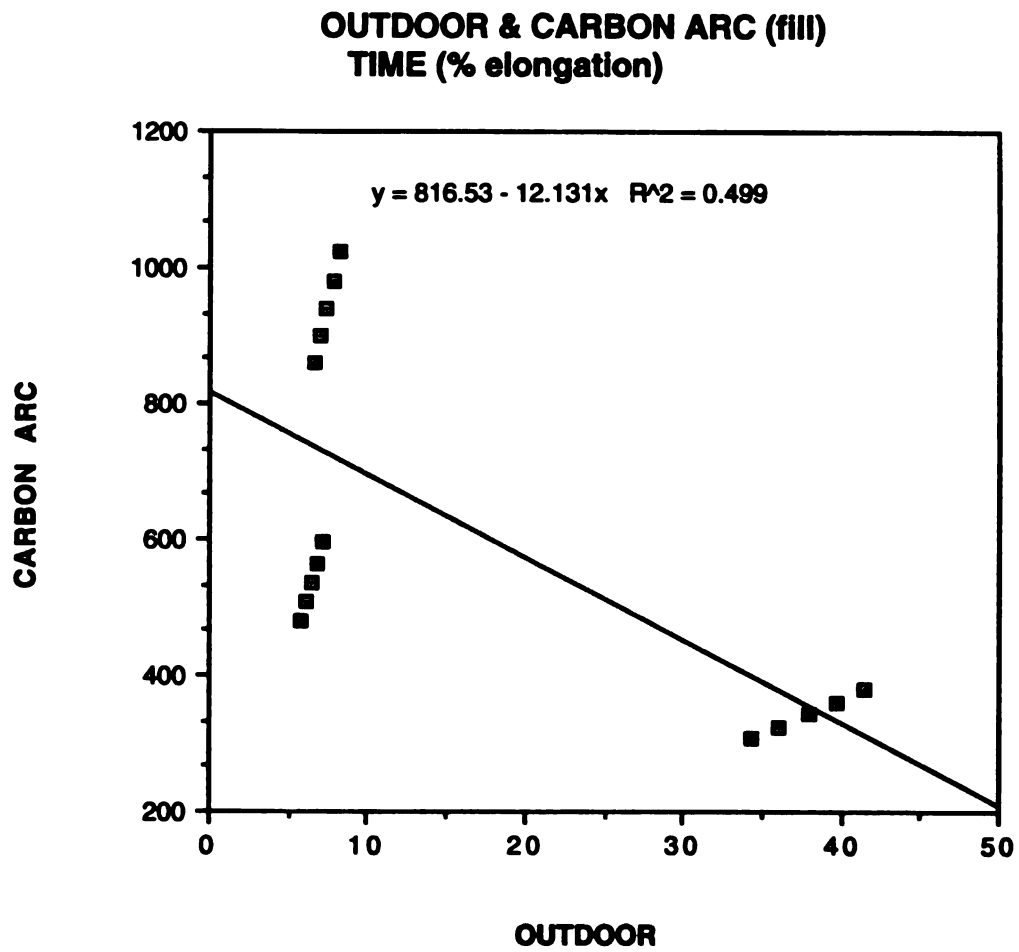


Fig. 68: Outdoor & Carbon Arc (fill) - % Elongation

## LIST OF REFERENCES

- Brennan**, Patrick and Carol Fedor, "Sunlight, UV and Accelerated Weathering", Q-Panel, poster, undated.
- Carlsson**, D.J., K.H. Chan, J.P. Tovborg Jensen, D.M. Wiles and J. Durmis, "Hindered Amines as Antioxidants in UV Exposed Polymers", Polymer Additives, New York: Plenum Press, 1984, 35-47.
- Cicchetti**, O., "Mechanisms of Oxidative Photodegradation and of UV Stabilization of Polyolefins", Adv. Polymer Science, 1970, 7(112):70-105.
- Crowdson**, Lesley F.E., "Correlation of Outdoor and Laboratory Accelerated Weathering Tests at Currently Used and Higher Irradiance Levels-Part II", Sun Spots, 4th Quarter 1993, 23(46).
- Encyclopedia of Chemical Technology**, "Plastics, Environmentally Degradable", New York: John Wiley & Sons, Inc., 1984, no author, 626-648.
- Fischer**, Richard, "Accelerated Weathering Test Development with Fluorescent UV-Condensation Devices", SAE Technical Paper Series, New York: Copyright Clearance Center, 1984, August 6-9; 1-9b.
- Fischer**, R.M. and W.D. Ketola, "The Use of a Nonparametric Statistics in Accelerated Weathering Test Design and Development", RETEC Review Issue, Fall-Winter 1993, 11(2):9-14.
- Grassie**, Norman and Gerald Scott, "Polymer Degradation and Stabilization", New York: Cambridge University Press, 1985.
- Grossman**, George W., "Correlation of Laboratory to Natural Weathering", Journal of Coatings Technology, Oct. 1977, 49(633):45-54.
- Hardy**, William B., "Light Stabilization of Polymers, Part I of II", Atlas Sun Spots, Summer 1983, 13(30) a.
- Hardy**, William B., "Light Stabilization of Polymers, Part II of II", Atlas Sun Spots, Autumn 1983, 13(31) b.
- Hawkins**, W. Lincoln, "Polymer Degradation and Stabilization", Springer-Verlag, 1984.

- Hirt**, Robert C and Norma D. Searle, "Energy Characteristics of Outdoor and Indoor Exposure Sources and Their Relation to the Weatherability of Plastics", Applied Polymer Symposia, 1967, 4:61-83.
- Kelen**, Tibor, "Polymer Degradation". New York: Van Nostram Reinhold. 1983.
- McTigue**, F. H. and M. Blumberg, "Factors Affecting Light Resistance of Polypropylene", Applied Polymer Symposia, 1967, 4:175-188.
- Miteff**, Steve, Personal Communication, May 12, 1993.
- Q-Panel** Technical Bulletin L-8004, "The QUV compared to Sunshine Carbon Arc", 1988.
- Schweltzer**, Philip A., "What Every Engineer Should Know About Corrosion", New York: Marcel Dekker, Inc., 1987.
- Searle**, Norma D., "Activation Spectra the Activation Spectrum and its Significance to Weathering of Polymeric Materials", Atlas Sun Spots, Fall 1984, 14(33):1-5.
- Searle**, Norma D., "Wavelength Sensitivity of Polymers", ANTEC, 1986, 62-74 b.
- Seppala**, J, Y-Y. Linko, and T. Su, "Photo and Biodegradation of High Volume Thermoplastics", Helsinki: Finnish Academy of Technology, 1991.
- Tobin**, William, and Fred Vigeant, "Ultraviolet Stabilization Systems", Plastics Compounding, 1981, Sept/Oct, 4:16-24.

MICHIGAN STATE UNIV. LIBRARIES



31293010317885