PB 264 161

T NOS. DOT-TSC-NHTSA-76-2

HS-802-103

PROOF PRESSURE EVALUATION OF WORN PASSENGER CAR TIRE CARCASSES

S. K. Clark
R. N. Dodge
D. W. Lee
J. R. Luchini

The Regents of the University of Michigan
Ann Arbor MI 48109

NOVEMBER 1976

FINAL REPORT

Prepared for

U.S DEPARTMENT OF TRANSPORTATION
National Highway Traffic Safety Administration
Research and Development
Washington DC 20590

Technical Report Documentation Page

1. Report No. HS-802-103	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle
PROOF PRESSURE EVALUATION OF WORN PASSENGER CAR TIRE CARCASSES

5. Report Date
November 1976

6. Performing Organization Code

7. Author(s) S. K. Clark, R. N. Dodge, D. W. Lee and J. R. Luchini

8. Performing Organization Report No.
DOT-TSC-NHTSA-76-2

9. Performing Organization Name and Address
The Regents of the University of Michigan*
Ann Arbor MI 48109

10. Work Unit No. (TRAIS)
HS603/R7405

11. Contract or Grant No.
DOT-TSC-316

12. Sponsoring Agency Name and Address
U.S. Department of Transportation
National Highway Traffic Safety Administration
Research and Development
Washington DC 20590

13. Type of Report and Period Covered
Final Report
March 1974 - March 1976

14. Sponsoring Agency Code

15. Supplementary Notes
U.S.
*Under contract to: U.S. Department of Transportation
Transportation Systems Center
Kendall Square
Cambridge MA 02142

16. Abstract

Test work is described that examines the value of hyrdostatic proof pressure testing in screening worn tire carcasses before retreading. Results are given from dynamometer wheel tests on a significant sample of retreaded passenger car tires. Each sample unit consisted of a pair of tires, one of which was hydrostatically pressurized to approximately 75% of the mean burst pressure before testing. There is evidence from the tests that the pressurization is neither beneficial nor harmful to the subsequent tire durability.

Acoustic emission, pressure, pressure rate and volume were also recorded as functions of time from a large sample of worn passenger car tires during hydrostatic pressurization. Correlation studies between these data and the carcass condition show no simple relationships between structural flaws and these recorded variables.

17. Key Words
Tire
Failure
Acoustic Emission
Burst Pressure

18. Distribution Statement
DOCUMENT IS AVAILABLE TO THE U.S. PUBLIC THROUGH THE NATIONAL TECHNICAL INFORMATION SERVICE, SPRINGFIELD, VIRGINIA 22161

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 56	22. Price

Form DOT F 1700.7 (8-72)

Reproduction of completed page authorized

PREFACE

While the pneumatic tire is much more than a simple pressure vessel, certain techniques useful in testing structural integrity of pressure vessels may also evaluate pressure testing of tire carcasses as a form of nondestructive inspection prior to retreading. The two fundamental questions to be answered by this work are: does such a test degrade the life of an otherwise adequate tire carcass, and does such a test prove superior to current inspection practices.

The known complexity of the tire as a structure requires that this work be approached experimentally since immediate data are needed. Various techniques from pressure vessel technology were adapted for this work, although the structure of the tire is quite different from that of the normal pressure vessel.

The work has been sponsored by the National Highway Traffic Safety Administration under a program administered by Mr. Manuel J. Lourenco, Office of Vehicle Safety Research, Office of Research and Development.

The cooperation of Firestone Tire and Rubber Company is gratefully acknowledged for the retreading of tires. Wheel testing was carried out by Compliance Testing, Inc., of Ravenna, Ohio. The contract technical monitor was Stephen N. Bobo, Department of Transportation, Transportation Systems Center, Cambridge, Massachusetts.

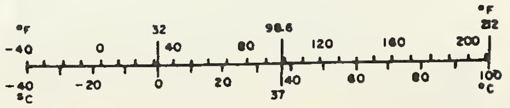
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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EXECUTIVE SUMMARY

This program contains two basic phases. In the first, it was desired to determine the influence on subsequent service life of a large hydrostatic pressure applied to a pneumatic tire. As part of this work, research was begun approximately two and one half years ago on the influence of large single loads on the subsequent fatigue life of typical textile cords used in pneumatic tire contruction. Single test loads close to those required for cord fracture were applied to selected cords, following which such cords were subjected to normal tension-tension fatigue testing. The results of these tests were compared to similar fatique tests carried out on cords which had not been preloaded.

In addition to this work on textile cords, a major program was carried out to assess the role of hydrostatic pressurization on the subsequent service life of passenger car tires. In order to lay a basis for this phase of the work, a complete study was made of the mean burst pressures of typical passenger car tires now in service. This was done by bursting over 100 tires using a high pressure nitrogen-over-water system. The mean burst pressure of worn 15-in. rim-diameter passenger car tires of all constructions was obtained. Data from this population allowed us to choose proof-pressure levels which would represent approximately 75% of the mean burst pressure of the population. This is believed to represent a logical proof pressure, since it results in a failure rate of approximately 15% during proof testing.

The data from these tests showed that tire construction affected the most probable location of failure. Two-ply and polyester-fiberglas bias-belted tires failed most often in the crown. Rayon-rayon bias-belted tires failed in the sidewall and bead, while radial tires tended to fail most often in the bead area. Four-ply bias tires failed in both crown and bead areas.

The average burst pressure also was a function of construction. Two-ply bias tires showed an average burst pressure of 188 psi, four-ply tires 218 psi, rayon-rayon bias-belted tires 215 psi, polyester-fiberglass bias-belted tires 201 psi and radial tires 208 psi. The mean burst of pressure of all the tires tested, weighted by a large fraction of polyester-fiberglas bias-belted tires, was 207 psi. The burst pressure data appeared to approximate a normal distribution curve.

During the process of carrying out this program a standard procedure was developed for applying hydrostatic pressure internally to these test tires. This involved using high pressure water backed by nitrogen, applied at constant volume rate to the tire up to a specified pressure level. This process will be referred to often during this report, and the term "pressurization process" will be used to mean application of such pressure up to approximately 170 psi. Following preparation of the paired tires, this phase of the research was completed by analysis of the data from durability and high-speed tests run on the retreaded tires. The code designating the pressurized and unpressurized tires was not known to the tire test facility at which the durability tests were run.

To determine the effect of proof pressures on subsequent tire service life, 68 pairs of worn passenger car tires were obtained. One tire of each pair was pressurized to an internal pressure of either 150, 160, or 170 psi. These pressures represented 70% to 80% of the mean burst pressure of the total population described above. Following this pressurization process, the tire pairs were recapped and subsequently tested on a dynamometer to the standard DOT endurance test or the standard DOT high-speed test, as described in MVSS 109. The test results showed that pressurized tires failed these tests just as frequently as unpressurized tires, and that no significant effect could be attributed to the pressurization process.

During the pressurization process internal pressure, contained volume, pressure rate, and acoustic emission output were recorded as functions of time. Consideration of this data shows that little correlation can be made between pressure, volume, pressure rate or acoustic emission, and the structural condition of the carcass. There is no obvious benefit to the use of the pressurization process as a screening device prior to tire recapping.

Based on the results of these tests, two general conclusions can be made concerning the use of proof pressures on worn passenger car tire carcass:

(a) The pressurization process applied to a sound tire carcass has no effect, either detrimental or beneficial, on the subsequent tire durability after recapping.

(b) The proof pressure process appears to have little benefit in the selection or screening of worn tire carcasses for the retreading industry. It cannot be used as a substitute for a good visual and tactile inspection technique.

1. INTRODUCTION

This program contains two basic phases. In the first, it was desired to determine the influence on subsequent service life of a large hydrostatic pressure applied to a pneumatic tire. As part of this work, research was begun approximately two and one half years ago on the influence of large single loads on the subsequent fatigue life of typical textile cords used in pneumatic tire construction. Single test loads close to those required for cord fracture were applied to selected cords, following which such cords were subjected to normal tension-tension fatigue testing. The results of these tests were compared to similar fatigue tests carried out on cords which had not been preloaded. This work was reported in the literature by J. R. Luchini [1].

In addition to this work on textile cords, a major program was carried out to assess the role of hydrostatic pressurization on the subsequent service life of passenger car tires. In order to lay a basis for this phase of the work, a complete study was made of the mean burst pressures of typical passenger car tires now in service. This was done by bursting over 100 tires using a high pressure nitrogen-over-water system. The mean burst pressure of worn 15-in. rim-diameter passenger car tires of all constructions was obtained. Data from this population allowed us to choose proof-pressure levels which would represent approximately 75% of the mean burst pressure of the population. This is believed to represent a logical proof pressure, since it results in a failure rate of approximately 15% during proof testing. This work was previously described in detail in Ref. [2].

The next phase of this work involved selecting 65 pairs of worn tires in a paired test design. These pairs were chosen to be as closely alike as possible, in regard to size, material, and manufacturer. One of each of these tires was hydrostatically pressurized to a proof pressure level of approximately 75% of the mean burst pressure level of the total tire population. The other tire was not pressurized. Following this, the tires were retreaded and were tested for durability or high-speed performance under MVSS 109. This work was previously reported in Ref. [3].

During the process of carrying out this program a standard procedure was developed for applying hydrostatic pressure internally to these test tires. This involved using high pressure water backed by nitrogen, applied at constant volume rate to the tire up to a specified pressure level. This process will be referred to often during this report, and the term "pressurization process" will be used to mean application of such pressure up to approximately 170 psi. Following preparation of the paired tires, this phase of the research was completed by analysis of the data from durability and high-speed tests run on the retreaded tires. The code designating the pressurized and unpressurized tires was not known to the tire test facility at which the durability tests were run.

The second major portion of this work centered on the use of recorded sensor output from the tire during the pressurization process in order to determine its structural integrity and its suitability for retreading. Basically this involved pressure, volume, pressure rate, and acoustic emission records taken as functions of time during the pressurization of these tires. Details of this apparatus have previously been reported in Ref. [3].

2. SUMMARY AND CONCLUSIONS

In order to choose a proper proof pressure for a typical population of passenger car tires, it is necessary to have reasonably good statistics in the burst pressure characteristics of such a population. Having this data allows one to choose proof pressures which statistically results in the proper rejection of degraded or poor quality carcasses while retaining those which are structurally sound. For this reason the first major effort associated with this program was a series of hydrostatic burst tests on over 100 worn passenger car tires representative of current average usage in the United States. These were burst using a high-pressure nitrogen-over-water system described in this report, in which tank nitrogen was used to force water into the tire up to burst. The reason for this type of system was that the energy stored in the pressurized tire was minimized, and that very simple and inexpensive safety precautions were quite sufficient to protect instrumentation and personnel with such minimum energy levels.

The data from these tests showed that tire construction affected the most probable location of failure as well as the failure pressures. Two-ply and polyester-fiberglass bias-belted tires failed most often in the crown. Rayon-rayon bias-belted tires failed in the side wall and bead, while radial tires tended to fail most often in the bead area. Four-ply bias tires exhibited failures in both crown and bead areas. This information is quantitatively presented in Table 1, where the failure percentages at the specific locations are indicated.

TABLE 1.-FAILURE PERCENTAGE AT SPECIFIC LOCATIONS

Tire Type	Location of Failure			
	Crown, %	Sidewall, %	Bead, %	Shoulder, %
2 Ply-Bias	71	23	6	0
4 Ply-Bias	43	13	38	6
Rayon-Rayon Bias-Belt	4	59	37	0
Polyester-Fiberglass Bias-Belt	68	2	30	0
Radial Ply	7	7	86	0

Numerical values of burst pressure were also dependent upon tire construction. Two-ply bias tires showed an average burst pressure of 188 psi, four-ply tires 218 psi, rayon-rayon bias-belted tires 215 psi, polyester-fiberglass bias-belted tires 201 psi and radial tires 208 psi. The mean burst pressure of all the tires tested, weighted by a large fraction of polyester-fiberglass bias-belted tires was 207 psi. The burst pressure data appeared to fit a normal distribution curve approximately. A summary of this data is given in Table 2.

TABLE 2.-BURST PRESSURES FOR DIFFERENT CONSTRUCTIONS

Tire Type	Average Burst Pressure, psi	Median Burst Pressure, psi
2 Ply-Bias	188	188
4 Ply-Bias	218	219
Rayon-Rayon Bias-Belt	215	225
Polyester-Fiberglass Bias-Belt	201	212
Radial Ply	208	218

To determine the effect of proof pressures on subsequent tire service life, 68 pairs of worn passenger car tires were obtained. One tire of each pair was pressurized to an internal pressure of either 150, 160, or 170 psi. These pressures represented 70% to 80% of the mean burst pressure of the total population described above. Following this pressurization process, the the tire pairs were recapped and subsequently tested on a dynamometer to the standard DOT endurance test or the standard DOT high-speed test, as described in MVSS 109. The testing was carried out by Compliance Testing Laboratories Inc., Ravenna, Ohio.

If one assigns a positive contribution of pressurization to that pair of tires in which the pressurized tire survived a test while the unpressurized tire did not, and a negative sign to the opposite situation, and a zero to the case in which either both tires of the pair failed the test or both passed the test, then the results of the total testing program may be presented as shown in Table 3, where the influence of pressurization on subsequent life is described both in terms of the proof pressure levels used and of the types of tires treated. Out of the total of 68 pairs of tires, it may be seen that there is very little net effect either with regard to level of proof pressure or tire type. The total conclusion of the experiment simply is that the null hypothesis must be accepted, i.e., there is no effect of pressurization on subsequent tire life, either beneficial or detrimental.

TABLE 3.-SIGN TEST RESULTS

	Sign Test			Total	Net
	+	0	-	Tires	Effect
Proof Pressure					
170 psi	2	9	2	13	0
160 psi	7	24	8	39	-1
150 psi	5	9	2	16	+3
Tire Type					
Bias	2	13	2	17	0
Bias-belted	7	19	8	34	-1
Radial	5	10	2	17	+3
Total Sample	14	42	12	68	+2

During the pressurization process internal pressure, contained volume, pressure rate, and acoustic emission output were recorded as functions of time. This data is described more fully in the present report. However, consideration of the data showed that only limited correlation can be made between this data and tire carcass characteristics. There is only minimal benefit to the use of the pressurization process as a screening device prior to recapping. For example, Figure 1 gives data taken from a typical radial tire which could be considered in good condition, suitable for retreading. Forcing water at nearly a constant volume rate into the tire results in pressure and acoustic emission output which probably is to be normally expected for a composite structure such as this. There is no clear way that departures from linearity can be used as an indication of impending structural failure such as is common in pressure vessel testing. Later results showed that probably the most significant flaw which could be located by means of the pressurization process was a small hole or leak not evident upon visual inspection. This type of flaw is difficult to detect in normal retreading practice and yet appears quite clearly in the pressurization process, where leakage of fluid can be sensed.

Based on the results of these tests, two general conclusions can be made concerning the use of proof pressures on worn passenger car tire carcasses:

(a) The pressurization process applied to a sound tire carcass has no effect, either detrimental or beneficial, on the subsequent tire durability after recapping.

(b) The proof pressure process appears to have limited benefit in the selection or screening of worn tire carcasses for the retreading

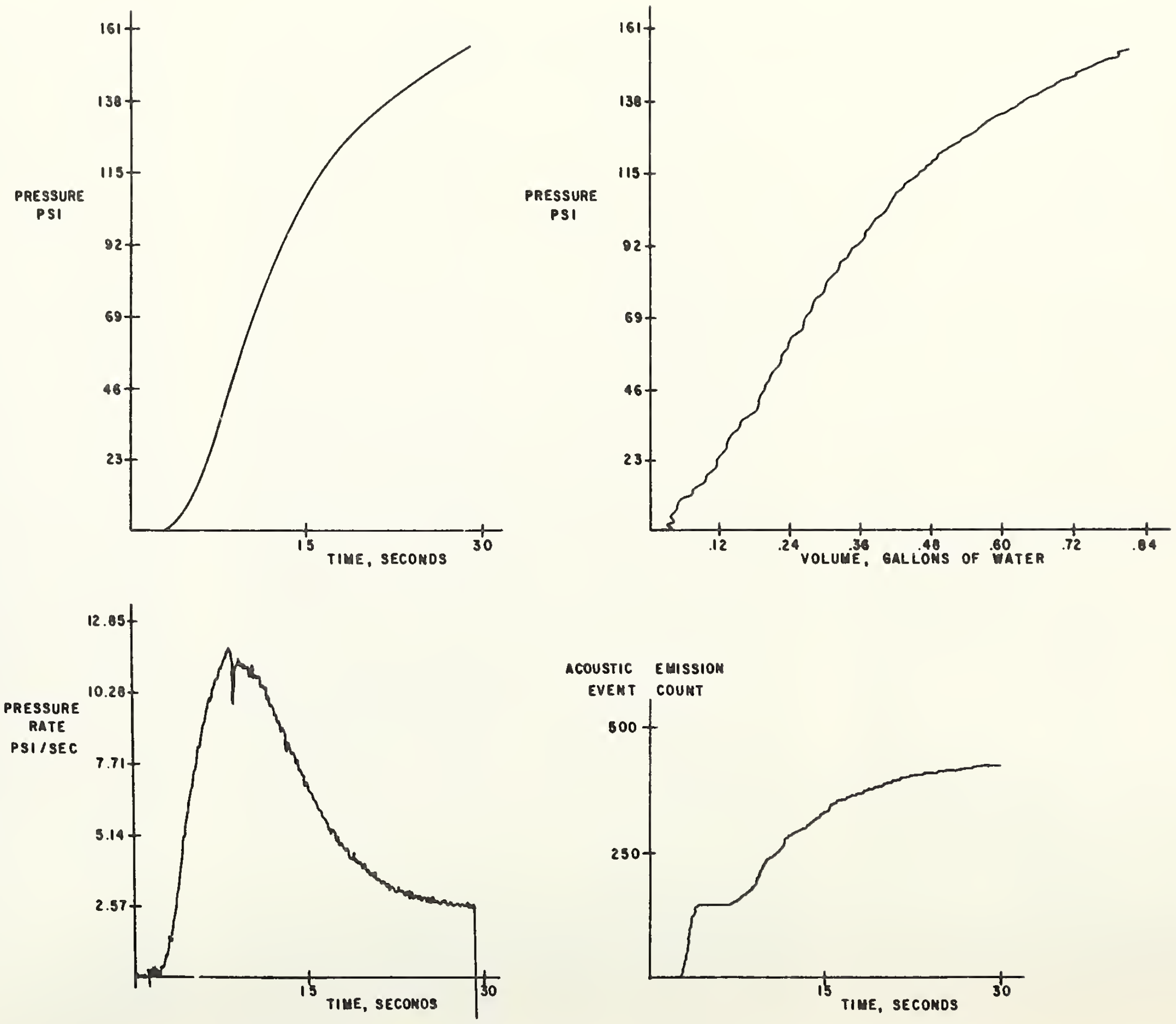


FIGURE 1. DATA FOR 165-SR 14 RADIAL—PAIRED EXPERIMENTS

industry. It cannot be used as a substitute for good visual and tactile inspection technique, although it is capable of detecting pinhole leaks in used carcasses.

3. RECOMMENDATIONS

Based on the results obtained in this study, it is recommended that a more detailed examination be carried out of the strength characteristics of passenger car tire beads, with special reference to radial tire beads. This recommendation is based primarily on the observation of the wide range of bead strengths obtained in the hydrostatic pressurization of the tires in this program, and the occurrence of several low bead strength values.

4. PHASE ONE

4.1 SINGLE CORD STUDIES

A preliminary study was carried out of the influence of a single preload on subsequent fatigue life of an individual 1260/2 nylon tire cord in the dipped condition, in air. The mean tensile strength of this cord was measured to be 43.65 lb with a standard deviation of 3.8 lb in fifty-one tests.

All fatigue tests were carried out in the tension-tension mode using a Baldwin-Sonntag rotating weight fatigue machine operating at 1800 cycles per minute.

The first attempt at measuring the effect of preload on fatigue life was to strain samples to approximately 70% of their mean breaking strength and then to fatigue the samples to failure. Thirteen samples were so treated and tested. Thirteen more unstrained cords were also fatigued as controls. Statistical analysis suggested there was a 60% chance the treatment had some effect. However, the effect might be negligibly small and, of course, there was a 40% probability that the treatment had no effect at all. This test was not truly conclusive.

To increase test significance, a larger value of preload was chosen and a larger number of experiments were run. Twenty-seven cords were loaded to 40 lb, or approximately 90% of their mean breaking strength, and then fatigued to failure. Thirteen data points from the untreated samples in the previous experiment could be used, and twenty-three more untreated samples were tested.

Subsequent statistical analysis and least squares regression showed that separate regressions account for 72.8% of the variation in the data for strained cords and for 78.3% of the variation for the unstrained cords. However, a regression for the combined data accounted for 76.3% of the variation.

The results of this experiment imply that a single large strain has an insignificant effect on the subsequent fatigue life of a tire cord. Since the properties of the cords to a great extent govern the properties of the laminated composite, and hence of a tire, these results may be extended to the testing of a tire carcass.

The data obtained is shown in Figure 2.

4.2 BURST TEST METHODS AND ANALYSIS

The first task of the experiment to receive attention was the gathering of worn tires for testing. The original plan was to collect worn tire carcasses according to a predetermined grouping until fifty sets of the tires

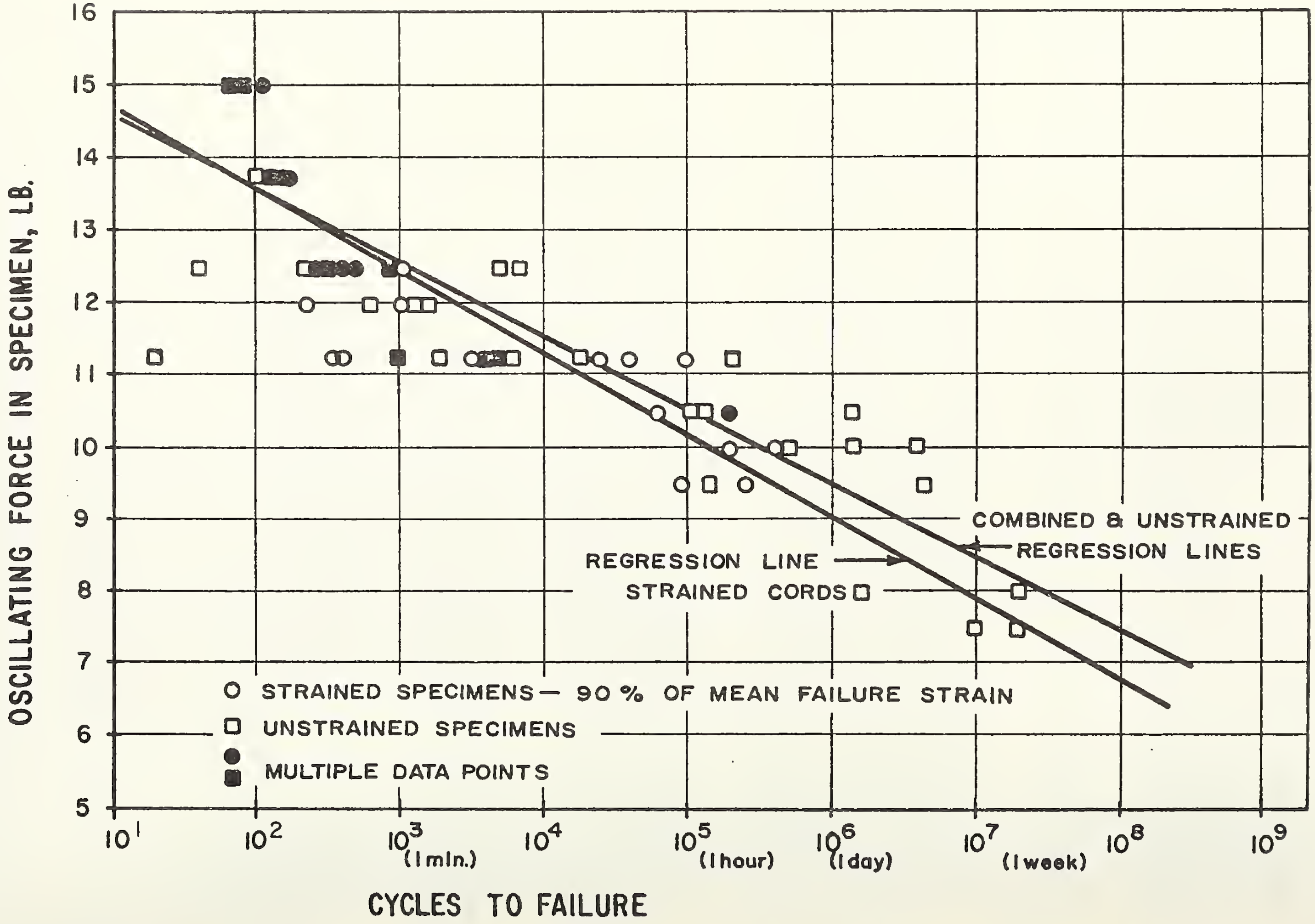


FIGURE 2. CYCLES TO FAILURE VS. OSCILLATING FORCE LEVEL FOR DIPPED NYLON CORD

were obtained. Each set was to be made up of three tires of the same size, manufacture and construction. It was found that tires could be located in such sets having similar wear and use patterns, but more often tires were available only in pairs. Only 15-in. tires were selected, simplifying the organization of the experiment and minimizing the testing equipment necessary.

Each carcass selected for testing in this program was of 15-in, rim diameter, marked "Load Range A" or "Load Range B," and was to be neither a recapped tire nor a snow tire. Once a satisfactory carcass was found, it was given a cursory inspection for obvious cuts or abrasions, bead damate, visible cords, plugs in the carcass, or sidewall damage. No criterion for tread thickness was used, since local recapping shops indicated no uniform standard was applicable. The tires selected then received a second more thorough visual inspection, and were then stored until sixty-five complete three-tire sets were obtained, each set being of identical size, manufacture, and construction.

The original test plan called for the tires to be organized into five different groups of ten tires per group. However, after some experience it became apparent that obtaining five groups of ten tires per group would be more difficult than originally anticipated. It was evident that the majority of available carcasses were of polyester-fiberglas bias-belted construction, while two-ply tires were a distinct minority. For this reason the five groupings were used only as guidelines. These construction groups were two-ply bias, four-ply bias, rayon-rayon bias-belted, polyester-fiberglas bias-belted, and radial ply.

After gathering the sixty-five complete sets of three tires each, each tire was measured for maximum and minimum tread depth in two different locations on the tire. Any characteristic wear pattern was noted, as was information regarding identification numbers. Each tire was also given a third visual inspection to locate any defects previously overlooked. In spite of the fact that three inspections of every tire were made, there were tires which, when proof tested under pressure, exhibited hidden flaws.

After the third inspection, each tire was assigned a set number and a letter. Those tires to be burst were designated as "A" tires; in a given set this was the tire with minimum remaining tread depth, based on the observation in preliminary testing that tread thickness had little or no effect on burst pressure. The remaining two tires in each set were designated "B" or "C" by a random process; "B" tires were to be partially pressurized and "C" tires were to be controls.

When an inventory of sixty-five complete sets of tires became available, a testing sequence for bursting was devised to assure the most reliable results. Several parameters were potential data-biasing factors: (1) the different constructions; (2) the different manufacturers; (3) the different widths of tires; (4) the changes in the untested instrumentation over the duration of the experiment; and (5) the changes in experimenter proficiency over the duration of the experiment. To reduce the potential impact of these factors, the experiment was designed using a randomization technique which insured that the results were not systematically biased by subtle changes in equipment or procedures. The resulting sequence was followed closely, deviations occurring only in the rare instance when the tire to be burst was defective to the extent that a burst test could not be performed.

After nearly fifty tires had been burst, an analysis of the completed test data showed results significantly less disperse than originally anticipated. The plot of percent of tires failed versus percent of mean burst pressure showed a curve of a continuous nature, but with some gaps in it. It was felt that this curve could be made more useful if more data points were included, so all extra tires at the laboratory not scheduled for later experiments were designated E tests and were burst, and this data was added to the plot. Most of the gaps existing in the fifty-tire data plot were filled in with this new data. In total, approximately fifty additional tires were burst. The complete data set is shown in Figure 3. For the second fifty tires, no randomized sequence was explicitly developed, since after the first half of the testing program it was apparent that the burst test results were independent of test order. It should be noted that this doubling of the sample size affected the median burst pressure by only three psi and the mean burst pressure by only 2 psi, or about 1%. This tends to support the view that the original population of fifty tires gave a good statistical measure of 15-in. tire burst pressure.

The data of Figure 3 may be compared with a normal distribution curve centered about the 100% of median burst pressure and arbitrarily adjusted to pass through the data point (132% mean burst pressure, 100% failed). This is the uppermost data point shown in Figure 3. It is seen that the data points follow the normal distribution quite well, and if we delete the very low burst pressure data, points probably could be adjusted to fit even better. The low burst pressure points are suspect since the tires causing them may have been damaged in service.

In the performance of the burst tests several interesting phenomena appeared. Only small differences were observed in the median and average burst pressures after doubling the number of tires considered in the computation. While this may not be physically illuminating, it does suggest that the experiment was reliable and should produce similar results given a random sample drawn from the same distribution of tires.

When the burst test was performed the type of failure was recorded. The failure modes were characterized as crown, shoulder, sidewall, or bead failures depending on the location of the carcass rupture. Photographs illustrating typical failures of the type mentioned are shown in Figure 4. On several occasions multiple failues occurred in a single tire, for example, both the crown and sidewalls having obvious ruptures.

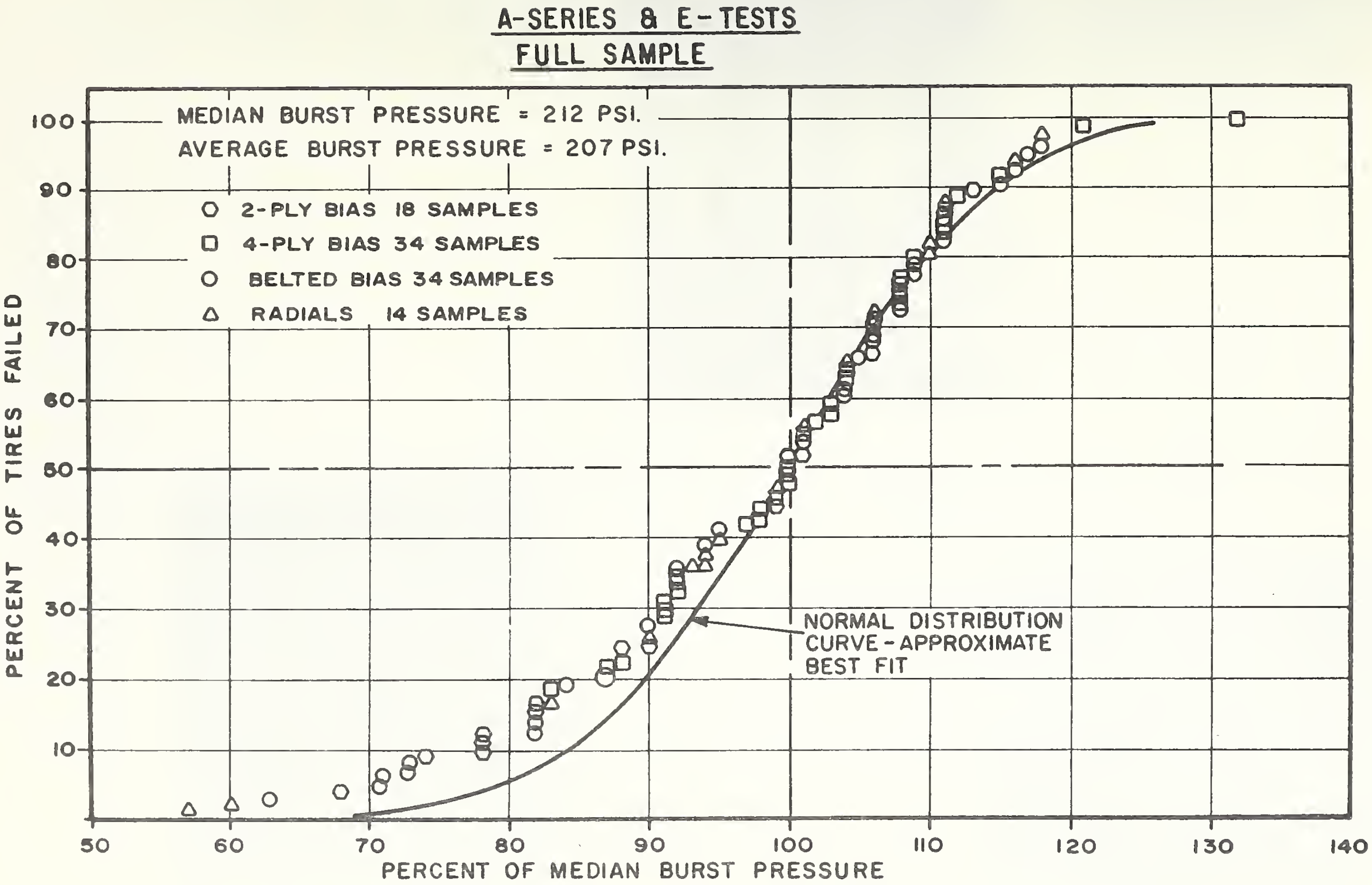


FIGURE 3. PERCENTAGE FAILURE RATE AFTER 100 TESTS

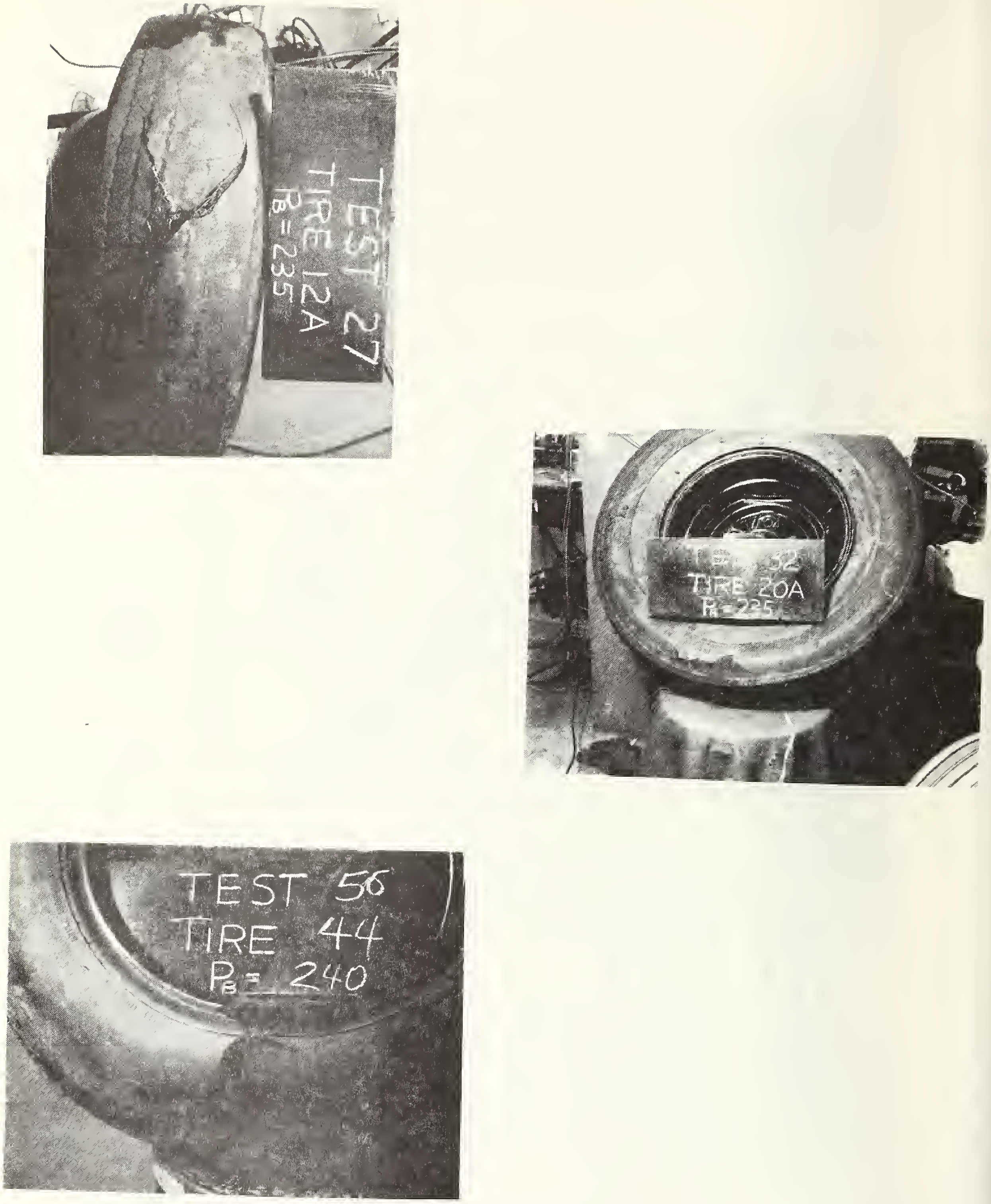


FIGURE 4. PHOTOS OF TYPICAL BURSTS

Table 1 showed the distribution of failures over the various constructions considered. The trends were much more dramatic than expected. The two-ply bias tires tended to fail more regularly in the crown area, whereas the radial ply tires tended to fail most often in the bead. The other constructions were divided in modes of failure. The polyester-fiberglas bias-belted tires tended to fail most often in the crown, while exhibiting some bead failures. In contrast, rayon-rayon belted-bias tires tended to fail most often in the sidewall, while exhibiting some failures in the bead. For the four-ply tires, failures seemed to be equally balanced between bead and crown failures.

The ultimate strength of the various constructions is indicated in Table 2 as a median and an average of the samples tested. It can be seen that the strongest tires are the four-ply bias and rayon-rayon bias-belted tires. These are followed by the radial ply, polyester-fiberglas bias-belted and the two-ply bias tires, in that order. This hierarchy of strength, for which there is no clear explanation, was not the anticipated result. In addition, in conducting the experiment it became evident that the carcass tread depth had no correlation with the burst pressure of the tire. This is to be expected. The tread is not a structural element.

Of final note is the cumulative distribution of failure pressure for each of the construction groups, which are plotted with respect to the full sample median in Figure 5. This graph is of particular importance in the selection of the pressure at which the carcasses are to be proof tested. This graph shows that the selection of a single pressure for all constructions may be prejudicial against certain constructions due to their lower burst pressure. Although there is not adequate data for statistically accurate conclusions, it appears likely that the two-ply bias tires and the polyester-fiberglas bias-belted tires will be penalized by a single pressure value, provided that the proof pressure is chosen high enough to cull out a significant portion of them by burst.

4.3 BURST TEST APPARATUS

In addition to simple survival of a proof pressure, other means of nondestructive inspection of the tire carcass were to be evaluated. The pressurization system was designed to provide a means of bursting passenger car tires, and recording related acoustic emission (A.E.) as described below, without danger and with minimum first cost. A safety box was constructed of 1/4 in. steel plate covered with 1-1/2 in. plywood. Due to the large quanity of energy stored in compression, air was felt to be too dangerous to use as a pressurizing medium. Thus, a system was designed so that a water filled tire was pressurized with nitrogen so that upon burst, the nitrogen was confined to a gas cylinder, as shown in Figure 6.

In Figure 6 it is seen that city water of nominal 65 psi pressure passed

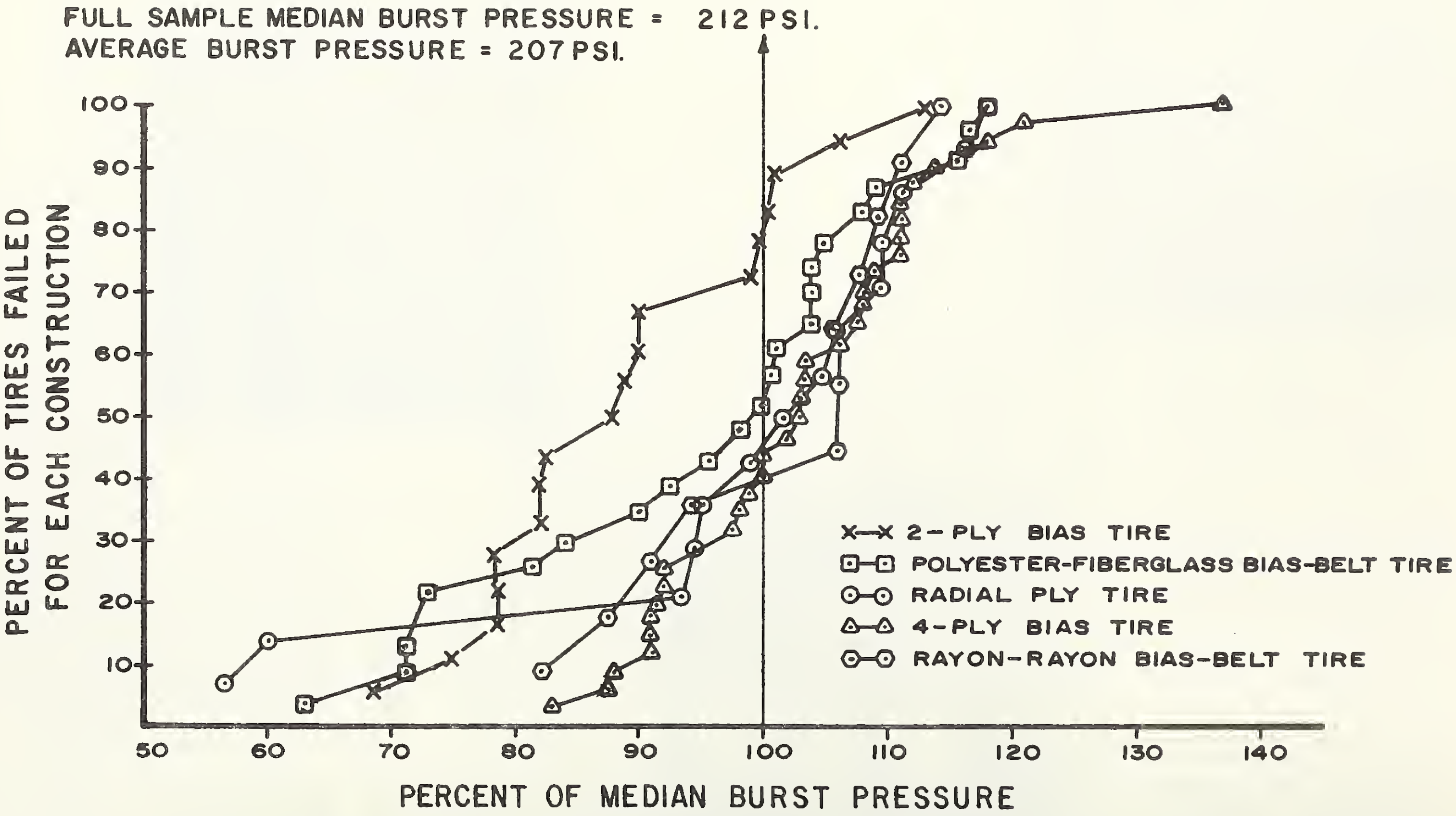


FIGURE 5. PERCENTAGE FAILURE RATE FOR EACH CONSTRUCTION RELATED TO THE FULL SAMPLE MEDIAN

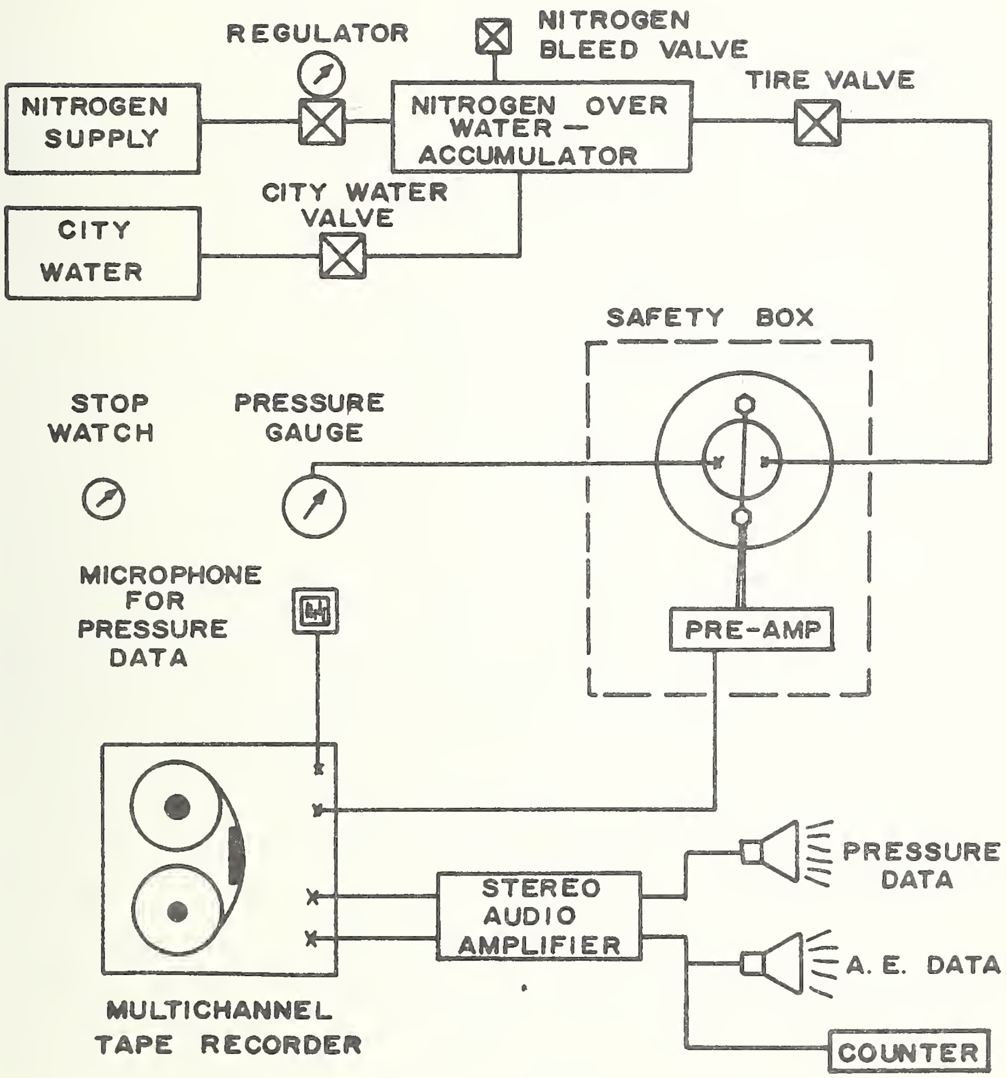


FIGURE 6. SCHEMATIC VIEW OF TIRE PRESSURIZATION SYSTEM

through a valve to a nitrogen cyclinder which was used as an accumulator. When a tire had been mounted, the tire valve was opened and city water flowed in to fill the tire. After the tire was filled with water, the A.E. equipment was attached to the wheel and the lid of the safety box was bolted down. The A.E. sensor consisted of two stereo phonograph cartridges, with large sewing needles replacing the standard needles. The cartridges were positioned diametrically opposite each other with the needles against the carcass sidewall. The cartridges were held in place by aluminum arms mounted on a plywood bar with rubber and corrugated paper gaskets to provide some acoustic insulation. The bar was bolted to the wheel and wires were run from the cartridges to a preamplifier located in the safety box beneath the wheel. A cable carried the A.E. signals out of the box to a multichannel tape recorder.

A pressure gauge with telltale was attached to the wheel through high pressure hose to give a reading of pressure in the tire. The regulator was operated by hand to effect a pressurization rate of approximately 5 psi per 10 sec, or 30 psi per minute, by visually tracking a stopwatch. The pressure was read into a microphone and recorded. When the tire burst, the pressure dropped but a telltale on the gauge recorded the final pressure. Then the tire valve was closed by hand, the regulator was turned down, and the high pressure nitrogen in the accumulator was bled off. The water in the tire was drained through the floor of the box. With the box unbolted, the pressure lines and A.E. equipment were disconnected and a photograph of the failure was taken. A new tire was mounted and the process was repeated.

Acoustic emission (A.E.) is the spontaneous generation of acoustic energy within a material, and its detection on the material surface. Recent work in the area of A.E. from composite materials indicates order of magnitude differences in energy of signals due to fiber breakage, fiber matrix slip or delamination, and matrix shear or plastic flow. These studies prompted questions as to the applicability of A.E. as a nondestructive test for automobile tires. It was accepted that the basis for the strength of a tire was its cord structure. Hence, the rupture of a tire carcass should be accompanied by high energy A.E. from cord breakage near the failure region. The possibility existed that other sources of emission might be detected earlier, such as pick cords, filament breakage or adhesive breakage. Other sources such as rubber-cord debonding, ply shear, or crack initiation in the tread rubber might also be detectable.

A series of simple experiments were undertaken to test the hypothesis that A.E. could be detected in tires. It was determined that tires have a resonant frequency near 1 kHz, where the cords aid in the transmission of a stress wave. This frequency range was chosen for the study since audio waves are not attenuated as rapidly as ultrasonic waves and can be processed with inexpensive equipment.

A single cord mounted in an Instron machine was pulled to failure while using a crystal phonograph cartridge as an A.E. sensor. These tests were promising, as a cassette recorder picked up the noise of fracture and an oscilloscope recorded almost 0.4 volt peak at the time of fracture, with some lower level signals visible above noise level before the cord broke.

Next, several sections of two-ply sidewall were removed from a radial tire and mounted in the Instron machine. A crystal microphone, a dynamic microphone, a condenser microphone, and a phonograph cartridge were each used to monitor A.E. from the test coupon. Signals were obtained by all of these sensors. Some of the tests showed A.E. build up similar to that in metals; however, no good method for mounting the sensor was found, with the results being inconclusive.

A rubber cylinder with embedded longitudinal cords was built. A phonograph cartridge was mounted on the side of the tube and when the tube was pressurized considerable A.E. was obtained. Upon removal of the pressure, more A.E. was produced. This phenomenon was inconsistent with A.E. work in metals. It was discovered that due to the large deformation of the tube the crystal was "rubbed" by the material displacing beneath it. This also explained some of the inconsistencies in the rubber coupon tests.

Two methods to avoid this problem in a tire test proved workable. Either a large sewing needle could be mounted in the phonograph cartridge and the needle placed against the carcass sidewall, or the cartridge alone could be mounted on the rim of the wheel. In an attempt to locate sources of emission within the tire, two cartridges with needles were mounted on diametrically opposite sidewalls of the tire. The system proved to be too crude to locate flaws but the duplicate crystals provided a backup if one was damaged during a test.

The data gathered thus far has not been conclusive. For example, pinhole leaks and some construction differences were found, but little else. Commercial apparatus was borrowed for use during several burst tests. The tires under pressure produced A.E. at the extremely high frequencies sensed by this equipment, and this was easily recorded.

Two pairs of tires are of particular interest. One pair of polyester-fiberglass bias-belted tires of identical size, manufacture, and wear were burst. One tire was known to have a damaged belt. The graph of the A.E. output from the two tires in Figure 7 shows the damaged tire (marked "G") began A.E. at a lower pressure and produced more than twice the A.E. of its mate. Although the failures were identical, it should be noted that both tires would have withstood hydrostatic pressurization even though one was clearly damaged.

The other pair of tires were of radial ply construction, which had shown characteristically low level emission hardly discernible above the noise level. With the commercial equipment at high gain, curves were produced which exhibited a sharp "knee" just before failure. These are shown in Figure 8. However, it was clear that there were random bursts of A.E. at low pressures and not simply a continuous curve produced by a constant noise level. Note also the similarity of the A.E. curves in Figure 8 and the fact that both tires failed in the sidewall at almost the same pressure.

These results suggest more study is needed into the fundamental aspects of A.E. in a fiber reinforced polymer composite material. The A.E. pattern for a given tire appears to be a function of material, construction, and failure mode, while micromechanical random processes determine the exact

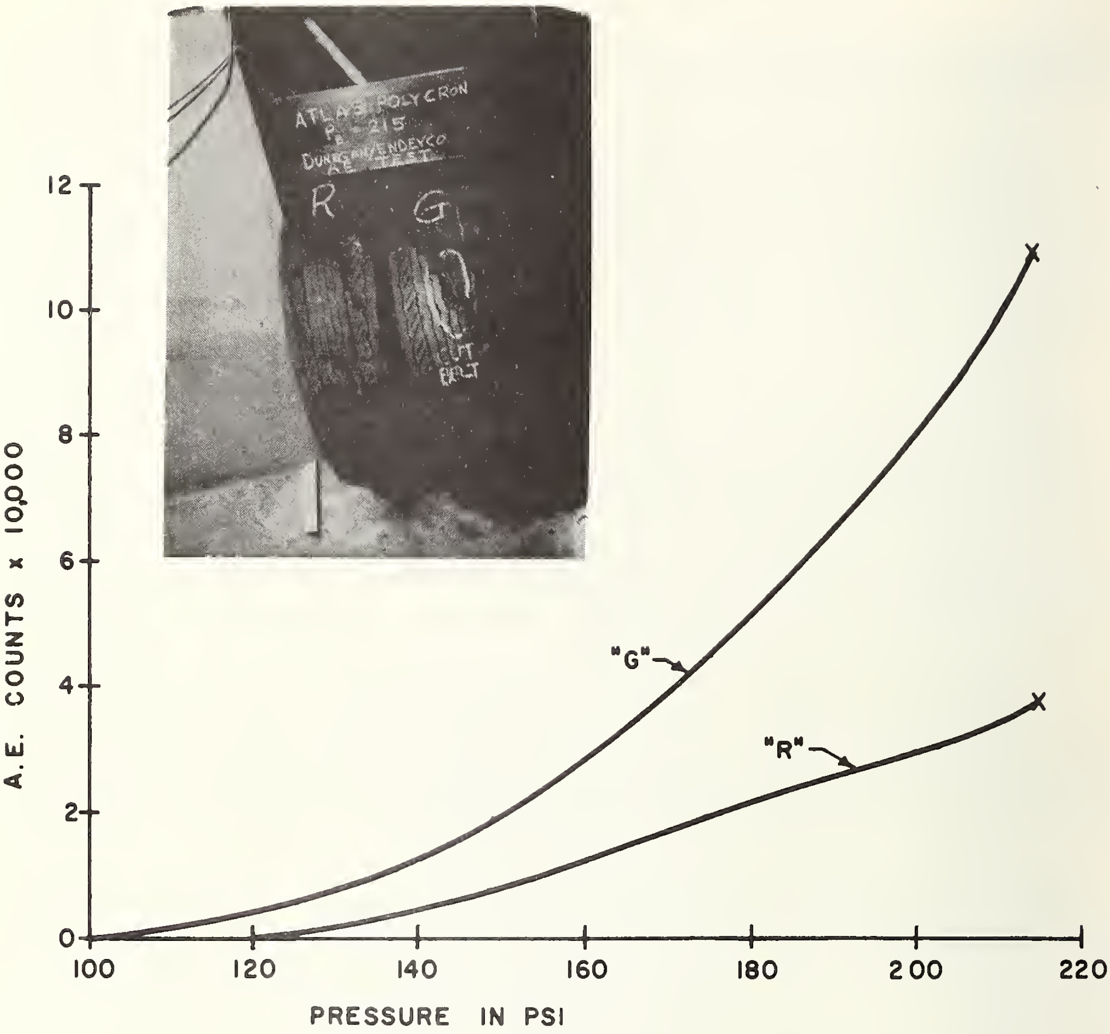


FIGURE 7. ACOUSTIC EMISSION OUTPUT FOR TWO IDENTICAL TIRES: TIRE "R" UNDAMAGED; TIRE "G" WITH CUT BELT

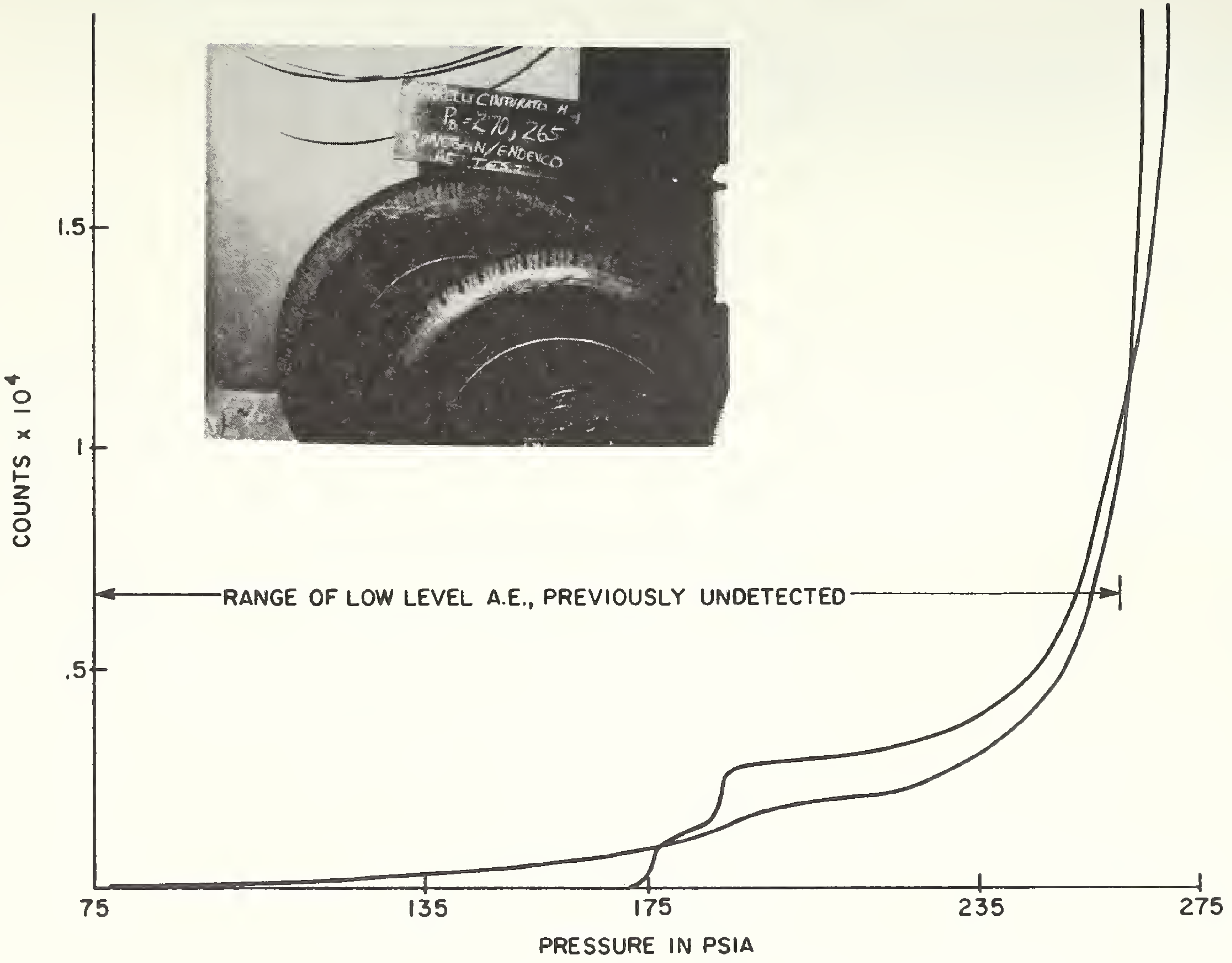


FIGURE 8. ACOUSTIC EMISSIONS VS. PRESSURE LEVEL FOR RAYON-RAYON RADIAL TIRES USING COMMERCIAL ACOUSTIC EMISSION SENSOR

shape of the curve. It appears possible that with a sufficient background of A.E. data on tires, and a knowledge of a specific tire's construction and material, a prediction of failure mode and pressure can be made from its A.E. under hydrostatic inflation. However, this experiment provided insufficient data to establish a characteristic pattern for any particular construction.

5. PHASE TWO

5.1 INITIAL PAIRED TIRE EXPERIMENTS

Prior to selection of a proof pressure and final experimental design sixty-five sets of tires were sent to DOT/TSC for nondestructive testing via holographic inspection techniques. This check revealed that separations in one or both tires of forty-two sets made them unacceptable for further testing. The twenty-three tire sets surviving the holographic inspection were subjected to the pressurization process at 170 psi which was equivalent to 80% of the full sample median burst pressure.

This pressure level suggested that only five tires should fail, but in the test eight tires failed. In Table 4 it can be seen that selection of a single pressure penalizes two-ply bias tires. The test sample was further reduced by the fact that the retreader selected for this portion of the project could not retread two of the pairs of tires which survived all the testing. Thus only thirteen pairs were sent for dynamometer testing from the original sample of sixty-five pairs.

TABLE 4.-FAILURES OF TEST TIRES UNDER PRESSURIZATION

Tire No.	Tire Type	Failure	Failure Pressure, psi
1	2 ply bias rayon	Crown Rupture	155
2	2 ply bias rayon	Crown Rupture	160
3	2 ply bias rayon	Crown Rupture	165
9	Rayon-rayon bias belt	Broken Bead	165
11	Rayon-rayon bias belt	Sidewall Rupture	160
14	Polyester-fiberglass bias-belt	Broken Bead	165
19	Rayon-steel radial	Broken Bead	135
23	2 ply bias rayon	Crown Rupture	165

This led to the following observations. Our selection technique and sample distribution must be better controlled. The proof pressure selected was probably too high. The tires which are selected for testing must be known to be retreadable. While A.E. showed promise of detecting defects, if any other nondestructive observations can be made during the pressure process, instrumentation should be installed to record such data. Finally, if this system were to be used commercially it must be automated.

5.2 AUTOMATED PRESSURIZATION APPARATUS

The next phase of the work required the design of a system which could automatically fill and pressurize a tire carcass to 50 psi, then raise the tire pressure to any set value at a fixed rate of volume flow, and finally bleed the pressure from the tire. Safety considerations as well as the constant volume flow requirement pointed to the use of an incompressible pressurizing fluid. Cost and convenience led to compressed nitrogen and a nitrogen-over-water accumulator as the source of high pressure fluid. The design was to include protection for the tire from potential damage from contact with high pressure water. Acoustic Emission (A.E.) vs. time, pressure vs. time, pressure rate vs. time, pressure vs. volume, and volume vs. time were to be continuously monitored throughout the test sequence.

Such a system was designed. The central concept of the system was to take a tire, mount it in a split rim assembly, fill an internal waterproof bladder with water and bleed the air from the tire. Such mechanisms are commercially available in the retreading industry, but their use would have required considerable modification. Equipment available in our laboratory was modified and improved to achieve the same result with less construction but needing more operator effort. Instrumentation was added to the equipment and the system is illustrated in Figure 9. The instrumentation controls were ganged and a solenoid valve control panel placed so a single operator could run a complete test. However, the tire mounting and filling was a non-automated and separate operation. Hence, for safety and faster turn over, at least two operators were present for all tests. In this way a complete test took about 30 min, 3 min to run the test and the remaining time used to remove the tested tire and mount and fill the next tire.

The instrumentation system consisted of a strain gage pressure transducer, a load cell to measure the weight of water used, an A.E. transducer and various signal processing and recording devices. Samples of the output appear later in this report.

A.E. was described earlier. This study showed that low frequency A.E. is produced in tires when pressurized. It was also found that A.E. transducers lose sensitivity in a high humidity environment. For the current phase of the work a commercial A.E. monitoring system, on loan from DOT/TSC, was used with a special low frequency transducer in a splash-proof canister.

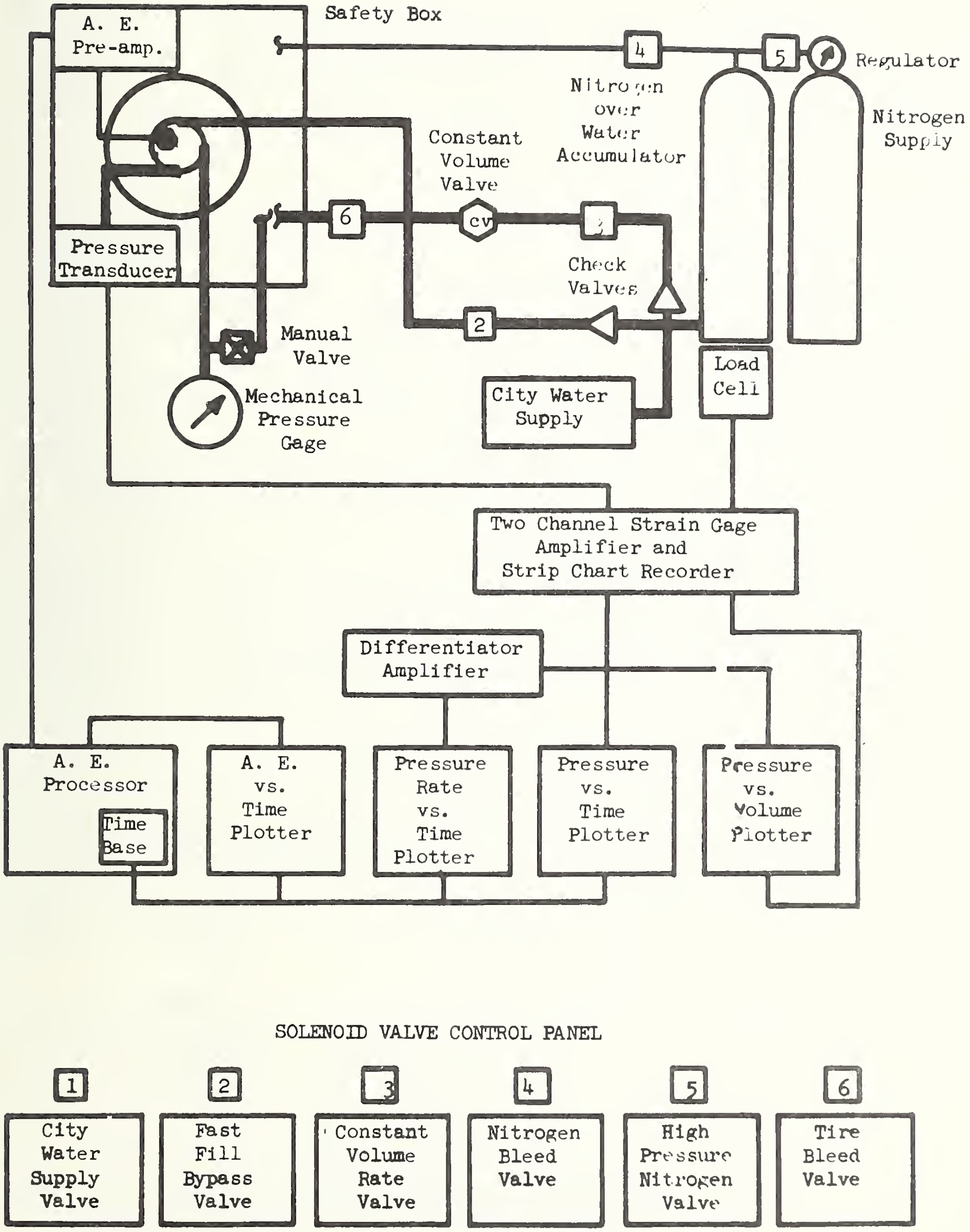


FIGURE 9. SCHEMATIC VIEW OF TIRE PRESSURIZATION SYSTEM

The transducer was mounted on the test wheel and connected to a preamplifier located within the safety box. The preamplified signals were carried out of the box to the A.E. processor. For these tests the processor was set to provide a voltage proportional to the number of A.E. events. The processor contained a module which produced a voltage proportional to time. These two outputs were connected to an X-Y plotter to produce a graph of A.E. counts vs. time.

The time drive was also used as the X axis signal for the plots of tire pressure vs. time (P-t) and pressure rate vs. time ($\dot{P}$-t). The pressure signal from the transducer was used as input to one channel of a two-channel strain gage amplifier and strip chart recorder. The volume measurement system used a load cell and a lever arm to measure the weight of water used; however, this gave spurious results due to vibration of the lever. Damping was added to suppress most of these vibrations. The signal from the load cell weighing the accumulator was used as input to the other channel of the amplifier-recorder. The signals were calibrated so that pressure and volume could be read directly from the X-Y plotters. A pressure volume (P-V) diagram was produced by using these signals into one plotter, while the P-t plot was produced on another plotter using the same pressure signal.

The pressure signal also was connected to the differentiator-amplifier. Due to the slow and monotonic increase of pressure during the test, the rate of pressure change was numerically small. An integrated circuit (IC) operational amplifier was used to construct an electronic differentiator, and another IC was used to amplify this signal thus providing an output on the order of one volt, which was proportional to the rate of pressure change.

After the pressurization experiments carried out on the twenty-three pairs of tires described previously and the rebuilding of the pressurization equipment described above, a preliminary set of tests were conducted to determine if correlation existed between external characteristics and pressure, pressure rate, volume, and acoustic emission. These tests were performed on a random sample of thirty-two tire carcasses, some of which clearly were not of retreading quality, having cuts, partially broken belts, irregular wear, plugs, and other flaws.

These tires were processed through the rebuilt, semiautomatic pressurization system, each tire pressurized until it burst. Pressure-time, pressure rate-time, and acoustic emission-time plots were recorded for each tire. A typical set of data from these tests is shown in Figure 10 for a tire considered to be recappable. A similar set of data is shown in Figure 11 for a tire of exactly the same construction and manufacturer, with a known flaw, a plug in the tread. An examination of this data and several similar sets show essentially no correlation between tire quality and P-t, $\dot{P}$-t, or AE-t diagrams. These diagrams seemed similar whether the tire had been damaged or whether it had not been damaged.

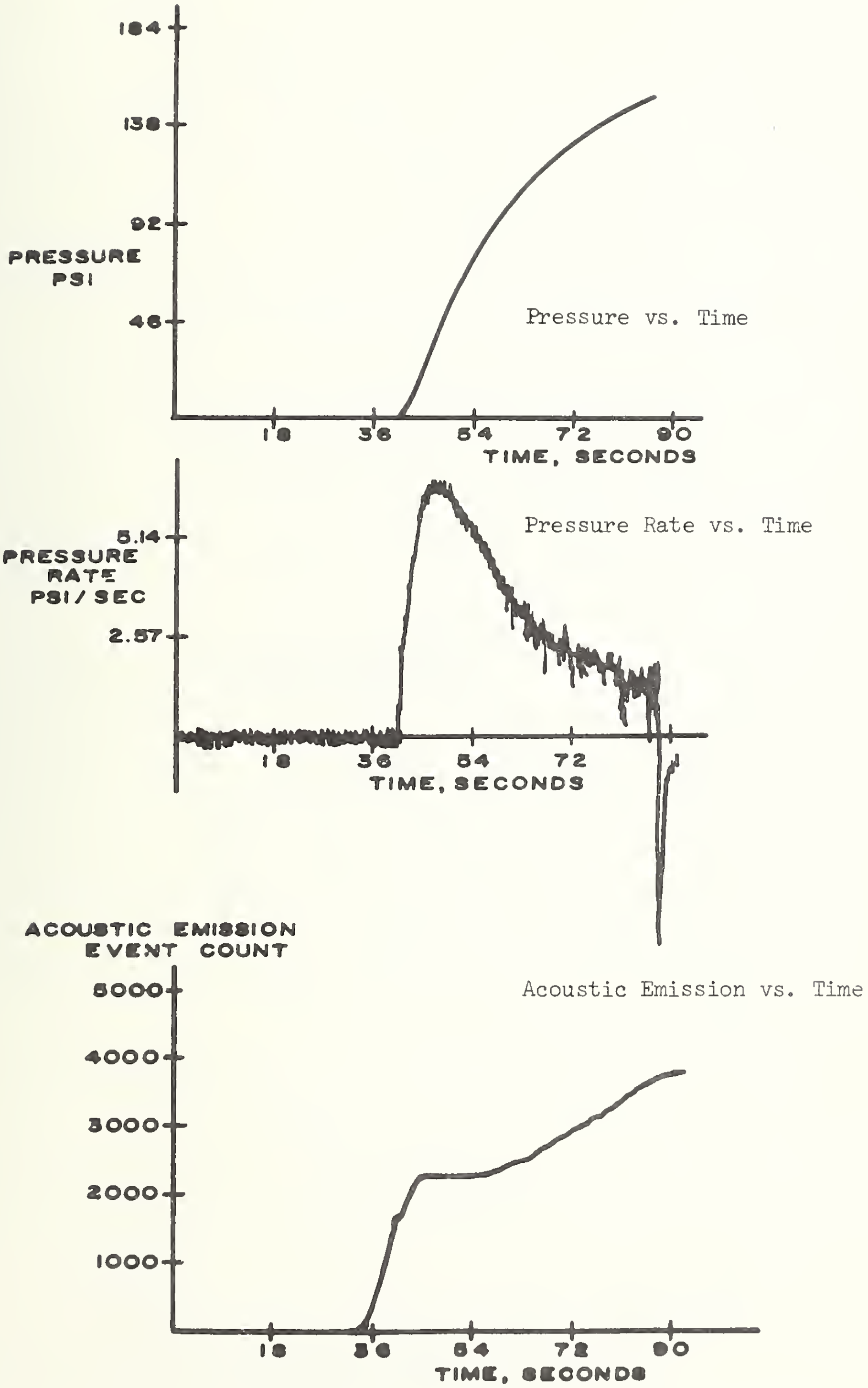


FIGURE 10. DATA FOR A GLASS BELTED F78 X 14—RECAPPABLE

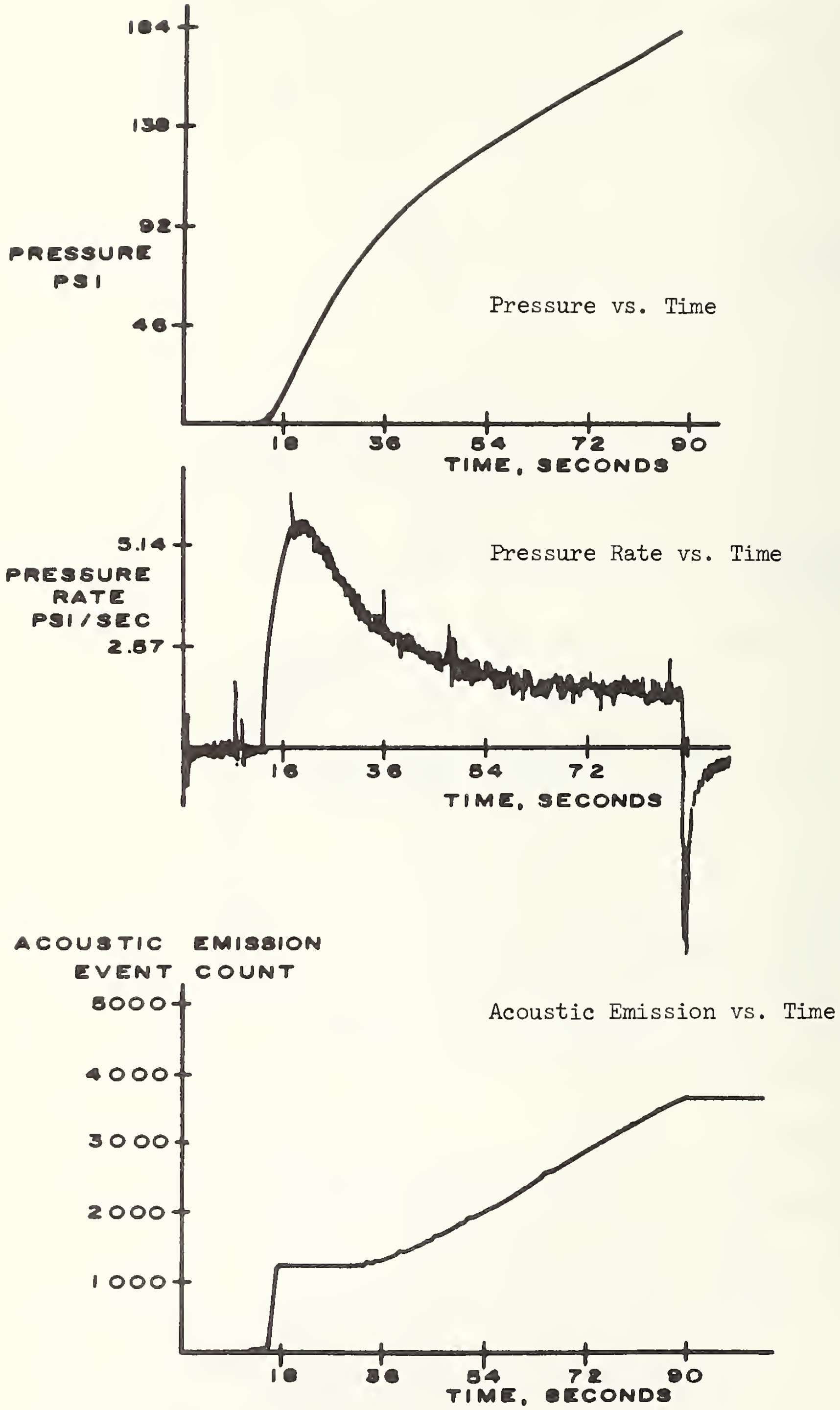


FIGURE 11. DATA FOR A GLASS BELTED F78 X 14—PLUG IN TREAD

The sets of data shown in Figures 12 and 13 illustrate the only flaw that seems detectable from these records, a leak in the tire. The tire in Figure 12 developed a leak about 120 psi while a similar tire shown in Figure 13 had no flaws. As can be seen from these two figures the plots for the tire with the leak are distinctly different than those for the tire with no leak. Also it is of interest to note that all of the plots in Figure 12 clearly indicate the occurrence of the leak.

Even though the acoustic emission data generated from this series of tires showed no correlation with tire condition it seemed to correlate well with the material used in the tire. This is in agreement with previously reported data using simpler equipment which indicated that acoustic emmission output is quite high for tires with fiberglass cords, moderate with rayon, polester and nylon cords, and very low with steel cord construction. This is clearly illustrated by comparing the AE-t curves in Figure 10 and 13. The A.E. output in Figure 10 is for a fiberglas belted tire, full scale plot of 5000 counts, while that in Figure 13 is for a two-ply polyester tire, full scale plot of 1000 counts. As can be seen the A.E. output is much greater for the tire with the fiberglas belts than it is for the tire with the polyester carcass.

The peculiar shape of the $\dot{P}$-t curve requires some discussion. Due to the tire being filled with water and the wheel axis being vertical, the tire undergoes a shape change as well as a size change. Three regions on the $\dot{P}$-t curve in Figure 14(a) may be distinguished. These regions correspond to the sagging tire in Figure 14(b), predominately tire shape change displayed in Figure 14(c), and predominantly size change as in Figure 14(d). In the sagging tire the pressure increases rapidly from a small increase in volume. At some point the shape change of the tire becomes significant and the pressure cannot increase with such a high rate for the same volume flow. The shape change cannot continue indefinitely and the pressure rate approaches a constant value where the tire maintains its shape but its size continues to increase until it ruptures as in an ordinary pressure vessel.

5.3 ADDITIONAL PAIRED TIRE EXPERIMENTS

Following the check of the new instrumentation system with thirty-two tires of varying quality, twenty-five pairs of used radial tires were obtained. This decision was based on the lack of radial tires in our distribution. These tires were of 14-in. rim size. A proof pressure of 150 psi was selected for this sequence of tests based on the results of the previous tests at 170 psi. This pressure was apparently somewhat low since none of the radial tires failed the proof test. Thirty-six percent of the sets returned to the retreader after proof testing were discarded by them as unsuitable for retreading. Only 16 sets survived inspection after buffing.

Having used the full instrumentation system on eighty-two tires,

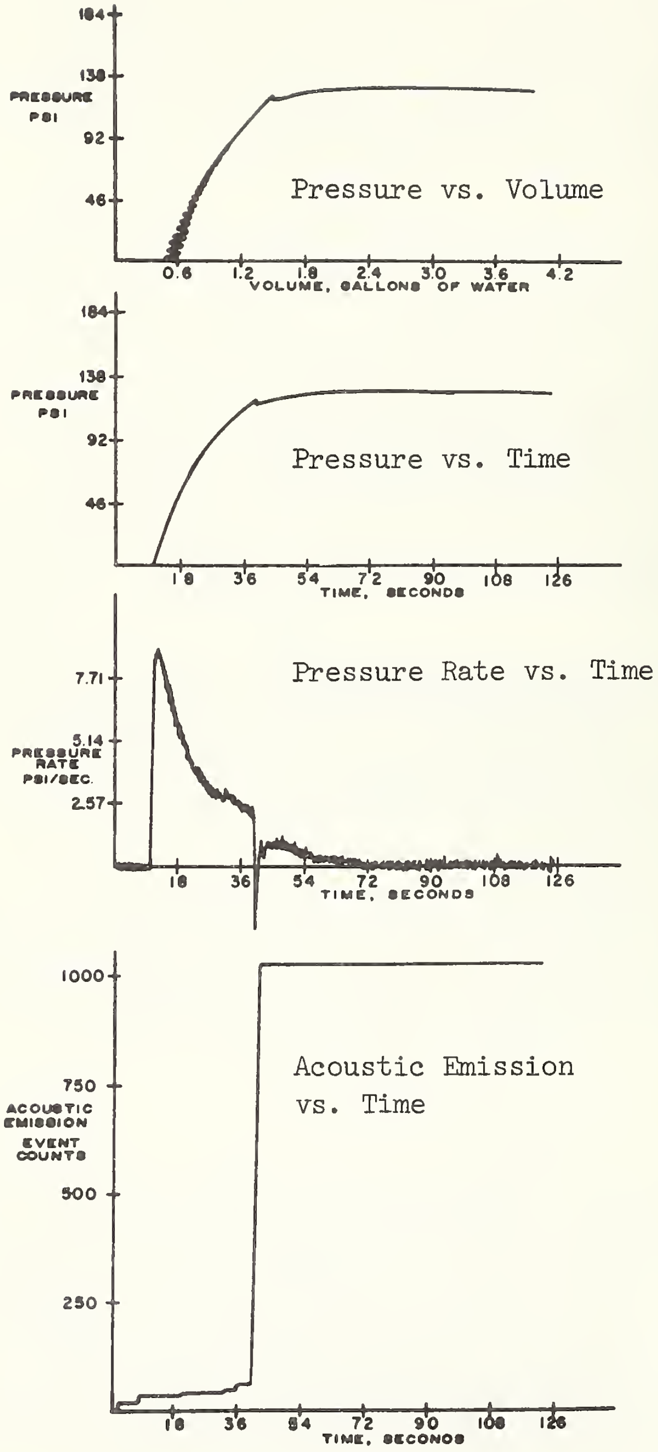


FIGURE 12. DATA FOR 6.45 X 14 TWO-PLY POLYESTER—LEAK

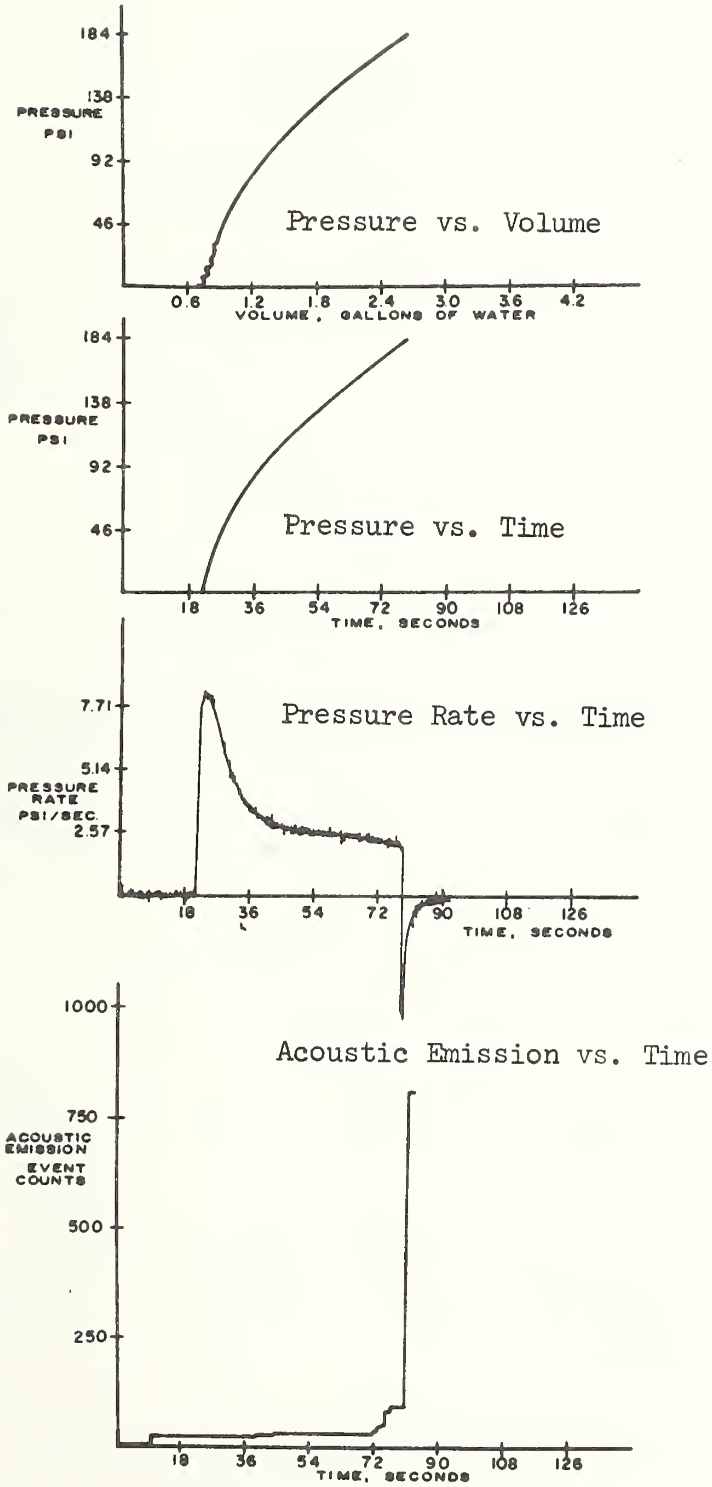
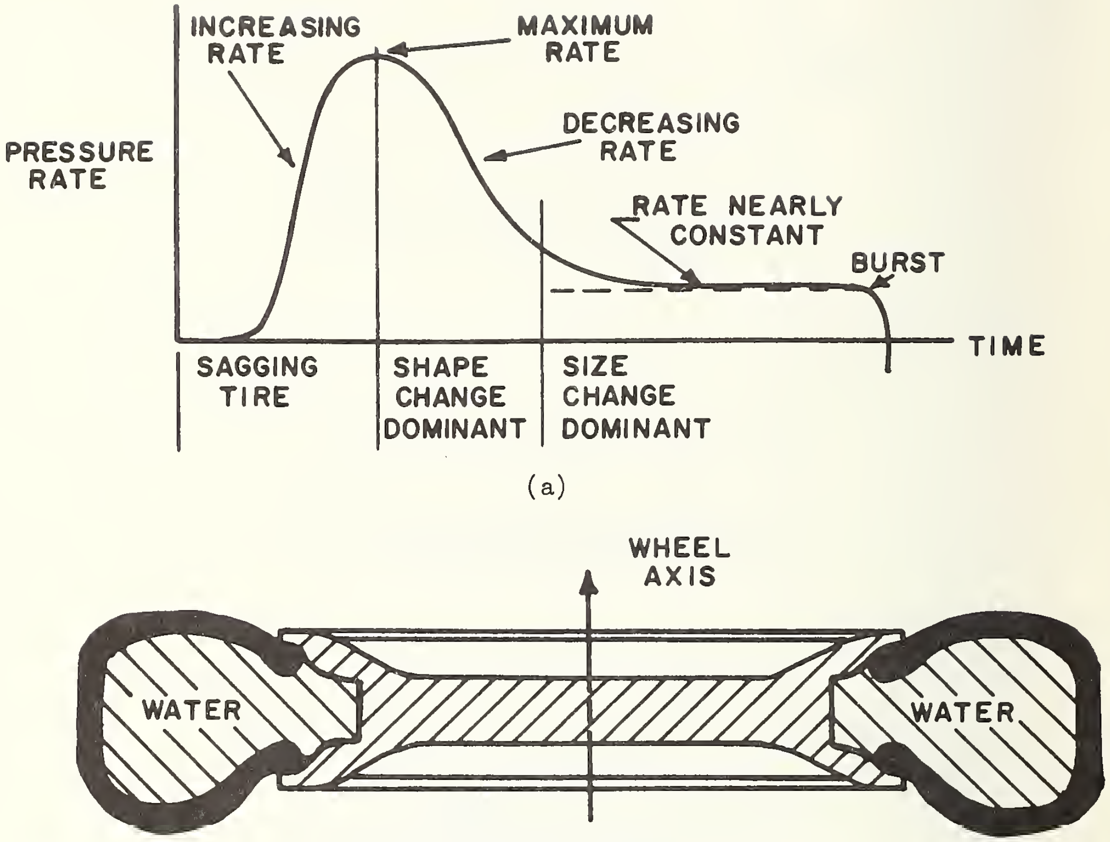
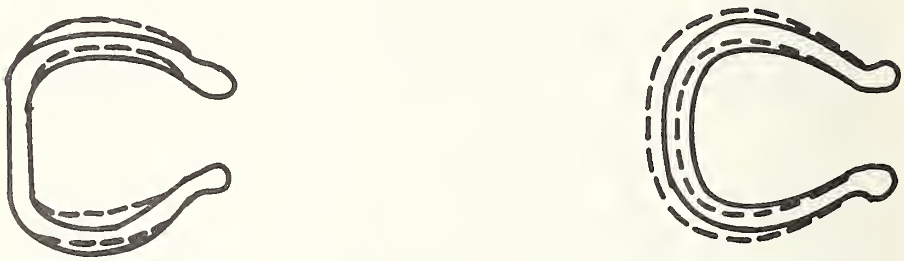


FIGURE 13. DATA FOR 6.45 X 14 TWO-PLY POLYESTER—NO LEAK



(b) SAGGING TIRE



(c) SHAPE CHANGE

(d) SIZE CHANGE

FIGURE 14. TYPICAL PRESSURE RATE VS. TIME CURVE

experience showed that the only detectable information was the type of cord material and the presence of a leak in the carcass. The preliminary dynamometer testing had shown that the commonest type of failure was a separation in the tire carcass or between the carcass and the new tread. It is not clear how the instrumentation used in the pressure process could locate such flaws. Therefore, the total instrumentation package was not necessary and in the last set of tests only pressure was recorded as a function of time.

To improve the distribution of tires tested and to further test the effect of pressure level, forty-two additional sets of tires were pressurized to 160 psi. This new sample contained approximately one-third bias ply tires and two-thirds bias belted tired. From Figure 6 it may be noted that less than 10% of the tires should fail at this pressure. Somewhat surprisingly, after proof testing thirty-nine sets survived, producing the final sample of seventeen pairs of radial tires, seventeen pairs of bias ply tires, and thirty-four pairs of bias belted tires. This compares favorably to the distribution of tires seen by retreaders in this country.

This sample of sixty-eight pairs of tires (thirteen pairs at 170 psi, sixteen pairs at 150 psi, and thirty-nine pairs at 160 psi) were all retreaded and run on the standard MVSS 109 schedule for endurance or high speed. The tests were run at Compliance Testing Laboratories Inc., Ohio. The laboratoty kept conditions for the testing of each tire of a pair as alike as possible. The data thus otained was returned to us for analysis.

5.4 METHODS FOR DATA ANALYSIS

There are basically four techniques for analysis of the data generated by this experiment: direct statistical comparison of groups, binomial paired experiment, direct paired comparison, and direct paired comparison under multiple pressurization levels. Each of these techniques was seriously considered for this research [2]. Direct statistical measures would consider the pressurized "B" tires and the unpressurized "C" tires as two distinct populations. The sample of test tires could be compared to the control tires by their respective means and standard deviations to see if either population was significantly better. A Latin Square experimental design could allow determination of an optimum pressure level for each size tire. However, it was determined early in the program that the number of tires required to make such a scheme produce statistically significant results would be so large as to be prohibitive.

The binomial paired sequential test described in [2] would use the power of a sequential design to determine an optimum pressure level, then use this level to test a sample of all sizes for their subsequent life. This design permits a decision on the proper level of proof pressure with a small fraction of the sample of tires. Then further studies could indicate the effects of various tire sizes and the overall value of the pressurization process, by testing the remaining tires in the sample. However, the tires would need to be pressurized in small groups, then sent out for retreading and dynamometer testing. This would result in substantial delays during which the recapping process or test procedure may change, affecting test results.

In a direct paired comparion test a single pressure level would be selected and the surviving pairs would be drum tested. A "sign test" would be used to evaluate the results. Such a test would credit a plus (+) to a pair in which the pressurized tire proved superior to the unpressurized tire, a minus (-) would be assigned to a pair in which the unpressurized tire proved superior, and a zero (0) assigned when both tires of the pair either fail or survive. This test requires the selection of a proof pressure for all the tires which culls out bad tires and does not degrade the subsequent life of good tires. Since it was not possible to do anything better than guess this value, and since the selection of this pressure could easily bias the resulting sample by construction type, a direct comparison under multiple pressurization levels was used.

It became clear early in the test program that certain unanticipated factors could easily change the character of the experiment, and this made the multiple paired design attractive. Note that the original set of sixty-five pairs of tires was reduced to thirteen pairs after holographic inspection, pressure testing, availability of retreading matrices, and inspection after buffing. The multiple paired design allowed us to change the pressure level and correct the distribution of our overall tire sample within the context of the experiment. The simple "sign test" was used to decide the value of the pressurization process.

6. FINAL ANALYSIS OF PAIRED TIRE EXPERIMENTS

Considerations of experimental cost and efficiency led to the conclusion that the most useful test plan would be one utilizing paired specimens. This made it possible to directly compare the subsequent durability of tires which had been pressurized prior to recapping, against those which had not been so pressurized.

A population of sixty-eight pairs of worn passengar car tires were obtained from local sources. Each pair of tires consisted of two that were as alike as could be found, that is of the same size and manufacture, construction, and degree of wear. In most cases these tires were removed as a pair from the same vehicle. The sample population included representative bias-ply tires (seventeen pairs), bias-belted tires (thirty-four pairs), and radial tires (seventeen pairs), all of 15-in. rim diameter except for the radial tires which were predominately 14-in. rim diameter. However, the tires varied widely over different manufacuturers and styles of construction, as subsequently indicated. The cord materials used included rayon, nylon, fiberglas, polyester, and steel. This group was chosen to represent an average of normal tire populations as would be encountered by a retreader.

One of each of the tire pairs was subjected to the pressurization process up to approximately 75% of the mean population burst pressure. Following this, all tires were recapped by a competent commercial retreader. The tires were then sent to Compliance Testing Laboratories, Inc., Ravenna, Ohio for testing under MVSS 109, using either the endurance or high-speed test schedule. Test conditions were the same for each tire of the pair, i.e., both tires of a pair were run on the same test schedule of MVSS 109, on the same test machine. The results of these tests are summarized in the table below, where the first tire in each pair is the one which had been subjected to the pressurization process.

Examination of Table 5 shows that there is no evidence that the pressurization process caused degradation or premature failure of the recapped tires. Considering as null a case where both tires of a pair failed or neither of the pairs failed, and considering the failure of the pressurized tire to represent a negative contribution of pressurization in the event that the unpressurized tire did not fail, while the reverse situation would represent a positive con-contribution, then it is seen that the negative and positive contributions are nearly balanced throughout the sixty-eight pairs of tires. There are 42 null cases, 14 positive cases, and 12 negative cases. These results strongly imply that there is no systematic degradation or loss of tire life associated with the proof pressurization process.

As was summarized earlier in Table 3 but can also be seen in Table 5 there is no obvious value to the pressurization process. The radial tires subjected to low pressure appear to have benefited by the process but it must be recalled that these tires were retreaded by a different shop from that used for the other fifty-two pairs. For the tires subjected to the pressurization

TABLE 5.-SUMMARY OF MULTIPLE PAIRED TIRE SIGN TEST RESULTS

Size of Pair	Sign Test +	Sign Test 0	Sign Test -	No. of Pairs	Proof Pressure
5.60 x 15	1			1	170
6.85 x 15		1		1	170
7.77 x 15		1		1	170
8.55 x 15		1		1	170
G78 x 15		3		3	170
H78 x 15	1	2	2	5	170
215R-15		1		1	170
Net Effect = 0				13	170
165SR-14	5	9	2	16	150
Net Effect = +3				16	150
8.15 x 15		1		1	160
8.25 x 15		5	1	6	160
8.55 x 15	1	4	1	6	160
H78 x 15	6	14	6	26	160
Net Effect = -1				39	160

process at 160 psi, the retreader was instructed to retread the tires regardless of their general acceptability at his establishment. This was done to eliminate the effect of a post-buff screening, although defects observed by the retreader in his regular inspections before and after buffing were noted. These tires, a sample of thirty-nine pairs, received a net effect of -1 in the sign test.

Table 6 includes most of the data obtained in this test program in somewhat expanded form.

As a final note, the output of the electronic instrumentation from the middle part of the program may be of interest to some researchers but due to the rather negative results of this testing it has not been included in this publication. These several hundred pages of data can be made available if necessary.

TABLE 6.-RESULTS OF ENDURANCE AND HIGH-SPEED TESTS (PAIRED TIRE EXPERIMENTS)

NOTE: The results given in this table should not be used to conclude that normal commercial retreading processes result in a product which consistently fails durability or high-speed tests under MVSS 109. Some of the tires selected for this test program were not of good retreading quality, but were used primarily because specific tire types or constructions were needed to fill out the test program, and such tire pairs were not easy to find in good condition. Therefore, in some cases, below-standard tires were accepted for this test program. This was done with care and the pairs of tires were kept as similar as possible so that the two were always of approximately equal quality.

Tire I.D. No.	Tire Size	Material Construction	Mfr. Code	Preinflat. Pressure	Type of Test	Results of Test
T4X- 994	6.85 x 15	2 Ply Rayon Bias	M-1	170	Endur.	Flex break - sidewall
T4X- 995				None	Endur.	Flex break - sidewall
T5X-1914	8.55 x 15	2 Ply Rayon Bias	M-5	160	H.S.	No failure
T5X-1915				None	H.S.	No failure
T4X- 983	5.60 x 15	2 Ply Rayon Bias	M-8	170	Endur.	No failure
T4X- 993				None	Endur.	Recap separation
T5X-1916	8.15 x 15	2 Ply Rayon Bias	M-1	160	H.S.	No failure
T5X-1917				None	H.S.	No failure
T4X- 876	8.55 x 15	2 Ply Polyester Bias	M-3	170	Endur.	No failure
T4X- 877				None	Endur.	No failure
T5X-1918	8.25 x 15	2 Ply Polyester Bias	M-3	160	H.S.	Recap separation - shoulder
T5X-1919				None	H.S.	Recap separation - shoulder
T5X-1920	8.55 x 15	2 Ply Polyester Bias	M-3	160	H.S.	No failure
T5X-1921				None	H.S.	No failure
T4X- 872	7.75 x 15	4 Ply Rayon Bias	M-2	170	Endur.	Shoulder separation
T4X- 873				None	Endur.	Shoulder separation

TABLE 6. CONTINUED

Tire I.D. No.	Tire Size	Material Construction	Mfr. Code	Preinflat. Pressure	Type of Test	Results of Test
T5X-1928	8.25 x 15	4 Ply Rayon Bias	M-[illegible]	160	H.S.	No failure
T5X-1929				None	H.S.	No failure
T5X-1922	8.55 x 15	4 Ply Nylon Bias	M-10	160	H.S.	No failure
T5X-1923				None	H.S.	Recap separation - shoulder
T5X-1924	8.55 x 15	4 Ply Nylon Bias	M-10	160	H.S.	Recap separation - shoulder
T5X-1925				None	H.S.	No failure - sidewall cracks
T5X-1926	8.55 x 15	4 Ply Nylon Bias	M-11	160	N.S.	No failure
T5X-1927				None	H.S.	No failure
T5X-1930	8.55 x 15	4 Ply Polyester Bias	M-3	160	H.S.	No failure
T5X-1931				None	H.S.	No failure
T5X-1932	8.25 x 15	4 Ply Polyester Bias	M-12	160	H.S.	Recap separation - shoulder
T5X-1933				None	H.S.	Recap separation - shoulder
T5X-1934	8.25 x 15	4 Ply Polyester Bias	M-12	160	H.S.	Recap separation - shoulder
T5X-1935				None	H.S.	Tread separation - shoulder
T5X-1936	8.25 x 15	4 Ply Polyester Bias	M-12	160	H.S.	Recap separation - shoulder
T5X-1937				None	H.S.	Recap separation - shoulder
T5X-1938	8.25 x 15	4 Ply Polyester Bias	M-12	160	H.S.	Recap separation - shoulder
T5X-1939				None	H.S.	No failure
T4X- 910	G78 x 15	2 Poly/2 Glass Bias-Belt	M-5	170	Endur.	No failure
T4X- 911				None	Endur.	No failure
T4X- 920	G78 x 15	2 Poly/2 Glass Bias-Belt	M-4	170	Endur.	Recap separation - tread
T4X- 922				None	Endur.	Recap separation - tread
T4X- 924	H78 x 15	2 Poly/2 Glass Bias-Belt	M-1	170	Endur.	Tread separation
T4X- 925				None	Endur.	No failure
T4X- 952	H78 x 15	2 Poly/2 Glass Bias Belt	M-4	170	Endur.	Recap separation - shoulder
T4X- 951				None	Endur.	No failure

TABLE 6. CONTINUED

Tire I.D. No.	Tire Size	Material Construction	Mfr. Code	Preinflat. Pressure	Type of Test	Results of Test
T4X- 930	H78 x 15	2 Poly/2 Glass Bias-Belt	M-7	170	Endur.	No failure
T4X- 934				None	Endur.	No failure
T5X-1940	H78 x 15	2 Poly/2 Glass Bias-Belt	M-3	160	H.S.	Breaker separation - shoulder
T5X-1941				None	H.S.	Breaker separation - shoulder
T5X-1998	H78 x 15	2 Poly/2 Glass Bias-Belt	M-3	160	H.S.	Breaker separation - shoulder
T5X-1999				None	H.S.	Breaker separation - shoulder
T5X-1942	H78 x 15	2 Poly/2 Glass Bias-Belt	M-7	160	H.S.	Breaker separation - shoulder
T5X-1943				None	H.S.	No failure
T5X-1944	H78 x 15	2 Poly/2 Glass Bias-Belt	M-7	160	H.S.	Complete breaker separation
T5X-1945				None	H.S.	No failure
T5X-1946	H78 x 15	2 Poly/2 Glass Bias-Belt	M-7	160	H.S.	Breaker separation - shoulder
T5X-1947				None	H.S.	No failure
T5X-1948	H78 x 15	2 Poly/2 Glass Bias-Belt	M-7	160	H.S.	No failure
T5X-1949				None	H.S.	No failure
T5X-1950	H78 x 15	2 Poly/2 Glass Bias-Belt	M-7	160	H.S.	No failure
T5X-1951				None	H.S.	No failure
T5X-1952	H78 x 15	2 Poly/2 Glass Bias-Belt	M-4	160	H.S.	No failure
T5X-1953				None	H.S.	No failure
T5X-1956	H78 x 15	2 Poly/2 Glass Bias-Belt	M-4	160	H.S.	Recap separation - shoulder
T5X-1957				None	H.S.	No failure
T5X-1958	H78 x 15	2 Poly/2 Glass Bias-Belt	M-4	None	H.S.	Recap separation -shoulder
T5X-1959				None	H.S.	No failure
T5X-1960	H78 x 15	2 Poly/2 Glass Bias-Belt	M-4	160	H.S.	No failure
T5X-1961				None	H.S.	No failure
T5X-1964	H78 x 15	2 Poly/2 Glass Bias-Belt	M-4	160	H.S.	No failure
T5X-1965				None	H.S.	No failure

TABLE 6. CONTINUED

Tire I.D. No.	Tire Size	Material Construction	Mfr. Code	Preinflat. Pressure	Type of Test	Results of Test
T5X-1966	H78 x 15	2 Poly/2 Glass Bias-Belt	M-4	160	H.S.	No failure
T5X-1967				None	H.S.	Breaker separation - shoulder
T5X-1968	H78 x 15	2 Poly/2 Glass Bias-Belt	M-4	160	H.S.	Breaker separation - shoulder
T5X-1969				None	H.S.	No failure
T5X-1970	H78 x 15	2 Poly/2 Glass Bias-Belt	M-4	160	H.S.	No failure
T5X-1971				None	H.S.	No failure
T5X-1972	H78 x 15	2 Poly/2 Glass Bias-Belt	M-4	160	H.S.	No failure
T5X-1973				None	H.S.	No failure
T5X-1974	H78 x 15	2 Poly/2 Glass Bias-Belt	M-1	160	H.S.	Tread separation
T5X-1975				None	H.S.	No failure
T5X-1994	H78 x 15	2 Poly/2 Glass Bias-Belt	M-1	None	H.S.	Breaker separation - shoulder
T5X-1995				None	H.S.	Breaker separation - shoulder
T4X- 886	G78 x 15	2 Rayon/2 Rayon Bias-Belt	M-1	170	Endur.	No failure
T4X- 889				None	Endur.	No failure
T4X- 896	H78 x 15	2 Rayon/2 Rayon Bias-Belt	M-1	170	Endur.	No failure
T4X- 897				None	Endur.	No failure
T5X-1976	H78 x 15	2 Rayon/2 Rayon Bias-Belt	M-1	160	H.S.	No failure
T5X-1977				None	H.S.	No failure
T5X-1978	H78 x 15	2 Rayon/2 Rayon Bias-Belt	M-1	160	H.S.	No failure
T5X-1979				None	H.S.	Breaker separation - shoulder
T5X-1980	H78 x 15	2 Rayon/2 Rayon Bias-Belt	M-1	160	H.S.	No failure
T5X-1981				None	H.S.	Breaker separation - shoulder
T5X-1982	H78 x 15	2 Rayon/2 Rayon Bias-Belt	M-1	160	H.S.	No failure
T5X-1983				None	H.S.	No failure
T5X-1984	H78 x 15	2 Rayon/2 Rayon Bias-Belt	M-1	160	H.S.	No failure
T5X-1985				None	H.S.	Tread separation

TABLE 6. CONTINUED

Tire I.D. No.	Tire Size	Material Construction	Mfr. Code	Preinflat. Pressure	Type of Test	Results of Test
T5X-1986	H78 x 15	2 Rayon/2 Rayon Bias-Belt	M-1	160	H.S.	No failure
T5X-1987				None	H.S.	No failure
T5X-1988	H78 x 15	2 Rayon/2 Rayon Bias-Belt	M-1	160	H.S.	Breaker separation - shoulder
T5X-1989				160	H.S.	Breaker separation - shoulder
T5X- 1990	H78 x 15	2 Rayon/2 Rayon Bias-Belt	M-1	160	H.S.	No failure
T5X-1991				None	H.S.	Breaker separation - shoulder
T5X-1992	H78 x 15	2 Rayon/2 Rayon Bias-Belt	M-1	160	H.S.	No failure
T5X-1993				None	H.S.	Breaker separation - shoulder
T5X-1996	H78 x 15	2 Rayon/2 Rayon Bias-Belt	M-1	160	H.S.	No failure
T5X-1997				None	H.S.	No failure
T4X- 902	H78 x 15	2 Rayon/2Rayon Bias-Belt	M-4	170	Ednur.	No failure
T4X- 903				None	Endur.	Carcass separation
T5X-1954	H78 x 15	2 Rayon/2 Rayon Bias-Belt	M-4	160	H.S.	Breaker separation - shoulder
T5X-1955				160	H.S.	Complete separation of recap from carcass
T5X-1962	H78 x 15	2 Rayon/2 Rayon Bias-Belt	M-4	160	H.S.	Breaker separation - shoulder
T5X-1963				None	H.S.	Breaker separation - shoulder
T5X-0319	165SR-14	2 Rayon/4 Rayon Radial	M-8	150	H.S.	No failure
T5X-0320				None	H.S.	Tread separation - shoulder
T5X-0323	165SR-14	2 Rayon/4 Rayon Radial	M-8	150	H.S.	No failure
T5X-0324				None	H.S.	Breaker separation
T5X-0325	165SR-14	2 Rayon/4 Rayon Radial	M-8	150	H.S.	Shoulder separation
T5X-0326				None	H.S.	Tread separation
T5X-0327	165SR-14	2 Rayon/4 Rayon Radial	M-8	150	Endur.	No failure
T5X-0330				None	Endur.	Breaker separation
T5X-0331	165SR-14	2 Rayon/4 Rayon Radial	M-8	150	Endur.	No failure
T5X-0332				None	Endur.	Breaker separation

TABLE 6. CONTINUED

Tire I.D. No.	Tire Size	Material Construction	Mfr. Code	Preinflat. Pressure	Type of Test	Results of Test
T5X-0337 T5X-0338	165SR-14	2 Rayon/4 Rayon Radial	M-8	150 None	H.S. H.S.	No failure Tread separation
T5X-0359 T5X-0360	165SR-14	2 Rayon/4 Rayon Radial	M-13	150 None	Endur. Endur.	No failure No failure
T5X-0341 T5X-0342	165SR-14	2 Rayon/4 Rayon Radial	M-14	150 None	Endur. Endur.	No failure No failure
T5X-0349 T5X-0350	165SR-14	2 Rayon/4 Rayon Radial	M-14	150 None	H.S. H.S.	No failure No failure
T5X-0351 T5X-0352	165SR-14	2 Rayon/4 Rayon Radial	M-9	150 None	Endur. Endur.	No failure No failure
T5X-0353 T5X-0354	165SR-14	2 Rayon/4 Rayon Radial	M-9	150 None	H.S. H.S.	No failure No failure
T5X-0365 T5X-0366	165SR-14	2 Rayon/4 Rayon Radial	M-15	150 None	Endur. Endur.	Flex break - sidewall Tread separation
T5X-0340	165SR-14	2 Rayon/4 Rayon Radial	M-14	None	H.S.	No failure
T5X-0348	165SR-14	2 Rayon/4 Rayon Radial	M-14	None	H.S.	No failure
T5X-0356	165SR-14	2 Rayon/4 Rayon Radial	M-9	None	H.S.	No failure
T5X-0358	165SR-14	2 Rayon/4 Rayon Radial	M-9	None	H.S.	No failure
T5X-0364	165SR-14	2 Poly/4 Rayon Radial	M-3	None	Endur.	No failure

TABLE 6. CONCLUDED

Tire I.D. No.	Tire Size	Material Construction	Mfr. Code	Preinflat. Pressure	Type of Test	Results of Test
T5X-0321	165SR-14	2 Rayon/4 Rayon Radial	M-8	150	Endur.	Shoulder separation
T5X-0322	165SR-14	2 Nylon/4 Rayon Radial	M-8	None	Endur.	No failure
T5X-0333	165SR-14	2 Nylon/4 Nylon Radial	M-8	150	Endur.	No failure
T5X-0334				None	Endur.	No failure
T5X-0361	165SR-14	3 Rayon/4 Rayon Radial	M-17	150	H.S.	No failure
T5X-0362	165SR-14	2 Rayon/5 Rayon Radial	M-17	None	H.S.	No failure
T5X-0367	165SR-14	2 Rayon/6 Rayon Radial	M-16	150	Endur.	Flex break - sidewall
T5X-0368	165SR-14	2 Nylon/6 Rayon Radial	M-16	None	Endur.	No failure
T4X- 962	215R x 15	2 Rayon/2 Steel Radial	M-6	170	Endur.	No failure
T4X- 963				None	Endur.	No failure

REFERENCES

[1] Luchini, J. R., "The Influence of Overloads on the Fatigue Life of Nylon Tire Cord," Journal of Coated Fabrics, Vol. 4, No. 3, pp. 154-157, January 1975.

[2] Clark, S. K., R. N. Dodge, D. W. Lee, and J. R. Luchini, "Pressure Effects on Worn Passenger Car Tire Carcasses," DOT-TSC-74-1, UM-010654-2-I, 1974.

[3] Clark, S. K., R. N. Dodge, D. W. Lee, and J. R. Luchini, "Pressure Effects on Worn Passenger Car Tire Carcasses," DOT-TSC-75-1, UM-010654-4-I, 1975.

APPENDIX

REPORT OF INVENTIONS

There were no inventions conceived during this research program since it consisted of application of known concepts to an old problem, namely, that of inspection and flaw detection in tire carcasses.

Some of the applied concepts, however, such as coupling acoustic emission, differential pressure/volume and invocation of an iterative statistical process in the same experiment were unique and advanced.

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