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PRESSURE EFFECTS ON WORN PASSENGER CAR TIRE CARCASSES

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16. Abstract

Work is described to examine the value of hydrostatic proof pressure testing in selecting used tire carcasses for retreading. Preliminary experiments on single tire cords indicate that overloads close to rupture do not damage subsequent fatigue life. A selected population of used 15-inch passenger car tires was selected and burst hydrostatically yielding a wear burst pressure of 207 psi. Additional tires are to be retreaded after pressurization to 170 psi. Their performance on MVSS 109 will be compared with an unpressurized control set of tires which are also to be recapped.

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PREFACE

Previous studies summarized in Appendix A have shown that a single overload of an individual tire cord does not significantly shorten its subsequent fatigue life. We desire to demonstrate the extension of this result to the nondestructive pressurization of a complete tire. The primary aim of this research program was to determine if a single pressure proof test reduced the later service life of a retreaded automobile tire. As a secondary aim, acoustic emission (A.E.) from pressurized tires was to be evaluated as a means of nondestructively testing tires for structural integrity.

There were three phases in the original project design. The first phase of the program was the experimental determination of the burst distribution of a typical population of worn passenger car tires. These distributions of burst pressures for various common tire constructions were obtained for 15-inch rim diameter tires. In the second phase of the experiment, a group of tires was to be proof tested to a pressure level chosen so as to be effective in eliminating damaged carcasses. These tires and a paired group of unpressurized control tires were then to be recapped. In the third phase, the recapped tires are to be run to failure on a roadwheel or on test vehicles. The final step is to be an analysis of the data thus obtained to determine the effect of proof pressurization on the subsequent fatigue life of the recapped tires.

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1. SUMMARY AND CONCLUSIONS

To determine the effect of a pressure overload on the subsequent fatigue life of an automobile tire, sixty-five sets of three similar tires each were collected. In the process of collecting sets of three tires with the same size, manufacturer, construction, and materials, many incomplete sets were formed. Over one hundred tires were burst using a high pressure nitrogen over water system, among these being one tire from each of the sixty-five complete sets. The remaining two tires of each set have been sent to DOT/TSC, Cambridge, Massachusetts, for nondestructive testing. The mean burst pressure of worn 15-inch rim diameter passenger car tires of all constructions, but weighted to a large fraction of polyester-glass bias-belted tires, is 207 psi. Allowing for damaged carcasses, the burst pressure probably fits a normal distribution curve best.

Data from the burst of one hundred tires indicated that tire construction affected the most probable location of a failure of the carcass as shown in Figure 1 and Table 1. 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. Radial ply tires failed most often in the bead. Four-ply tires failed in both the crown and bead.

TABLE 1.-FAILURE PERCENTAGES 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-Fiberglas Bias-Belt	68	2	30	0
Radial Ply	7	7	86	0

The average burst pressure was also a function of construction as shown in Table 2. Two-ply tires and polyester-fiberglas bias-belted tires were statistically weaker in hydrostatic inflation to burst than were rayon-rayon bias-belted tires, radial ply tires, or four-ply tires. Notice that in the two types of bias-belted tires, the cord materials appeared to have a significant effect on both failure mode and failure pressure.

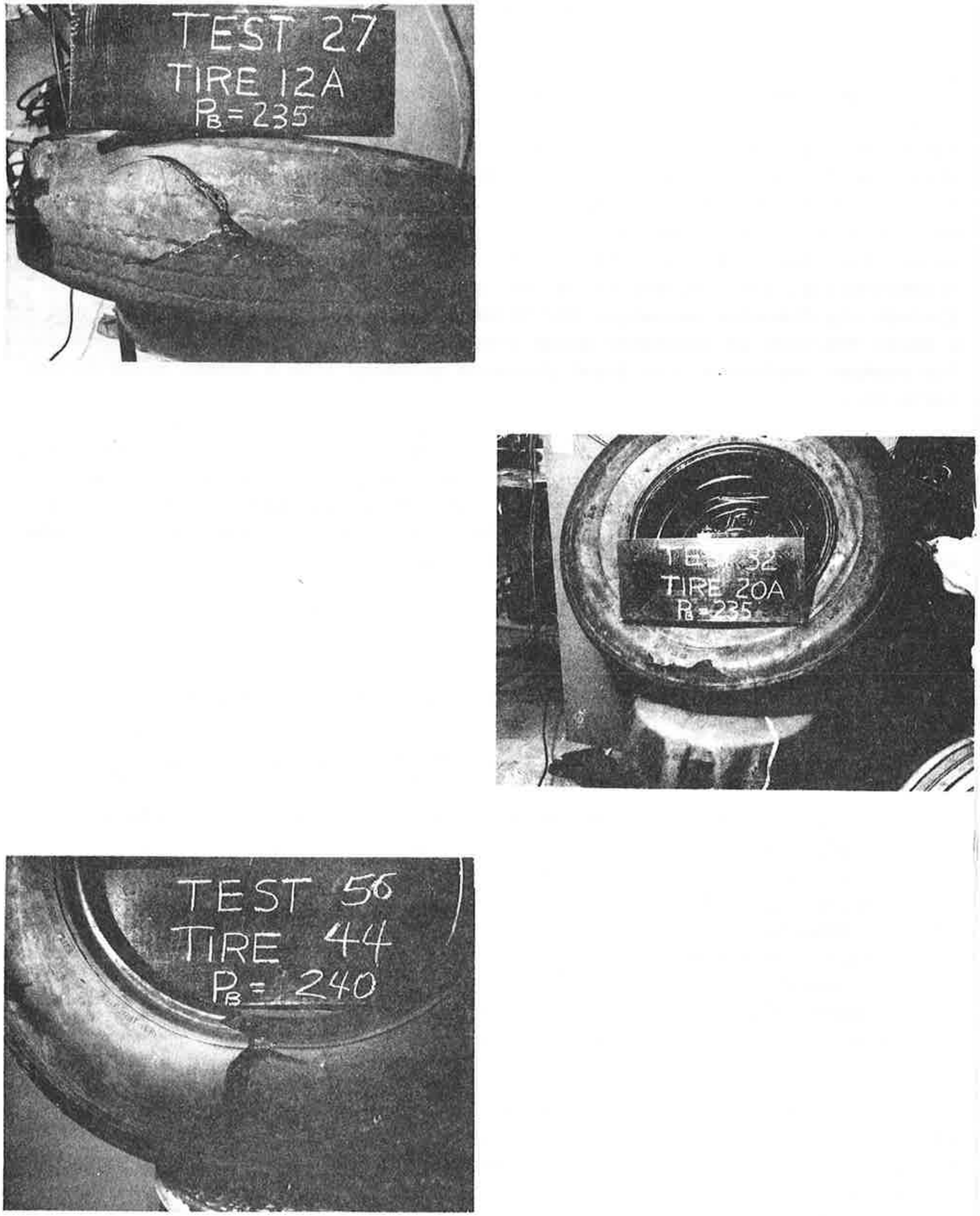

FIGURE 1. PHOTOS OF TYPICAL BURSTS

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-Fiberglas Bias-Belt	201	212
Radial Ply	208	218

Figure 2 shows the cumulative distribution of failure pressure for each of the construction groups plotted against the full sample median. This curve is of considerable importance in selecting a pressurization level which removes defective tires from a sample but does not damage the survivors of the test.

Acoustic emission (A.E.), the spontaneous generation of energy from within a material, was found to be present in hydrostatically pressurized automobile tires. Both "home-made" and commercially produced acoustic emission sensing systems were used and gave essentially similar results, although the commercial equipment was electronically quieter, could be set at greater gain levels, and produced more easily read output. The data accumulated was inconclusive but indicated that the character of the A.E. from tires probably is affected by the material and construction of the carcass, and possibly by prior damage to the tire.

There is some preliminary indication that in similar tires a flaw results in a difference in A.E. as shown in Figure 3 where two similar tires, one with a cut belt and one undamaged, were burst. The damaged tire exhibited considerably greater acoustic emission. However, in general similar tires did not give exactly the same A.E. due to randomness of the effect. This is shown in Figures 4 and 5.

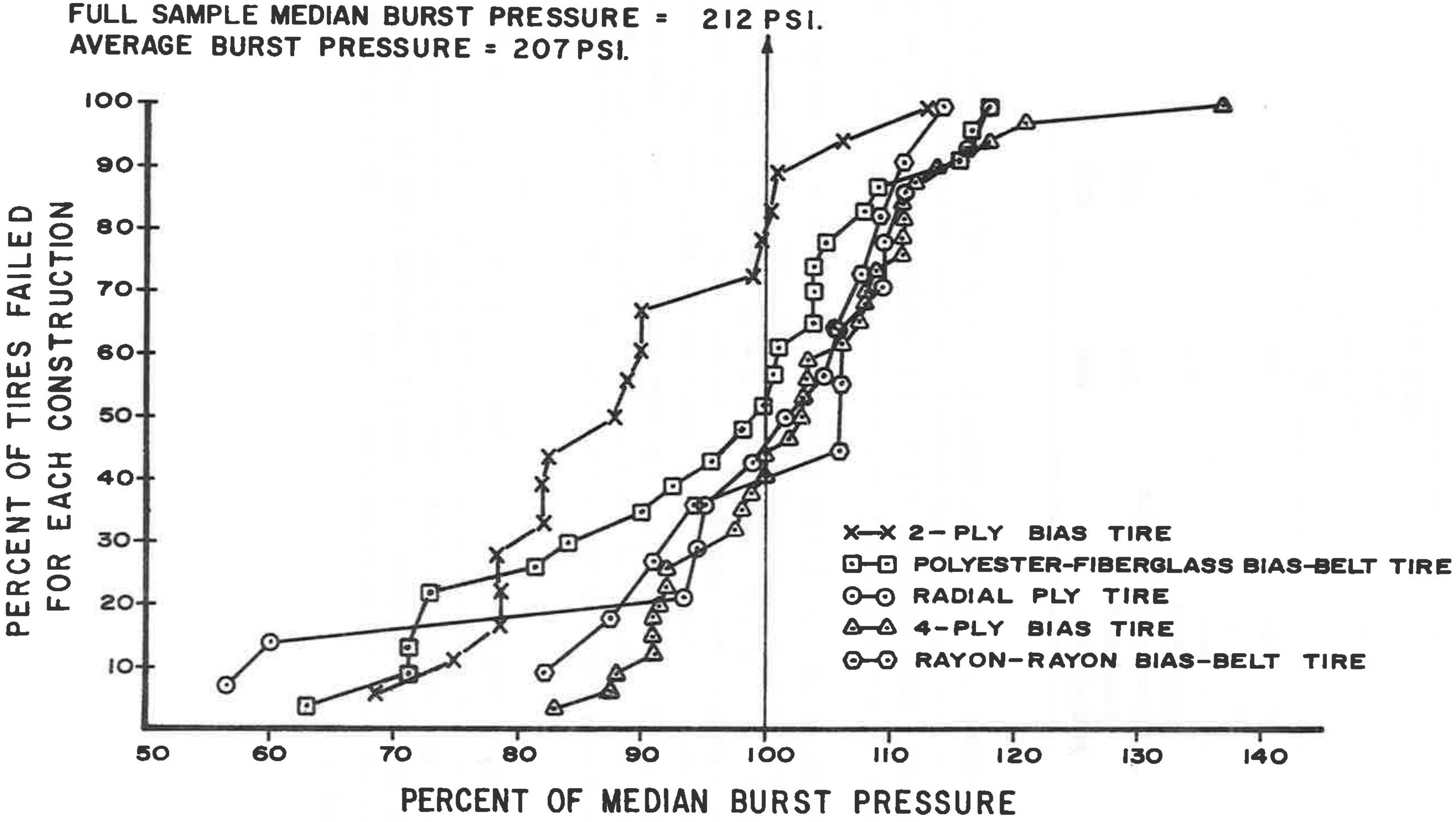

FIGURE 2. PERCENTAGE FAILURE RATE FOR EACH CONSTRUCTION RELATED TO THE FULL SAMPLE MEDIAN

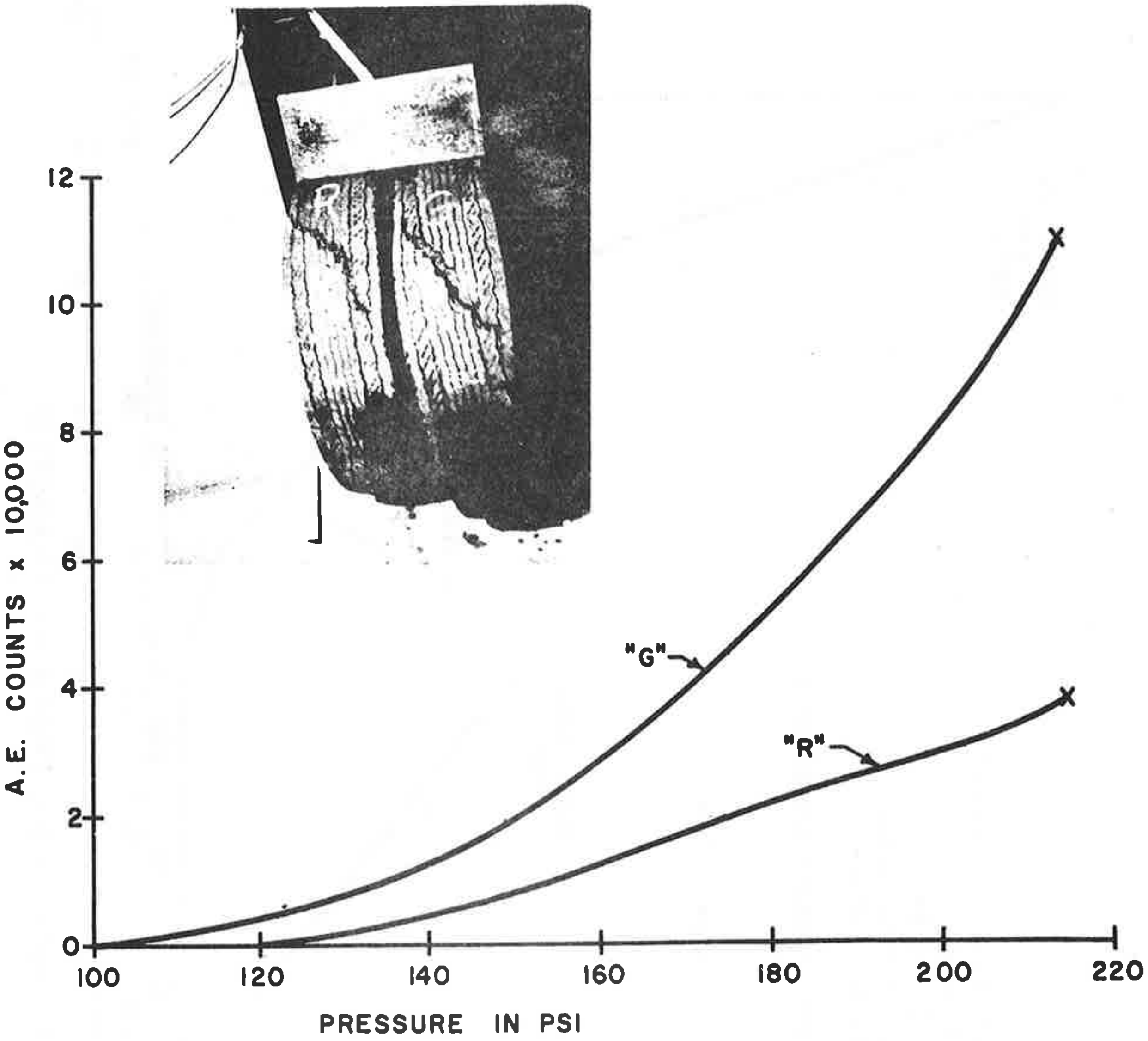

FIGURE 3. ACOUSTIC EMISSION OUTPUT FOR TWO IDENTICAL TIRES:
TIRE "R" UNDAMAGED; TIRE "G" WITHOUT BELT

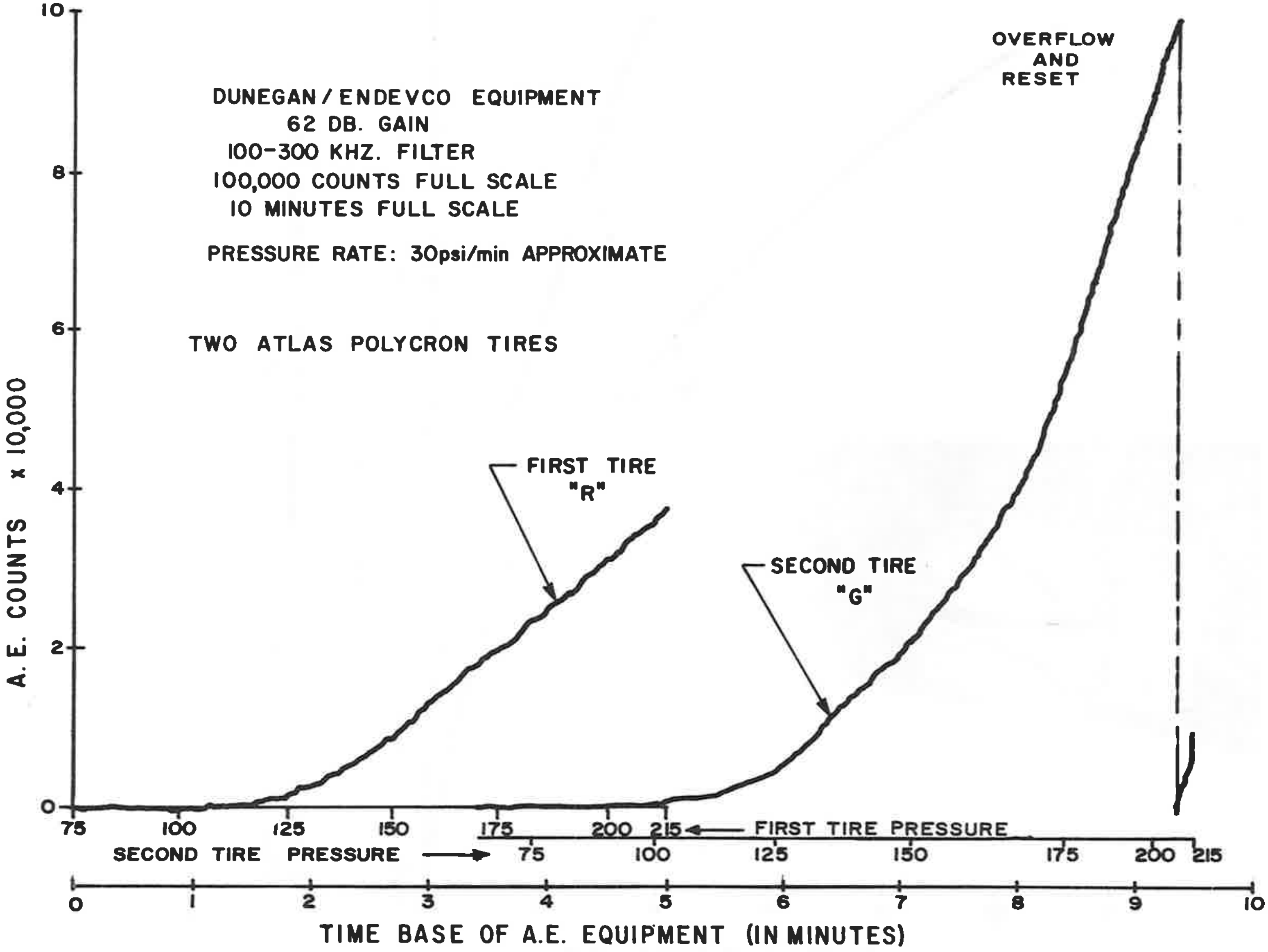

FIGURE 4. EXAMPLE A.E. OUTPUT

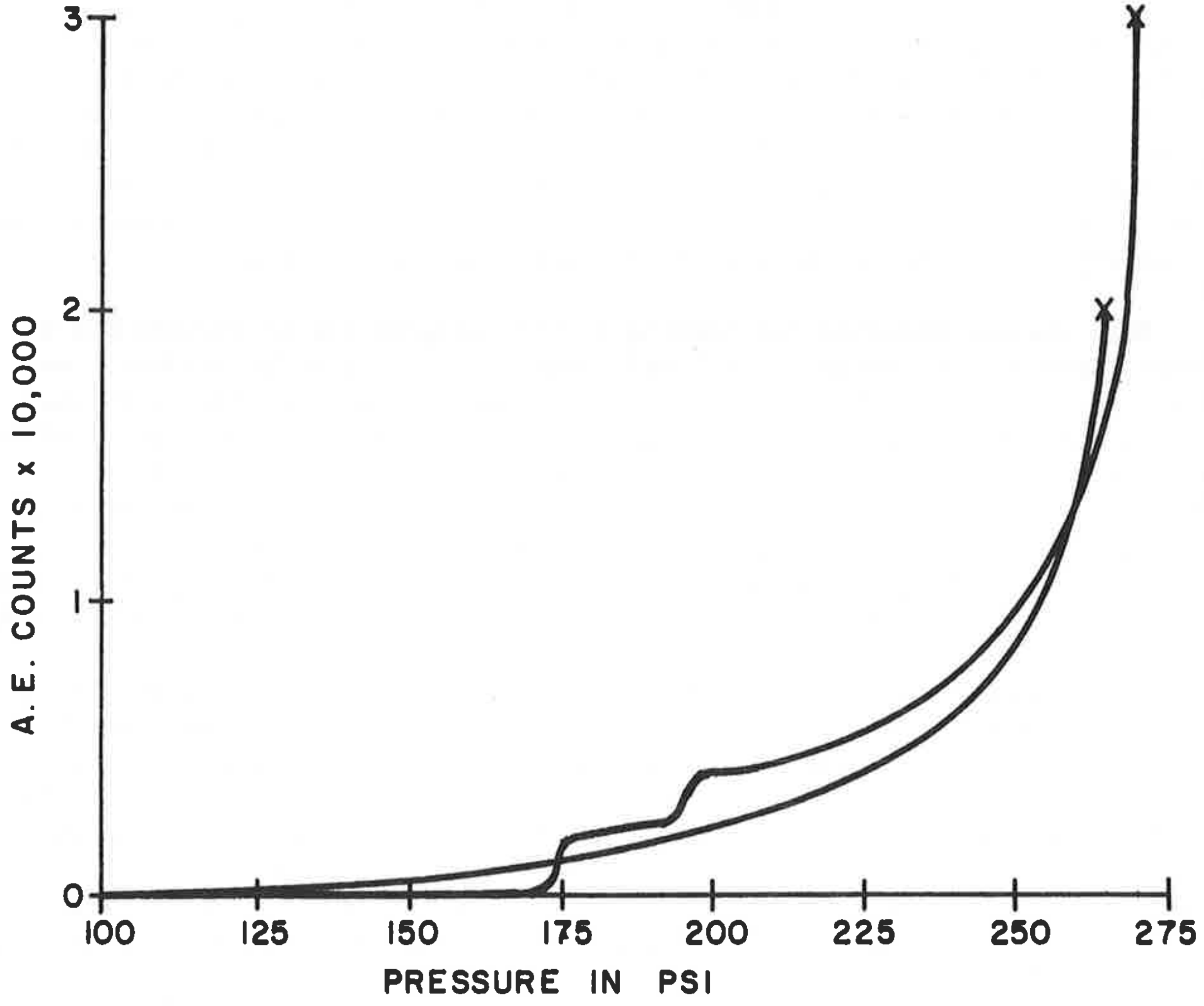

FIGURE 5. ACOUSTIC EMMISSION FOR TWO SIMILAR TIRES

2. TIRE SELECTION

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 tires 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-inch 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-inch 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 damage, 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.

3. TEST PLAN DEVELOPMENT

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 given in Figure 6 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 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 6. 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-inch tire burst pressure.

The data of Figure 6 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 6. It is seen that the data points follow the normal distribution quite well, and if we deleted 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.

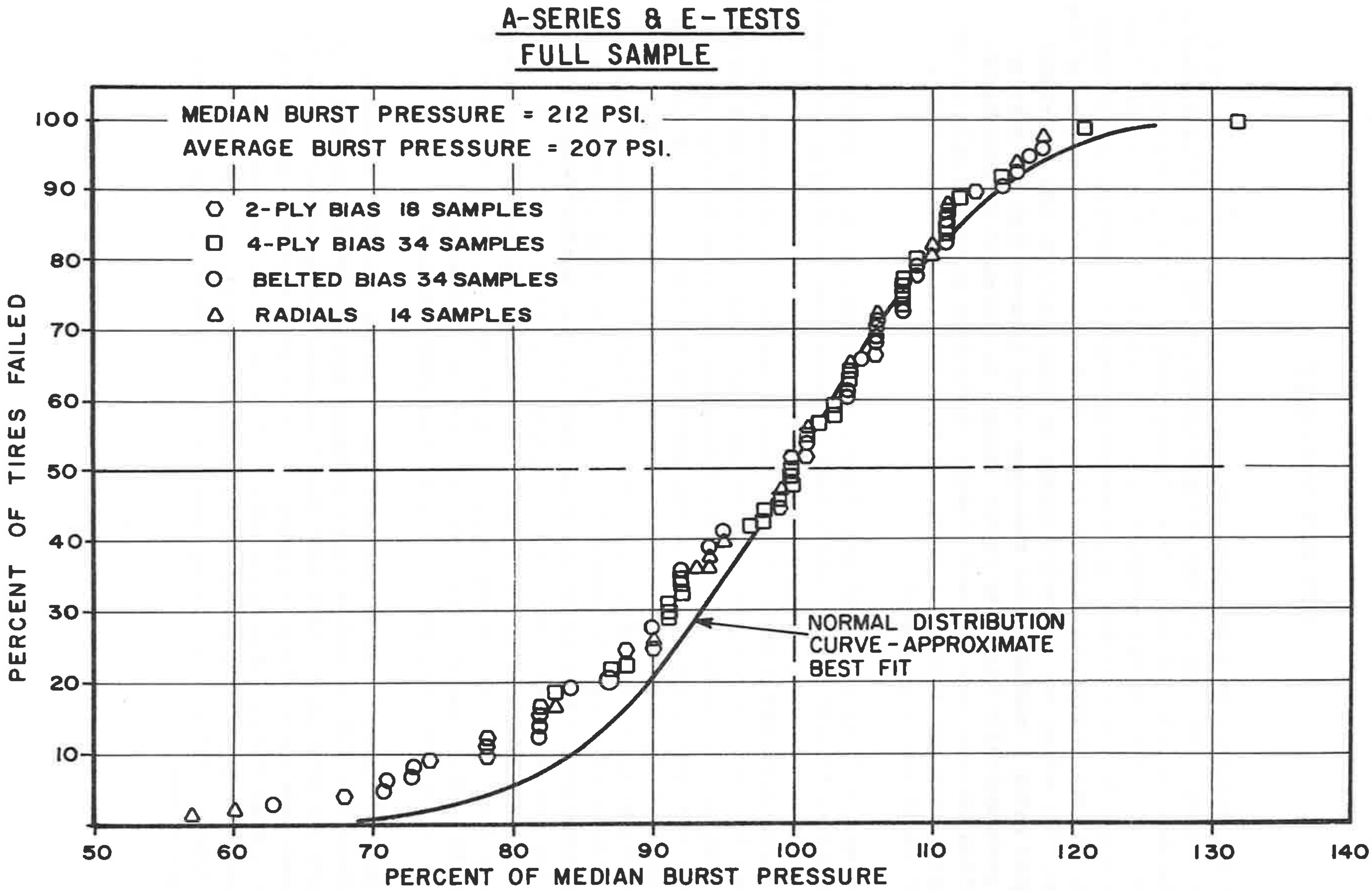

FIGURE 6. PERCENTAGE FAILURE RATE AFTER 100 TESTS

4. APPARATUS AND TEST METHOD

The pressurization system was intended to provide a means of bursting passenger car tires and recording related acoustic emission (A.E.) without danger and with minimum first cost. A safety box was constructed of 1/4 inch steel plate covered with 1-1/2 inches of plywood. Due to the large quantity 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 7.

In Figure 7 it is seen that city water of nominal 65 psi pressure passed through a valve to a nitrogen cylinder 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 isolation The bar was bolted to the wheel and wires were run from the cartridges to a pre-amplifier 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 seconds, 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.

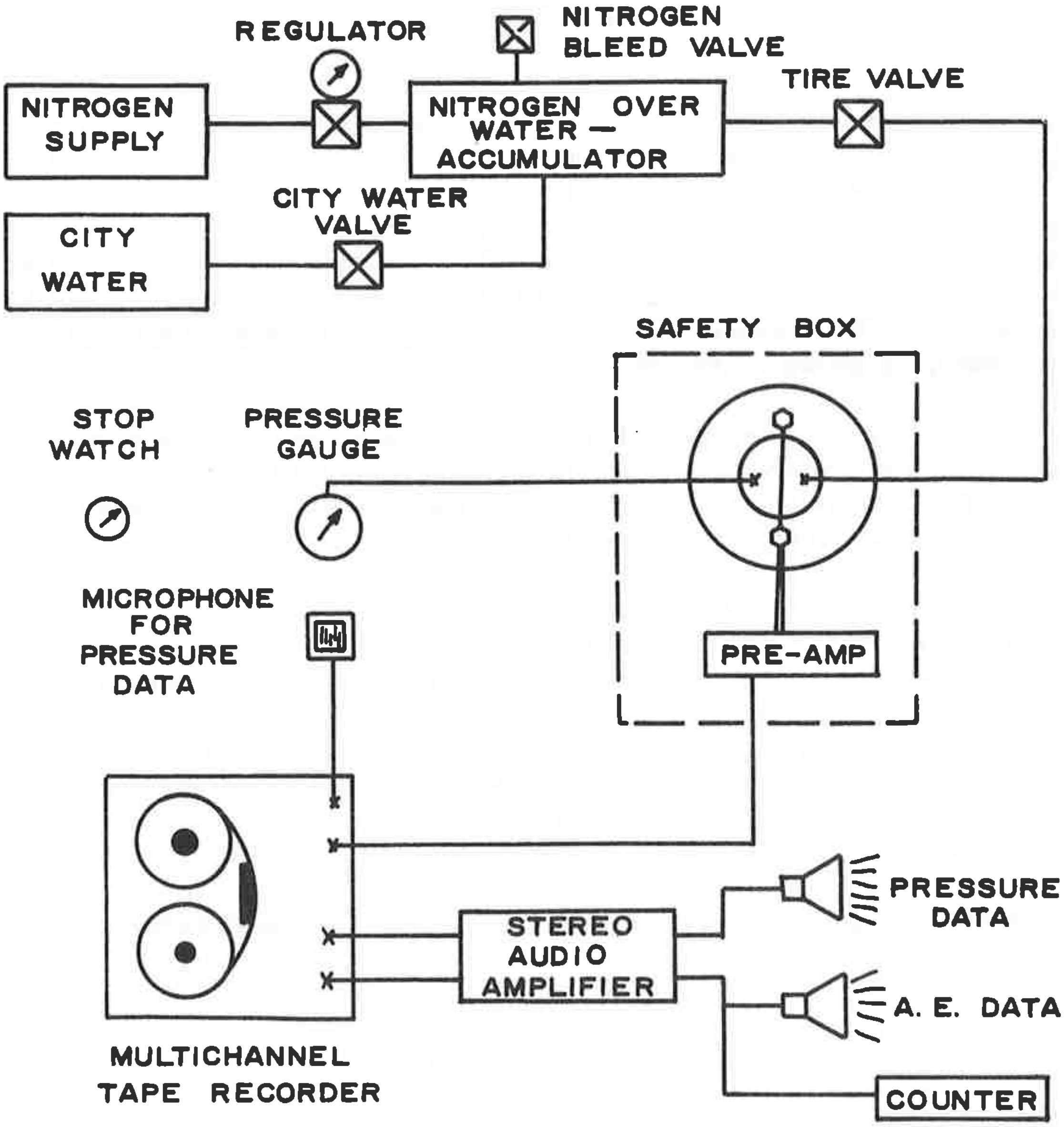

FIGURE 7. SCHEMATIC VIEW OF TIRE PRESSURIZATION SYSTEM

5. PROPOSED FUTURE WORK

A sequential paired experiment using the tires already selected will be performed as detailed in Appendix D. The basis for this test is that a proof pressure which causes strong degradation of service life will manifest itself in the first few sample results. By starting with a pressure likely to cause degradation of survivor fatigue life, an upper bound on the pressure level can be obtained with a small sample. Subsequent drops in the pressure level should enable location of a pressure which causes negligible damage to fatigue life using a minimum number of test samples, and yet which is capable of culling out damaged tire carcasses.

The study of hydrostatic burst and fatigue of automobile tires and related A.E. offers promise of valuable insights into the degradation of pneumatic tires.

APPENDIX A

SINGLE CORD STUDIES

A preliminary study was carried out on the influence of a single preload on subsequent fatigue life of an individual 840/2 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, we hope to extend these results to the testing of a tire carcass. While subjecting the carcass to a large prestrain may not imply an unchanged fatigue life, it may not significantly alter the fatigue life of the tire.

The data obtained is shown in Figure 8.

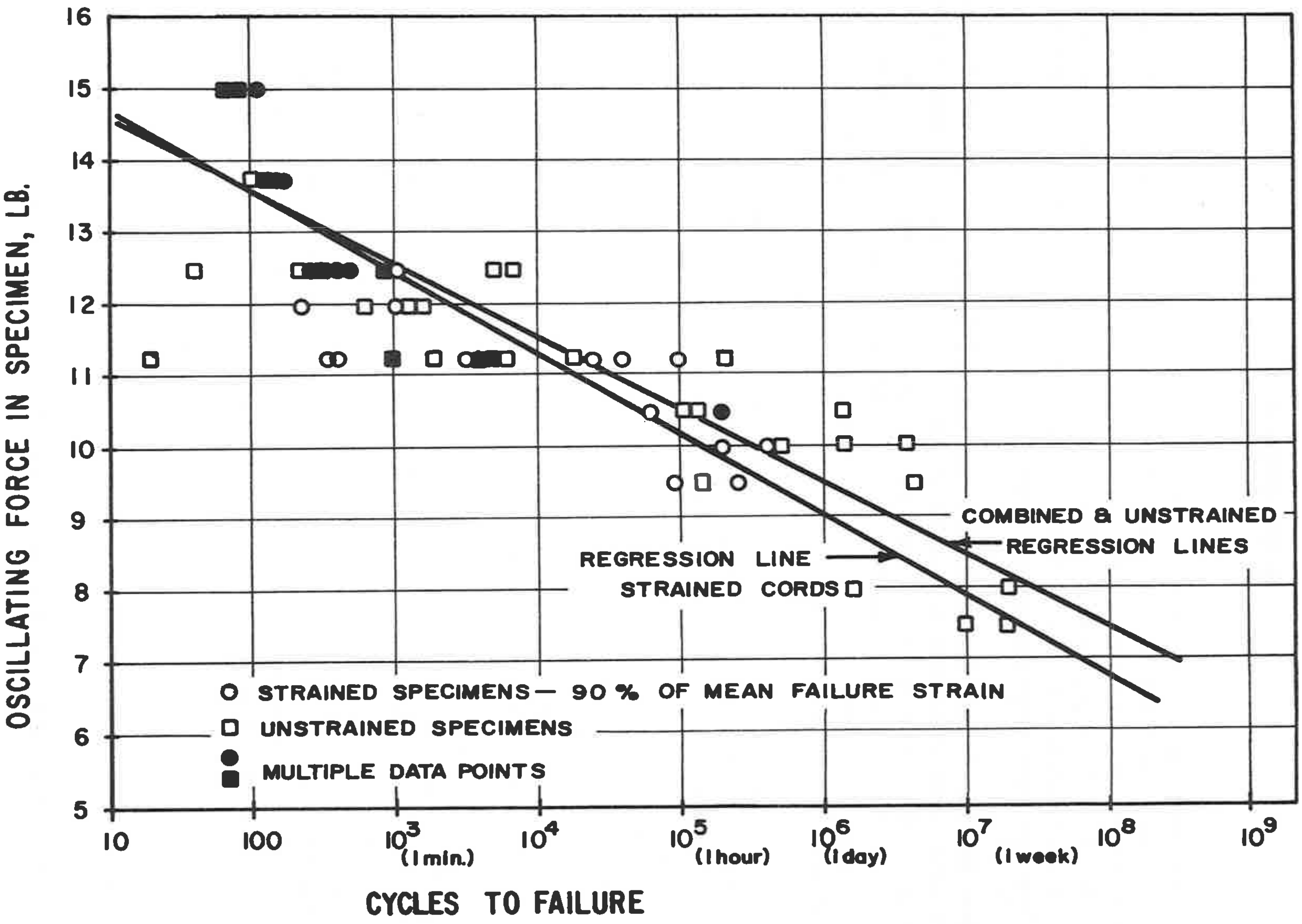

FIGURE 8. CYCLES TO FAILURE VS. OSCILLATING FORCE LEVEL FOR DIPPED NYLON CORD

APPENDIX B

BURST ANALYSIS

In the performance of the burst tests several interesting phenomena were observed. 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 1. On several occasions multiple failures occurred in a single tire, for example, both the crown and sidewalls having obvious ruptures.

Table 1 shows 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 evidence 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 2. 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.

APPENDIX C

ACOUSTIC EMISSION (A.E.)

Acoustic emission (A.E.) is the spontaneous generation of an 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 kilohertz, 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 have not been conclusive. For example, pinhole leaks can be detected, but there is no overall pattern as yet. 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 3 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 9. 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 9 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 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.

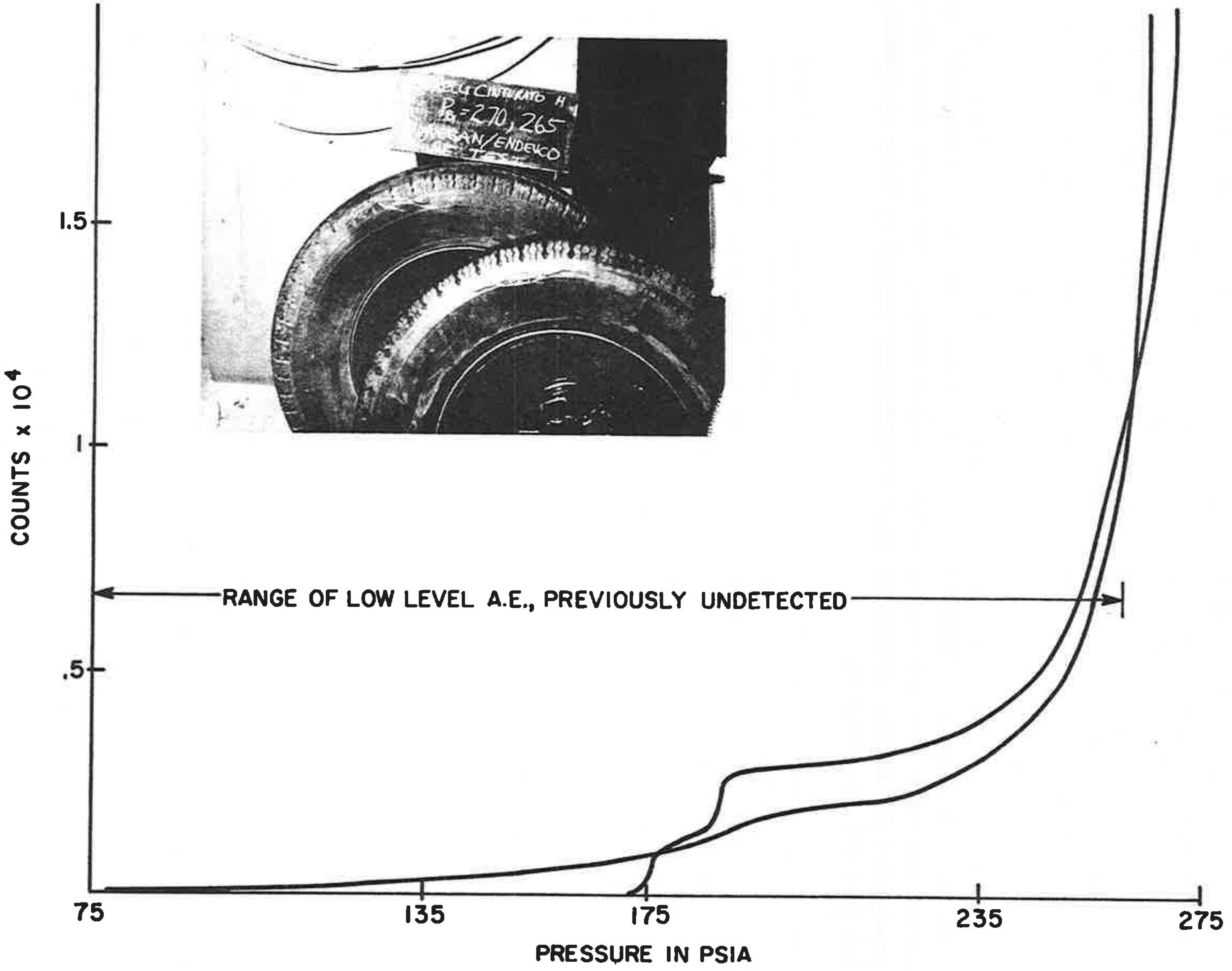

FIGURE 9. ACOUSTIC EMISSIONS VS. PRESSURE LEVEL FOR RAYON-RAYON RADIAL TIRES USING COMMERCIAL ACOUSTIC EMISSION SENSOR

APPENDIX D

ANALYSIS OF EXPERIMENTAL PROCEDURE FOR COMPARING PRESSURIZED TIRES VS. CONTROL TIRES

In the experiment in question 65 pairs of worn tires have been selected for recapping and durability testing. These pairs are chosen to be as closely alike as possible, in regard to width material and manufacture. The "B" tire of each of these pairs of tires will be hydrostatically pressurized to some proof test level. The other tire, denoted as the "C" tire, will serve as a control and will not be so pressurized. It is anticipated that during this pressurization process a certain number of flawed or defective tires will be found, and in some cases these will fail by rupture. In any event those defective tires will not be available for subsequent retreading. Therefore, the total number of paired samples available at the beginning of the retreading process will be somewhat less than 65, although the exact number cannot be determined at this time. After the pressurization of the "B" group of tires, all of the tires will be retreaded, and following that all will be tested both by the MVSS 109 test on dynamometer drums and by being run on test automobiles. Since the latter procedure is quite costly, it is planned that very few tires will be tested on the highway on automobiles. It is necessary that the proper level of pressurization and the associated test procedure be selected carefully to assure useful results.

In general this situation is one in which very little control exists over the absolute life of any single tire after it is retreaded. It is well known that there is considerable variation in test results on the life or wearout characteristics of tires, and it is suspected that due to the different tire widths involved in this total sample, there will be variations in life due to width as well. For this reason it seems imperative that the test be considered fundamentally as a paired comparison test, where two tires of the same size, construction, and manufacturer are tested and compared against one another, rather than in terms of absolute values. Furthermore, since one of the most important questions to be answered is the influence of pressurization on subsequent life of a retreaded tire, then it seems even more important that the paired design be retained since this will give a direct one-to-one comparison in all cases. While these statements represent general comments on the design of the experiment as originally conceived, subsequent questions have been raised concerning the use of the paired samples.

It should be noted that the primary difficulty with design of this experiment lies in the fact that the pressurization process on the "B" group of tires has the potential for both improving the quality of the "B" group and for degrading it. It tends to improve the quality of the "B" group by virtue of the fact that those tires which are faulty will be located and removed from the "B" population. In this sense it will tend to make the "B" population better than the "C" population, which presumably will contain, by random distribution, an equal number of damaged or defective tires. On the other hand, the pressurization level chosen by us may be such as to degrade the subsequent fatigue life of the "B" tires by virtue of the large loads imposed on the tire structure. In a sense this may be visualized more clearly by reference to Figure 2, which is a plot of the percentage failure rate of a large sample of tires of this size against the median burst pressure of the population, plotted from data taken earlier this year. It should be emphasized that Figure 2 contains one piece of data from tires which are identical mates of each of the pairs of "B" and "C" tires. This was accomplished by collecting tires in sets of three, and using one of them for the burst tests whose results are collected in Figure 2. In addition, Figure 2 contains further data from single tires of this size, but this data does not significantly change the median burst pressure or the shape of the failure curve.

It is anticipated that the pressurization level chosen will be somewhere in the range of 70% to 80% of mean burst pressure as shown in Figure 2. For this reason the possiblity for structural damage clearly exists.

The various experimental designs which are possible will now be discussed and criticized in terms of the amount of information which can be gotten from them.

1. Direct Paired Comparison Test

This was the experiment planned originally when the work began, and consists of selecting a single pressurization level for the entire group of 65 "B" population tires. Each of these would be pressurized to that level, for example 80% of mean burst pressure or approximately 170 psi, following which both "B" and "C" groups would be recapped and tested. In the process of pressurization it would be anticipated from Figure 2 that approximately 15% of the "B" group would be lost, or about 9 tires. Working on the assumption that the corresponding mates of these tires in the "C" group would also be culled out, one would be left with approximately 55 pairs of tires which could be tested directly for their subsequent life after recapping. In this experiment, the "sign test" could be used directly to ascertain whether the "B" group was statistically better or worse than the "C" group. On the other hand, one would be forced to accept the hypothesis that the two groups were statistically the same if no major changes from randomness occurred in the resulting comparisons of "B" vs. "C" pairs of tires.

Since the field testing program is lengthy and expensive, there is little chance that it could be repeated. Therefore this approximately 55 pairs of tires represents our only effort to select the proper pressurization level and to determine its influence on subsequent tire life. This is the great weakness in this experimental design, because it is not possible to do anything other than guess at the correct pressurization level which simultaneously culls out bad tires and yet at the same time does not degrade the subsequent strength of good tires. For this reason this experiment may be considered as something in the nature of a "all or nothing" experiment. If the guess for the pressurization level is done well, it will result in no degradation of future life of the "B" tires, and may actually improve the life of the "B" group compared to the "C" group. On the other hand if the pressurization level is poorly chosen then there will be no second chance to do it again, and the process will be considered a failure. This seems to be too great a risk to take.

2. Direct Statistical Measures of Life

A completely different experimental procedure is suggested by considering the two populations ("B" being the pressurized tires and "C" being the control tires) as two separate and distinct groups. The process in this experiment consists of taking the 55 or so "B" tires and the 65 "C" tires and simply testing them in the same type of experiment, as closely controlled as possible, such as the MVSS 109 test. Again a single pressurization level would be chosen for the "B" group. We may then compare the mean and standard deviation of the life of the pressurized or "B" group with the mean and standard deviation of the life of the unpressurized or "C" group. This will give strong statistical evidence concerning the influence of pressurization level on the subsequent fatigue lives of the two samples. Again we are faced with the problem of choosing the proper pressurization level. Since presumably a single pressurization level would be chosen, then we have exactly the same dilemma as in the paired comparison experiment described under No. 1 above. If the pressurization level is chosen too high we may degrade the subsequent fatigue life of the remaining "B" tires, while of course culling out some of the bad ones. If the pressurization level is too low we may not cull out anything and subsequently do essentially no good, while at the same time doing no harm. Again the choice of the pressurization level is critical and since the testing is an expensive and lengthy process there is only one chance to do this. Again the risk of choosing the wrong pressurization level appears so great that other test processes should be explored.

3. Direct Comparison of Sample Lives Under Multiple Pressurization Levels

Modification on the second experimental design consists of breaking the 65 pairs of tires up into smaller groups and choosing a different pressurization level for each of the groups. This has some advantages since it tends to increase the likelihood of finding a favorable pressurization level, although at the same time reducing statistical confidence in the experiment since the number of tires become smaller in each group. This type of experiment might be visualized as given in Tables 3 and 4. In Table 3 the types of tires in the "B" and "C" populations are listed, while in Table 4 suggested experimental blocks are presented for splitting the experiment into three separate parts. Each part would be subjected to a different pressurization segment of the various types of tires. At the pressurization levels listed, various fractions of the samples would be lost during pressurization and the remaining numbers of tires, predicted on a statistical basis, are presented in the last column. It is seen that after pressurization we could anticipate between 16 and 20 pairs of tires in each of the three blocks.

TABLE 3.-TIRE TYPES AND QUANTITIES
EACH UNIT IS ONE MATCHED PAIR

Bias 2-PLY	Bias 4-PLY	Bias BELT	Radial
7	9	37	12

TABLE 4.-SUGGESTED DECOMPOSITION OF TIRE GROUP
AND PRESSURIZATION LEVELS

	Bias 2-PLY	Bias 4-PLY	Bias Belt	Radial	Pressurization Level, % Mean	Anticipated Number Remaining
Group 1	2	3	12	4	70%	20
Group 2	2	3	12	4	80%	18
Group 3	3	3	13	4	90%	16

Subsequent to this, testing could be carried out in the normal way and the resulting comparisons of pairs could be made, as well as could comparisons of mean lives and their standard deviations. This should give a measure of the relative efficiency of the three pressurization levels, since the numbers of test samples in each of the blocks is large enough to be statistically significant.

One of the criticisms of this type of experiment is that each block contains a very small number of certain types of tires, for example two-ply bias tires and radial tires. For this reason if an inordinate number of either of them are lost in the pressurization process then the block in question contains very little true information concerning that particular type of tire in subsequent testing. For this reason this experiment tends to be somewhat weak.

In general this experiment lends itself both to analysis by means of a paired sign test and analysis by means of the mean lives of the "C" vs. the "B" group. Both types of information could be gained from it.

While it is felt that this test design is somewhat stronger than either of those listed in 1 or 2 above, it still suffers from the shortcoming of very small amounts of information about certain types of tires.

4. Binominal Paired Sequential Test

In this type of test design we attempt to utilize the power of a sequential experiment in order to make a decision concerning the proper level of pressurization with the smallest number of test samples. While the details of this type of test require a considerable amount of time to work out, its basic format follows the concept that strong degradation of the pressurized tires in group "B" compared with the control group "C" will immediately manifest itself in the first few sample results. For example, if five pairs of tires are compared on a life test and it is found in all five cases that the pressurized tire fails earlier than the control tire, then one would immediately conclude from statistical analysis that the probability is very high that damage to subsequent life is being done at that particular pressurization level. This will allow us to drop the pressurization level to a lower value and continue with another small sample of tires. By this process it should be possible to find the pressurization level for the "B" tires which results in negligible damage to subsequent fatigue life using the minimum number of test samples. There should be no particular reason why this could not be done since the tires may be pressurized in small groups and sent out for retreading as they are pressurized.

One possible shortcoming of this experiment is that the recapping process may change during the intervals between test samples. While this is admittedly true, it is felt that this can be overcome readily by retaining the paired nature of this experiment, and always treating pairs of tires together and comparing their subsequent fatigue life on a sign test basis, as opposed to a quantitative life basis. This would allow the quality of retreading to be a variable in the overall experiment as long as it was the same for each pair of tires. Similarly, such a process would also allow the tires to be tested either on the MVSS 109 test or on the highway without loss of experimental validity.

A number of standard sequential analysis test designs have been prepared for paired comparison tests. For example, one of these is given in Figure 10 on the basis of a total test sample of 14 pairs and assuming that on the whole 80% or more of the test tires will be damaged by unduly high pressurization. It may be seen that in the most fortunate circumstances one may reach a decision concerning this hypothesis after 6, 7, or 8 samples have been tested.

Assuming that this test plan is followed, it should be possible to search out the optimum pressurization level using something of the order of 25 to 30 test pairs. This should allow us to locate that pressurization level which seems to be the largest tolerable and yet which does not result in subsequent damage to the treated population.

Following this determination of optimum pressurization level, approximately 25 to 30 pairs of tires should be available to act as a population out of which the "B" group which could be then proof tested under this pressurization level, both groups "B" and "C" could be retreaded using the same retreading procedures, and then could be tested using the same test procedures, such as MVSS 109, for example. The comparisons of the subsequent fatigue lives of these two groups should then give a clear picture of the resulting <u>value</u> of this total overall process to a retreader. It would show clearly, for example, if there was benefit to the residual pressurized population by means of culling out the damaged tires, since if this were so the residual pressurized population would exhibit a higher mean fatigue life than the control population. This would give clear statistical evidence of the worth or value of the pressurization process in the selection of used tire carcasses, and should be valuable evidence in any subsequent use of this type of test procedure.

In view of the potentially large benefits associated with the use of a paired sequential analysis, followed by a direct comparison of subsequent lives of pressurized and control groups, we recommend that the test procedure be carried out as outlined here in design 4.

We realize that in the event it is difficult to make the decision on optimum pressure due to large random fluctuations in the data, that nevertheless we will be in no worse shape by conducting a sequential experiment than we would be had we started out directly by design to conduct an experiment such as described in design 3 above. At the best, we will gain considerable improvement and potentially will be able to demonstrate the value of the process conclusively.

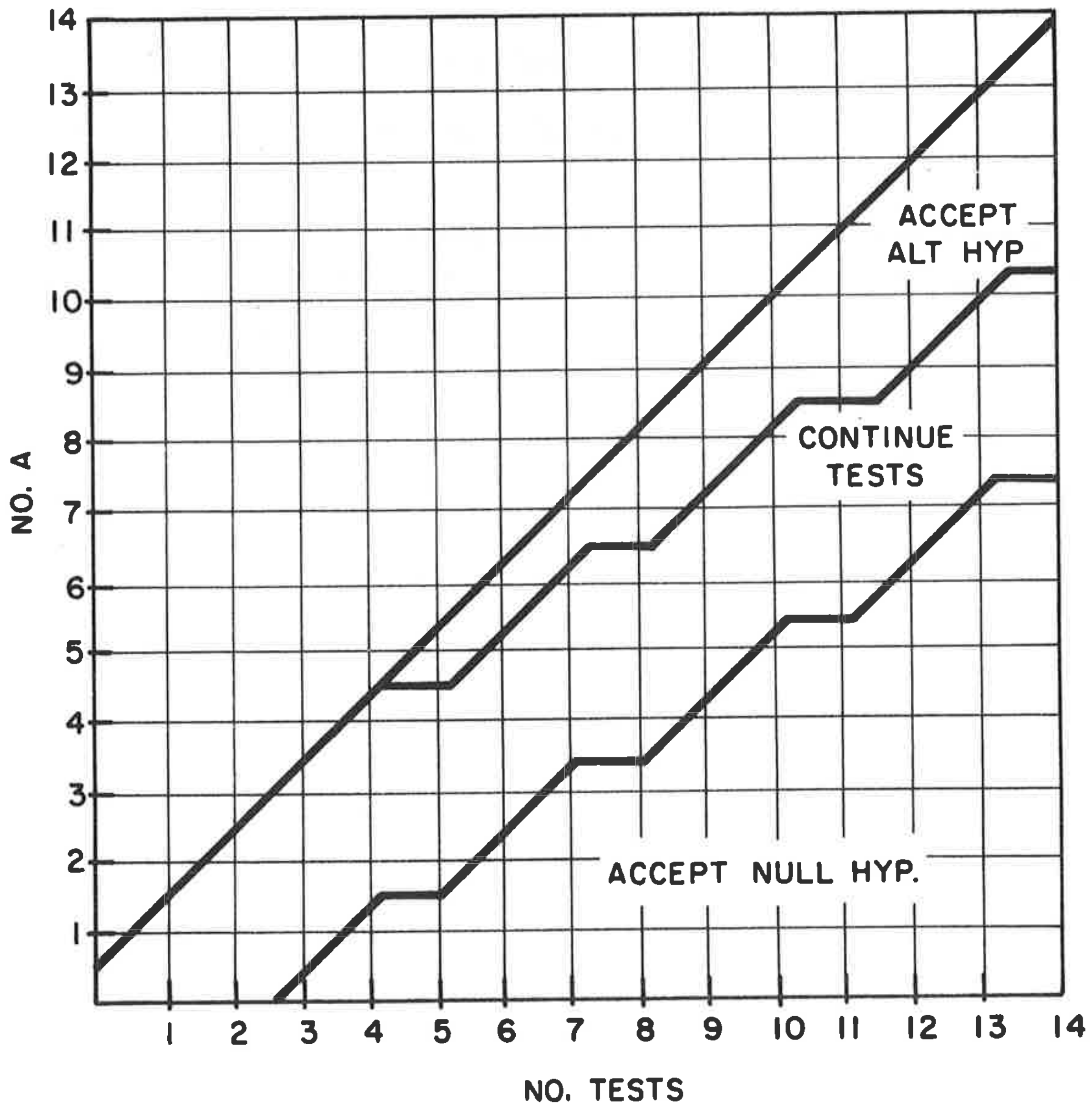

FIGURE 10. DECISION DIAGRAM FOR PAIRED COMPARISON TEST. Null hypothesis is that A = B. Alternative hypothesis is that A > B in 80 percent of tests in long run. Number of tests in which A > B is plotted against total number of tests. A particular series is shown by broken lines with arrows. Dashed lines separate decision regions based on n = 14. Solid lines separate decision regions based on sequential analysis. $\alpha = 0.09$; $\beta = 0.13$.

APPENDIX E

REPORT OF INVENTIONS

After a diligent review of the work performed under this contract, no new innovation, discovery, improvement or invention was made.