EPORT NOS. DOT-TSC-NHTSA-79-51 HS-805-030

CORRELATION BETWEEN ULTRASONIC NONDESTRUCTIVE INSPECTION AND WHEEL TEST OF 34 RETREADED TIRES

S.N. Bobo

U.S. DEPARTMENT OF TRANSPORTATION
RESEARCH AND SPECIAL PROGRAMS ADMINISTRATION
Transportation Systems Center
Cambridge MA 02142

NOVEMBER 1979

FINAL REPORT

Prepared for

U.S. DEPARTMENT OF TRANSPORTATION
NATIONAL HIGHWAY TRAFFIC SAFETY ADMINISTRATION
Office of Research and Development
Washington DC 20590

Technical Report Documentation Page

1. Report No. HS-805-030	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle CORRELATION BETWEEN ULTRASONIC NONDESTRUCTIVE INSPECTION AND WHEEL TEST OF 34 RETREADED TIRES		5. Report Date November 1979
		6. Performing Organization Code
7. Author's) S. N. Bobo		8. Performing Organization Report No. DOT-TSC-NHTSA-79-51
9. Performing Organization Name and Address U.S. Department of Transportation Research and Special Programs Administration Transportation Systems Center Cambridge MA 02142		10. Work Unit No. (TRAIS) HS 027/R0404
		11. Contract or Grant No.
12. Sponsoring Agency Name and Address U.S. Department of Transportation National Highway Traffic Safety Administration Office of Research and Development Washington DC 20590		13. Type of Report and Period Covered Interim Report Feb. 1977 - Mar. 1978
		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

This report covers a test in which 34 retread tires were inspected using reflection ultrasound nondestructive inspection, wheel tested and then subjected to failure analysis by sectioning. The results of this work demonstrate for the first time the ability of ultrasound to identify and classify defects in tires which lead to failures.

The nondestructive inspection (NDI) carried out on all 34 tires identified five tires which had major flaws, predominantly separations, and five tires with minor flaws. The wheel test was an 8-hour full-load 55 MPH test in which six of the 34 tires failed. All six failed tires were analyzed by an outside contractor and the results compared with flaw assessments made by nondestructive inspection. All six failed tires came from the ten identified by NDI as having flaws. Five of the six were tires listed as having major flaws by NDI with agreement between non-destructive inspection and failure analysis. Recommendations arising from the study are that the work be used more extensively to support NHTSA's ongoing rule enforcement activities; particularly in the area of identifying and defining separations as cited in FMVSS 109 and buff damage as cited in FMVSS 117.

17. Key Words Nondestructive Inspection Nondestructive Testing Tire Tire Inspection	18. Distribution Statement DOCUMENT IS AVAILABLE TO THE PUBLIC THROUGH THE NATIONAL TECHNICAL INFORMATION SERVICE, SPRINGFIELD VIRGINIA 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	88	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

PREFACE

This report covers the results of work performed at the Transportation Systems Center (TSC) by the author with the assistance of George Hallenborg (G&J Techniques), who performed the wheel tests, and of Robert Erlandson (FRL, An Albany International Company) who carried out the sectioning and failure analysis.

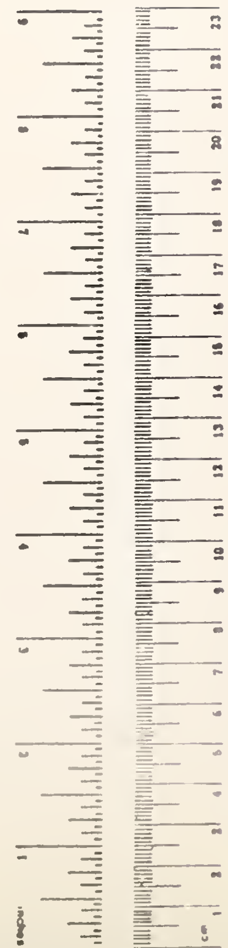
The project was directed by M.J.Lourenco, Program Director, Office of Passenger Vehicle Research, NHTSA, as part of a study in support of the enforcement activities.

The report appearing in the Appendix is reproduced by permission and was prepared by FRL, An Albany International Company under contract to the Transportation Systems Center.

METRIC CONVERSION FACTORS

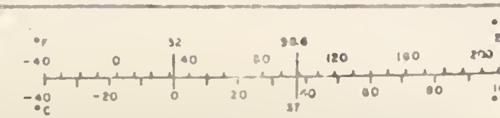
Approximate Conversions to Metric Measures

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



CONTENTS

Section		Page
1.	INTRODUCTION AND SUMMARY	1
	1.1 Introduction	1
	1.2 Summary	2
2.	TEST PROCEDURES	4
	2.1 Test Description	4
	2.1.1 General	4
	2.1.2 Tire Selection	5
	2.1.3 Retread Procedure	5
	2.1.4 Makeup Tires	6
	2.1.5 Tire Assignment for Test	6
	2.2 Inspection Procedure	10
	2.2.1 Inspection Plan	10
	2.2.2 Flaw Characteristics-General	11
	2.2.3 Separations	12
	2.2.4 Belt Breakage	12
	2.2.5 Undertread Thickness	15
	2.2.6 Overbuff and Buffline Adhesion	15
	2.2.7 Other Conditions	17
	2.3 Roadwheel Endurance Test Procedure	19
	2.4 Failure Analysis	19
3.	INSPECTION RESULTS	21
	3.1 General	21
	3.2 Satisfactory Tires	21
	3.3 Tire T5X 1161R	25
	3.4 Tire T5X 1172R	27
	3.5 Tire T5X 1183R	27
	3.6 Tire T5X 1204R	32
	3.7 Tire T5X 1223R	32
	3.8 Tire T5X 1239R	32
	3.9 Tire T5X 1245R	36
	3.10 Tire T5X 1259R	36
	3.11 Tire T6X 2084R	36
	3.12 Tire T7X 2169R	41

CONTENTS (CONT.)

Section		Page
4.	TEST RESULTS................................	43
	4.1 Wheel Test Results....................	43
	4.2 Failure Analysis Results..............	43
5.	FLAW FAILURE CORRELATION....................	45
6.	CONCLUSIONS AND RECOMMENDATIONS.............	47
	6.1 Conclusions...........................	47
	6.2 Recommendations.......................	48
APPENDIX	DEFECT CHARACTERIZATION OF A SERIES OF RE-CAPPED TIRES PREVIOUSLY WHEEL TESTED................................	A-1
GLOSSARY	....	G-1
REFERENCES	....	R-1

LIST OF ILLUSTRATIONS

Figure		Page
2-1	Buffed Interface and Belt Edge Separation T5X 1223	13
2-2	Severe Belt Breakage and Failure Area T5X 1183	14
2-3	Burnt Mold Groove Line T5X 1223	16
2-4	Sidewall Separation and Area of Poor Rubber Adhesion T5X 1161	18
3-1	Tire T5X 1717	24
3-2	Tire T5X 1161R After Retreading	26
3-3	Tire T5X 1172R	28
3-4	Tire T5X 1172R	29
3-5	Tire T5X 1183R Before Retreading	30
3-6	Tire T5X 1183R After Retreading	31
3-7	Tire T5X 1204	33
3-8	Tire T5X 1223R	34
3-9	Tire T5X 1239 Before Retreading	35
3-10	Tire T5X 1239R After Retreading	37
3-11	Tire T5X 1245R	38
3-12	Tire T5X 1259R	39
3-13	Tire T6X 2084R	40
3-14	Tire T7X 2169R	42

LIST OF TABLES

Table		Page
2-1	TIRE CHARACTERISTICS	7
3-1	TIRE ANALYSIS DATA	22
4-1	WHEEL TEST FAILURE ANALYSIS	44
5-1	FLAW FAILURE CORRELATION	45

1. INTRODUCTION AND SUMMARY

1.1 INTRODUCTION

Under the National Traffic Safety Act of 1967, the National Highway Traffic Safety Administration requires all tires sold in the United States to meet performance test standards as specified in FMVSS 109. Consequently, a need exists to screen tires for conformance as inexpensively and rapidly as possible.

Of a variety of nondestructive inspection techniques evaluated, an automated reflection ultrasonic system developed by TSC showed the most promise for revealing anomalies which may cause tire failure [Reference 1]. The objective of the work described in this report was to relate anomalies detected by nondestructive inspection to actual failures under road and laboratory tests using retread tires provided by the Tire Retreaders Institute (TRI) and the American Retreaders Association (ARA). Specific tasks were structured to:

1) Determine whether the point of initiation of failure could be predicted by ultrasound before wheel test
2) Determine whether failures during wheel test and failures during road test were caused by the same or different defects and whether these flaws were differentiable beforehand by ultrasonic inspection
3) Characterize the predominant failure modes of retreads in order to determine how these differ from new tire failures.

Retreads were chosen over new tires for this study because of indications that retreads have a higher failure rate than new tires [Reference 2].

1.2 SUMMARY

The TRI and the ARA agreed to supply 300 first-quality tire casings for the test. Of the original 200 casings actually supplied, only 51 survived retreading, requiring two additional groups of makeup tires to complete the study. The final total tire population was 109 tires composed of 20 percent radial and 40 percent bias and 40 percent belted. They were first inspected by reflection ultrasound and augmented by other nondestructive inspection techniques. Thirty-four tires were then subjected to wheel test and the balance were reserved for road test. This report covers only the 34 wheel-tested tires and will supplement a contractor final report describing the road test study.

Included in this report is a description of the retread procedure, the method of tire selection and allocation, the inspection procedure and a description of the type and character of the anomalies detected during the inspection.

The nondestructive inspection (NDI) carried out on all 34 tires identified five tires which had defects that could be considered severe, predominantly separations, and five tires with minor flaws. The wheel test was an eight hour, full-load, 55 miles per hour test in which six of the 34 tires failed.

All six failed tires were analyzed by an outside contractor and the results correlated with flaw assessment made by non-destructive inspection. All six failed tires were from the group identified by NDI as having flaws. There was agreement in five of the six cases between the location of failure cited by NDI and the location judged by failure analysis to be the site of the initiation of failure.

Recommendations arising from this study are that the ultrasonic nondestructive inspection techniques be used more extensively to support NHTSA's ongoing rule enforcement activities, particularly in the identification and definition of cord separations as cited in FMVSS 109 and buff damage as cited in FMVSS 117.

2. TEST PROCEDURES

2.1 TEST DESCRIPTION

2.1.1 General

The study consisted of the following:

1. Procurement of a large number of tire casings and inspection of these casings using presently available nondestructive inspection technology, specifically reflection ultrasound.
2. Selection and retreading of casings. The majority of casings were to be perfect; however, some casings passed by retreader inspection procedures but known to have separations as detected by ultrasound, were left in the population to demonstrate the ability of ultrasound to detect this condition. These defective tires were evenly distributed throughout the population of tires.
3. Reinspection. Tires were reinspected after retreading to determine whether the retreading process had introduced additional anomalies which could be detected ultrasonically.
4. Separation of the retreaded tires into two groups. One group was assigned to the wheel test and one to the road test with proportional numbers of defective tires in each group.
5. Actual tests.

6. Reinspection of the tires by sectioning and analysis of tires.
7. Examination, analysis and comparison of the results of NDI inspection with failure assessment.

2.1.2 Tire Selection

Tires to be used in this test were to be made from the best available casings using the best retread practices. The American Retreaders Association was to provide 150 bias and belted casings, all of the same G78-15 size, and the Tire Retreaders Institute, a division of the National Tire Dealers and Retreaders Association, was to provide a similar number of radial casings. In practice, three molds and tread patterns with the same groove depth were used.

2.1.3 Retread Procedure

When a population of tires is retreaded, the casings come from a variety of manufacturers and represent diverse construction methods. Of a population of "select" casings, only about 30 percent ever become saleable retreads. Not only is the construction nonuniform, but the size of the tires covers a wide range. To obtain uniformity, the tire is measured or "sized" after the buffing operation in which the remaining tread is removed from the tire preparatory to adding new rubber. The tire is then assigned a mold in the production line; and, as it sometimes happens, a tire of a different size, an "F" or "H" for example, will fit a "G" mold after it is buffed. The retread procedures for radial and bias tires are also different. For this program, the final population represented three separate construction procedures and three separate tread designs: 1) Bias and belted hot-cap or standard procedure, 2) Radial hot-cap or standard procedure, and 3) Radial precure procedure.

Retread quality varies greatly between manufacturers and depends heavily upon the quality of the casing and the ability of the inspector to detect casing defects. The tires provided in this study were to be of the highest quality. The assumption during this study, therefore, was that the tires received represented the industry standard as set forth by the TRI and the ARA.

2.1.4 Makeup Tires

Of over 300 hundred casings originally selected for retreading, only 51 were acceptable for the road and wheel tests. Two additional lots of 30 makeup tires were added to the 51 retreads. Some of the tires shipped to the road test site in Nevada[3] were considered non-roadworthy, thus requiring a supplemental shipment of 28 replacement tires.

2.1.5 Tire Assignment for Test

The tires inspected were apportioned to road test and to wheel test on the basis of approximately two tires for the road test to one for the wheel test. Final tire assignment for wheel testing is shown in Table 2-1.

TABLE 2-1. TIRE CHARACTERISTICS

SERIAL NO.	NEW TIRE SIZE	RETREAD SIZE	CASING CONSTRUCTION	RETREAD METHOD	ORIGINAL MANUF.	ORIGINAL SERIAL#	PASSED* OR FAILED	RETREAD SERIAL	
T5X 1136R	625-15		4 NYL	HOTCAP BIAS	PENN TNPK 200	WKN9 BCA 521	P		1
T5X 1140R	825-15		4 NYL	HOTCAP BIAS	ZENITH JET AGE 300	VXN9 9EJ	P		2
T5X 1161R	825-15	G78-15	4 RAY	HOTCAP BIAS	ATLAS PLYCRON UNIROYAL	DOT 127 02027	F	RBHDAN 296	3
T5X 1165R	G78-15		2 PY 2 GL	HOT BIAS BELTED	GOODYEAR	CDND K9DB	P		4
T5X 1172R	G78-15		2 PY 2 GL	HOT BIAS BELTED	ATLAS PACE SETTER	PLVV A24182	P		5
T5X 1183R	G78-15	G78-15	2 PY + 2 FG	HOTCAP BIAS	UNIROYAL FASTRAK	AKVV 000133	F	RBHDAN 286	6
T5X 1191R	G78-15		2 PY 2 GL	HOT BIAS BELTED	GOODYEAR	MBVV LUA 472	P		7
T5X 1204R	G78-15	G78-15	2 PY + 2 FG	HOTCAP BIAS	FIRESTONE SUP-R-BELT	VJVV DD4013	F	RBHDAN 306	8
T5X 1210R	G78-15		2 RAY 2 RAY	HOT BIAS BELTED	FIRESTONE SUP-R-BELT	VJVV DDD461	P		9
T5X 1213R	G78-15		2 PY 2 GL	HOT BIAS BELTED	FIRESTONE	000SL 975	P		10
T5X 1219R	G78-15		2 PY 2 GL	HOT BIAS BELTED	FISK SAFETY CLASSIC	ASVV FACD85	P		11
T5X T5X 1223R	G78-15	G78-15	2 RAY + 2 RAY	HOTCAP BIAS	FIRESTONE SUP-R-BELT	VFVV DDD402	F	RBHDAN 306	12
T5X 1235R	215-15		2 ST 2 RAY	RADIAL PRECURE	SEARS	HDTU A2 8182	P		13

*Failed is defined as having an audible noise or losing structural integrity at any point in the wheel test. At this point the tire is removed from the test.

TABLE 2-1. TIRE CHARACTERISTICS (Cont.)

SERIAL NO.	NEW SIZE	RETREAD SIZE	CASING CONSTRUCTION	RETREAD METHOD	ORIGINAL MANUF.	ORIGINAL SERIAL#	PASSED OR FAILED	RETREAD SERIAL	
T5X 1239R	215-15		2 ST 2 RAY	RADIAL PRECURE	SEARS	HDTU	P		14
T5X 1242R	215-15		2 ST 2 RAY	RADIAL PRECURE	SEARS	HDTU	P		15
T5X 1245R	215-15		2 ST 2 RAY	RADIAL PRECURE	SEARS	HDTU	P		16
T5X 1259R	205-15		2 ST 2 RAY	RADIAL HOT	MICHELIN	HATP A2NX 213	P		17
T5X 1262R	205-15		2 RAY	RADIAL HOT	MICHELIN	HATP A2NX 432	P		18
T5X 1264R	205-15		2 RAY	RADIAL HOT	MICHELIN	HATP A2NX 213	P		19
T5X 1703R	215-15		2 ST 2 RAY	RADIAL HOT	SEARS	FNTN A2PH 113	P		20
T5X 1709R	215-15		2 RAY	RADIAL PRECURE	SEARS	HDTU A2P 8163	P		21
T5X 1716R	215-15		2 RAY	RADIAL PRECURE	SEARS	FTTU A2P 9463	P		22
T5X 1717R	215-15		2 RAY	RADIAL PRECURE	SEARS	FNTU A2P H473	P		23
T5X 1724R	215-15		2 RAY	RADIAL PRECURE	SEARS	FTTU A2P 9034	P		24
T5X 1737R	215-15		2 RAY	RADIAL PRECURE	SEARS	FTTU A2P 9104	P		25
T6X 2044R	215-14		2 RAY 2 ST	RADIAL HOT	MICHELIN	FJKC A2NX493	P		26
T6X 2046R	205-15		2 RAY 2 ST	RADIAL HOT	MICHELIN	HLYO 73188	P		27

TABLE 2-1. TIRE CHARACTERISTICS (Cont.)

SERIAL NO.	NEW SIZE	RETREAD SIZE	CASING CONSTRUCTION	RETREAD METHOD	ORIGINAL MANUF.	ORIGINAL SERIAL#	PASSED OR FAILED	RETREAD SERIAL	
T6X 2049R	GR78-15		2 PY 2 ST	RADIAL HOT	COOPER	UPFW HDP304	P		28
T6X 2053R	GR78-15		2 PY 2 ST	RADIAL HOT	COOPER	UTVW F8N115	P		29
T6X 2054R	HR78-15		2 PY 2 ST	RADIAL HOT	COOPER	UTVY F8P154	P		30
T6X 2057R	LR78-15		2 PY 2 ST	RADIAL HOT	COOPER	UTVU HDY234	P		31
T6X 2060R	HR78-15		2 RAY 2 ST	RADIAL PRECURE	GENERAL DUAL	ACVY W5B093	P		32
T6X 2084R	G78-15	G78-15	4 PY	HOTCAP BIAS	KS EXPLOR. 78	PKVW KBE242	F	RBHDAN 316	33
T6X 2172R	G78-15	G78-15	2 PY + 2 FG	HOTCAP BIAS	FIRESTONE SUP-R-BELT	VFVV DD 1013	F	RBHDAN	34

FG = Fiberglass
GL = Glass
NYL = Nylon
PY = Polyester
RAY = Rayon
ST = Steel
+ = Plus

2.2 INSPECTION PROCEDURE

2.2.1 Inspection Plan

The inspection plan called for use of the best procedures available to find potential problems with the tires. Liquid-coupled reflection ultrasound was employed as a baseline technique for determining dimension variances, flaw location and severity and other anomalous conditions. The following supplementary methods were used to augment the findings of reflection ultrasound:

1. Holography as a corroborative technique to liquid-coupled ultrasound.
2. Air-coupled transmission ultrasound to determine the feasibility of the technique for low cost flaw identification.
3. X-rays to find builders' flaws such as belt placement and as a confirmatory method for the detection of inclusions such as buffing dust, broken belts and areas of missing plies due to overbuffing. The use of X-rays in this work was minimal.

These inspection techniques are described in detail in References 1, 2 and 3.

The inspection procedure called for a preliminary inspection of unretreaded casings, after which the tires were sent away for retreading. Upon return from retreading, the tires were then reinspected and shipped to Nevada for road test. Data from the earlier reflection ultrasound inspections were of much poorer quality than those from subsequent inspections because of equipment limitations. However, these data have been included in Section 3 as a comparison.

2.2.2 Flaw Characteristics-General

Defects leading to failure of retread tires generally tend to be more obvious than defects in new tires. They fall into three categories:

1) Defects created within the carcass during its first service life such as separations, puncture damage and broken belts.
2) Changes in tire dynamics because of inappropriate mold design producing such anomalies as heavy shoulders in radial tires.
3) Defects introduced during retreading such as asymmetrical application of tread rubber, poor tread adhesion from improper buffing or cementing procedures, mold hotspots or improper cure pressure.

In contrast, defects in new tires tend to be more subtle and fall into two categories:

1) Design defects such as improper cord angle or improper compounding.
2) Builders' defects such as off-center belts, poor splices or inclusions.

It is difficult by analyzing defects in retreads to infer the relationship between those found in new tires and those in retreads. However, if sufficient latitude is assumed in the flaw description, certain defects of different basic nature but similar in generic classification appear in both new tires and retreads. To this extent some commonality may be postulated in flaw characterization of new and retread tires. Two examples of this are separations and broken belts. The following subsections contain a discussion of the flaw characteristics that have been identified using the available inspection methods.

2.2.3 Separations

It is commonly accepted that separations above one-half inch in size, if located at critical sites, will eventually cause failure of a tire. This criterion seems to be true whether the tire is new or retreaded. The rate of degradation of a tire with a separation is highly dependent on the location of the separation and appears to be different for new and retread tires. It is generally thought that belt edge separation is one of the most common and destructive causes of tire failure. These separations seem to occur in most radial tires after a period of service but, if the tire is properly built, they remain small and only achieve accelerated growth toward the end of wear-out. However, for retreaded radial tires, belt edge separations appear to be the principal cause of failure. A typical example of this is shown in Figure 2-1.

2.2.4 Belt Breakage

Belt breakage, shown in Figure 2-2, is far more prevalent in retreads than in new tires. Although new green tires are sometimes "trapped" in a mold in such a way that the expanding

FIGURE 2-1. BUFFED INTERFACE AND BELT EDGE SEPARATION T5X 1223

FIGURE 2-2. SEVERE BELT BREAKAGE AND FAILURE AREA T5X 1183

mold bag will break the belt during curing, this is a rare phenomenon. Belt breakage usually occurs either as a result of marginal design practice on early glass belted tires, or by abuse or road hazard damage during the service life of the tire.

2.2.5 Undertread Thickness

A principal cause of the early failure of retreads and a problem in new tire manufacture is the amount of tread thickness between the groove bottom and the outer ply of the belt. Figure 2-3 is a picture of the condition as found in one of the tires in this study. The groove bottom is nearly in contact with the outside belt and the result is a burned groove bottom and a failed tire.

2.2.6 Overbuff and Buffline Adhesion

One of the rigorous requirements of Federal Motor Vehicle Safety Standard 117 for retread tires is that the retreader observe certain rules about buffing into the ply or belt structure of tires. An earlier study provides a description of the use of ultrasonics in inspecting casings for this condition [Reference 4]. It describes the character of the faying surface as detected by ultrasonics when the cord structure has been damaged. Essentially, if a nap has been raised on the material by a buffing rasp, the surface looks very much like a separation and adhesion values are little better than those in a separation area. Although there is inadequate data on

FIGURE 2-3. BURNT MOLD GROOVE LINE T5X 1223

the relationship between overbuffing and failure, modern retread practice considers overbuff a harmful condition. Figure 2-4 is a clear representation of many of the major problems of the modern retreader. This casing selected by a casing supplier and inspected several times prior to retreading had in it an area which was in an incipient failure mode, probably from the beginning of the tire's life. Careful use had permitted the tire to run through one service life with an area of poor adhesion in the tread and sidewall. However, when the tire was subjected to the thermal wheel test, the old problem became aggravated, resulting in heat buildup and causing an adhesion failure in the buff line.

2.2.7 Other Conditions

There are other modes of failure in both retread and new tires that occur with regularity such as loss of air and bead damage. Moreover, the character of failures has changed as tires have evolved over the years; for example, flex-breaks and sidewall blowouts are seldom encountered anymore. One problem that is still with us, however, warrants discussion: bead damage. Several studies have concluded that the bead area is one of the weaker parts of the radial tire. This problem was recognized early by American manufacturers but imperfectly solved in some cases. As a result, some casings may have unsuspected problems in the bead and turnup areas. Therefore all radial casings should be carefully

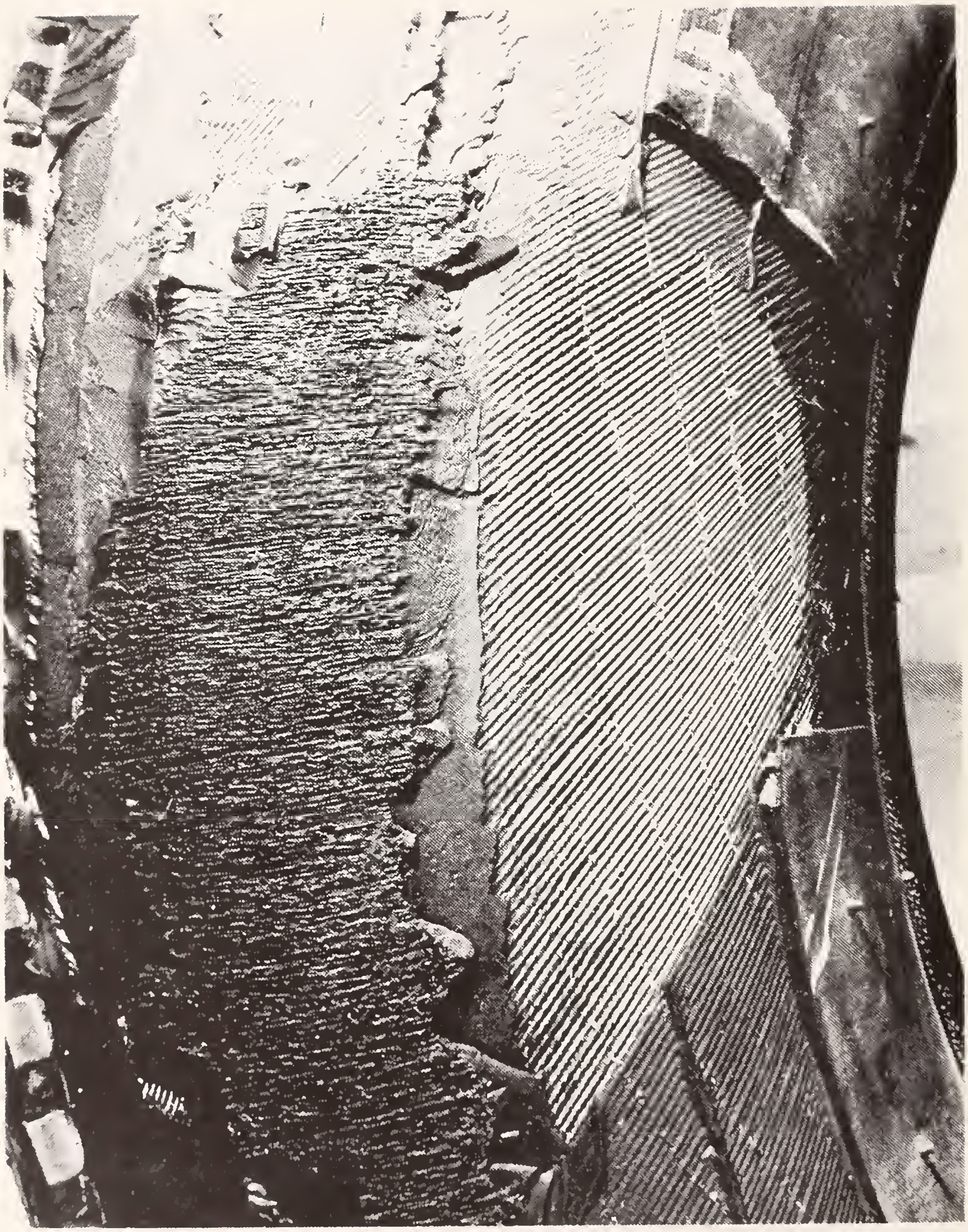


FIGURE 2-4. SIDEWALL SEPARATION AND AREA OF POOR RUBBER ADHESION T5X 1161

inspected for bead damage because, if a radial fails as a blowout, the failure will generally be accompanied by a bead break [Reference 6].

2.3 ROADWHEEL ENDURANCE TEST PROCEDURE

The test procedure adopted was a modified road wheel endurance test in which the tires were inflated to 28 psi and subjected to 100 percent load at that pressure. The tires were then run against a drum at 55 miles per hour for eight hours. The test temperature was 100°F. Two tires were run simultaneously against the standard 67.2 inch diameter road wheel and if a tire became noisy or showed erratic behavior the test was aborted, the time recorded and the tire held for failure analysis. The wheel test, because of its short duration of 440 miles, was not expected to yield a large number of failures since it was not a severe test. The objective of the test was to make it as closely similar to the planned road test as possible. While the road test was to be run at 24 psi tire inflation pressure and rated load, the wheel test was run at 28 psi to compensate for drum curvature.

2.4 FAILURE ANALYSIS

Failure analysis of the six failed tires was done by FRL Inc., an independent analysis laboratory, under contract to the Department of Transportation. The results of the non-destructive inspection were not available to the FRL analysis personnel until after the analysis was complete. On each tire the failure mode predicted by NDI was corroborated by the FRL analysis. A copy of the failure analysis report appears in the Appendix.

3. INSPECTION RESULTS

3.1 GENERAL

Table 3-1 is a summary of inspection results. Of the six tires which failed the wheel test, major separations or other damage was conclusively found in five and failure analysis confirmed the site of this damage as being the origin of failure. The specific details of these findings are given in the individual tire descriptions. Previously, reflection ultrasound found ten tires which had one or more anomalies. The following subsections describe ultrasonic traces representing good tires and analyze the ten discrepancies found.

3.2 SATISFACTORY TIRES

Figure 3-1 is an ultrasonic trace of a good tire. Additional descriptive data concerning ultrasonic inspection may be found in Reference 1 and 4, but a summary is given here to assist in understanding the means by which anomalies are identified. The tire is displayed as if cut at the serial number, opened up and laid out flat. Each channel numbered from 2 to 21 represents a cross-section cut through the tire casing from outside to liner. In each channel, outside is to the left and the liner is to the right. The channels progress from channel 2 which is near the serial side bead to channel 5 near the turnup to channels 8,11,16,18 and 21 which are, respectively, the blackwall or serial shoulder, tread center, the white sidewall shoulder, the white sidewall turnup area and close to the white sidewall bead. In vertical orientation, each channel represents one complete tire rotation, beginning at

TABLE 3-1. TIRE ANALYSIS DATA

	HOLOGRAPHY	AIR COUPLED	LIQUID COUPLED	COMMENTS
1	NO DATA	BAD SHOULDERS	NO DATA	
2	OK	PLUG $\theta=260$ $\phi=153$	OK	POOR DATA-POSSIBLE PLUG AT SITE BEFORE RETREAD
3	OK	MASEP $\theta=270$ $\phi=270$	MASEP $\theta=300$ $\phi=270$	MAJOR SEP IN SIDEWALL IN TIRE PRIOR TO RETREADING
4	OK	SCALLOPED TREAD	OK	UNIFORM ULTRASONIC TRACES-GOOD TIRE
5	SEPS AT BELT EDGE	OK	MISEP $\theta=270$ $\phi=240$	MINOR BELT EDGE SEPS SHOW UP AFTER RETREADING
6	OK	OK	MASEP $\theta=090$ $\phi=135$	SEP AT SITE OF FAILURE, EVIDENCE OF SEP PRIOR TO RETREAD, BELT BREAK AFTER RETREAD
7	NO DATA	MISEP $\theta=150$ $\phi=180$	OK	HOLOGRAPHY IDENTIFIED BELT SPLICE
8	OK	OK	MASEP $\theta=240$ OTH $\phi=140$	MAJOR SEP NEAR FAILURE SITE, IRREGULAR TREAD THICKNESS, HEAVY AT FAILURE
9	OK	BAD TIRE	DATA MISSING	
10	OK	OK	OK	
11	OK	OK	OK	
12	OK	NO DATA	MASEP $\theta=240$ $\phi=140$	ACCORDING TO ULTRASOUND, CONDITION OF BLACK SHOULDER IS POOR/ NO CORRESP. WITH FAIL. ANALYSIS
13	OK	OK	OK	
14	OK	OK	OTH $\theta=300$ $\phi=180$	ULTRASONIC SHOWS HEAVY SPLICE AREA BEFORE RETREAD: NOT PRESENT AFTERWARD
15	OK	OK	OK	POOR ULTRASONIC DATA
16	MISEP $\theta=400$ $\phi=220$	OK	OTH $\theta=210$ $\phi=180$	HEAVY SPLICE, SOME EVIDENCE OF BELT-EDGE IRREGULARITY, POOR TRACE
17	OK	OK	MISEP $\theta=190$ $\phi=170$	EVIDENCE OF BELT EDGE IRREGULARITY BOTH SIDEWALLS
18	OK	NO DATA	OK	
19	OK	OK	OK	POOR ULTRASONIC DATA
20	OK	BAD TIRE	OK	
21	OK	OK	OK	
22	OK	OK	OK	

TABLE 3-1. TIRE ANALYSIS DATA (Cont.)

	HOLOGRAPHY	AIR COUPLED	LIQUID COUPLED	COMMENTS
23	OK	OK	OK	
24	OK	OK	OK	
25	OK	OK	OK	
26	OK	OK	OK	
27	OK	OK	OK	POOR ULTRASONIC TRACE
28	OK	SEPS WW SHOUL	OTH	WIDE LINER SPLICE
29	OK	OK	OK	POOR ULTRASONIC TRACE
30	OK	OK	NO DATA	
31	OK	OK	OK	
32	OK	NO DATA	NO DATA	
33	OK	OK	MASEP Θ=090 ϕ=240	SEP CORRELATES WITH FAILURE OVERBUFF SPLICE AT Θ=300 ϕ=090
34	NO DATA	NO DATA	OTH Θ=330 ϕ=180	INSUFFICIENT TREAD RUBBER AT SITE OF FAILURE

MAJOR SEPS = MASEP
MINOR SEPS = MISEP
BELT BREAKS = BX
OVERBUFF = OVB

OTHER LISTED OTH
1 RUNOUT
2 INCLUSIONS
3 HEAVY SPLICE
4 SPLICE GAP
5 OTHER

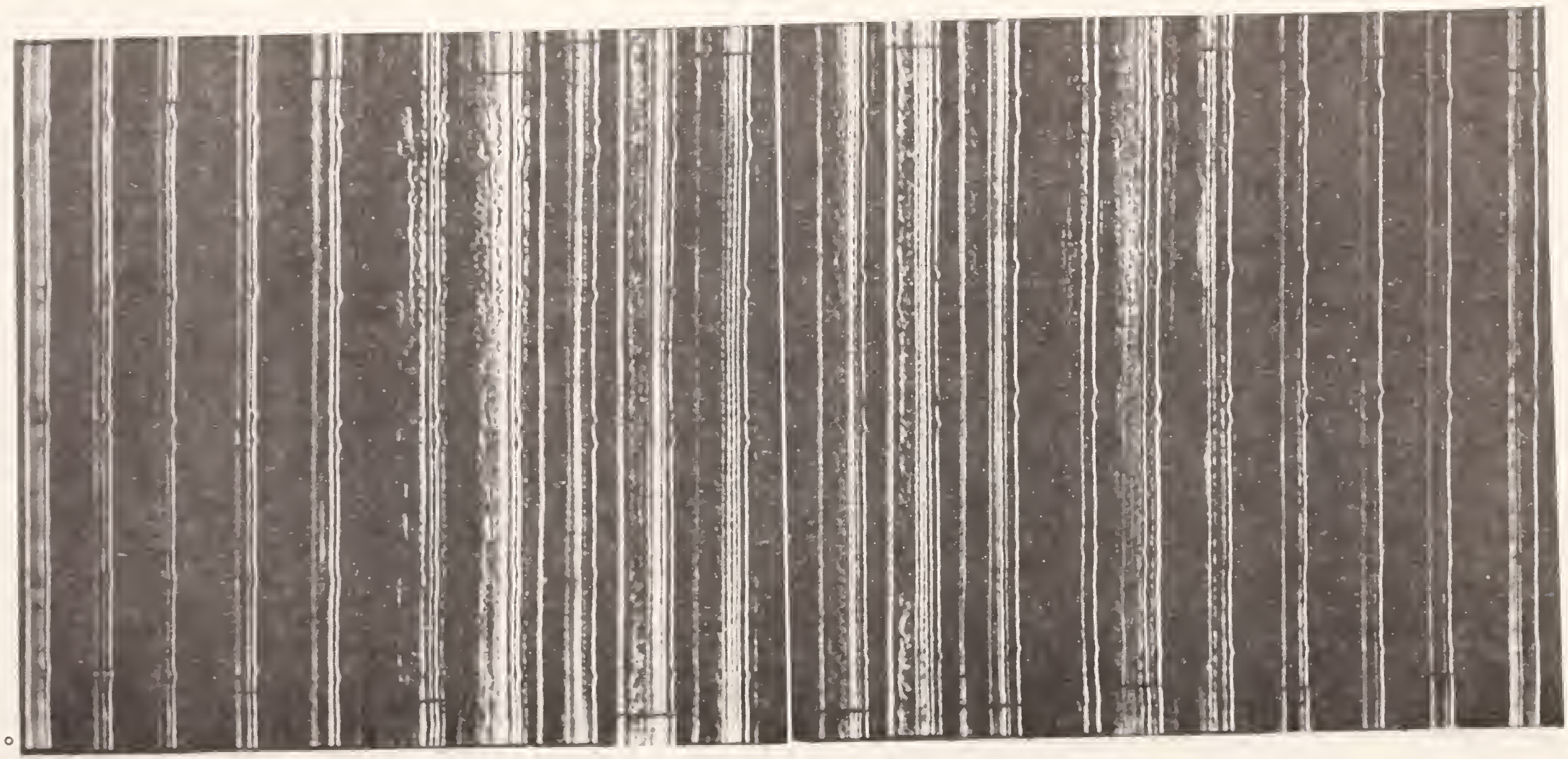


FIGURE 3-1. TIRE T5X 1717

the serial number and going clockwise, looking at the serial side. In this text, references to Θ describe rotational position and references to ϕ describe location on the tire surface. Channels 2 through 6 and 18 through 21 are dimensionally thinner than channels 7 through 17 as the latter are in the heavier tread area. Vertical lines in each channel are approximately representative of the lamina within the tire. Channel 11, the left most vertical white line, represents the tread surface at the approximate tread center of the tire. The blurred system of dots and dark area immediately to the right is modulation caused by grooves within the tire and the next line interrupted by 15 gaps is the groove bottom. In this case the 15 gaps are tread wear indicators although a pattern of six or eight is more common. Still further to the right in channel 11, the solid white vertical stripes represent the ply structure and the last white line is the liner surface of the tire. There are several systems of bumps which appear in all channels across the tire. These are splices. They are diagonal if the tire is bias ply and horizontal if the tire is radial (Figure 3-1). Successive paragraphs will point out the anomalies found in this set of tires using the conventions established here.

3.3 TIRE T5X 1161R

Figure 3-2 is a trace of this tire. The enclosed rectangle shows evidence of a massive separation in an otherwise fairly uniform tire. The separation is accompanied by some dimensional deformation as well as a shadow indicating a high reflection

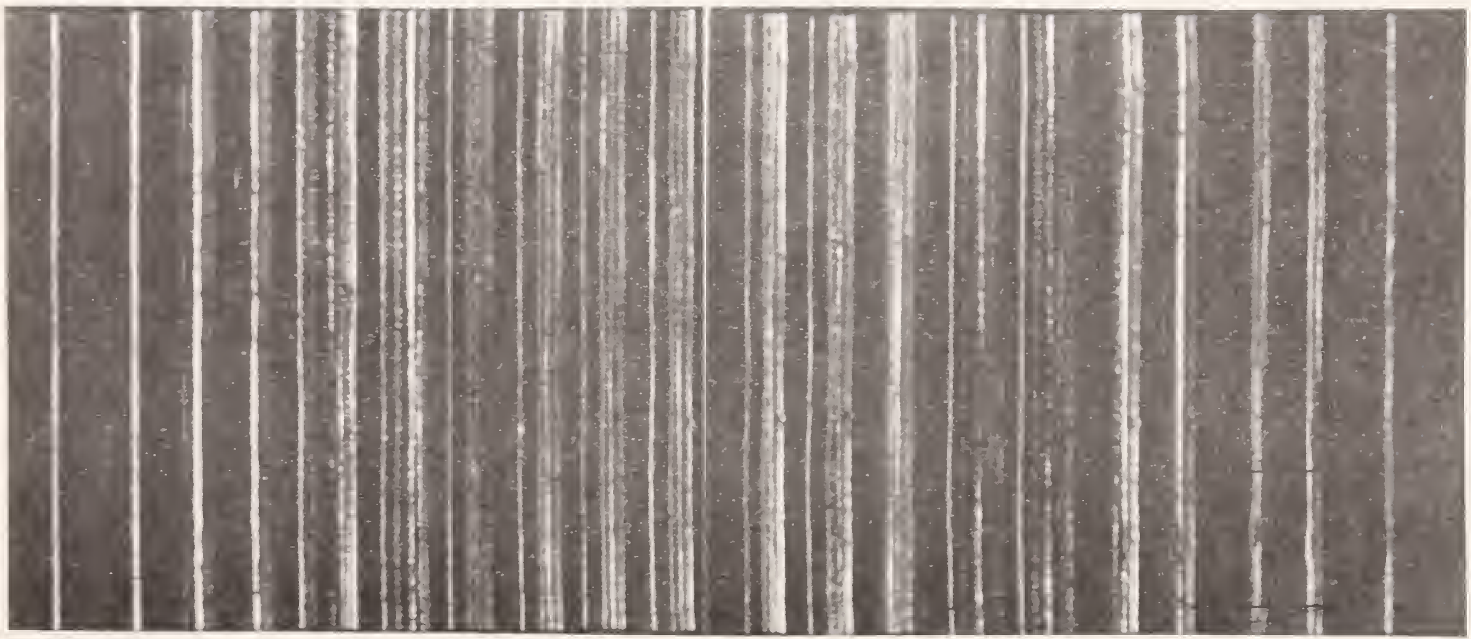


FIGURE 3-2. TIRE T5X 1161R AFTER RETREADING

directly under the surface and no sound travelling through the ply structure at greater depths. Additional shadows appear in channel 20 at Θ=200 to 210. This is indicative of poor laminar integrity.

3.4 TIRE T5X 1172R

Although this tire passed the wheel test, Figure 3-3 shows evidence of some abuse in the white sidewall shoulder. Channel 17 (trace in rectangle) is indicative of belt edge separation. The anomalies in channel 7 are generally caused by bagmarks in the liner and are not considered abnormal. The anomaly in Channel 9 would have been considered if it did not look so much like those in channel 7. Inspection of the tire showed nothing that would account for these conditions.

Figure 3-4 is an earlier trace showing problems in the same area prior to retreading. Quality of these traces is poor as they were made prior to improvements in the ultrasonic equipment which greatly enhanced display quality. However, all of the information is present in these earlier traces.

3.5 TIRE T5X 1183R

This tire failed as a result of a separation in the black sidewall shoulder. The rectangle in Figure 3-5 blocks out a separation in a scan prior to the retreading of the tire. A much smaller but more clearly defined spot is apparent after retreading in Figure 3-6.

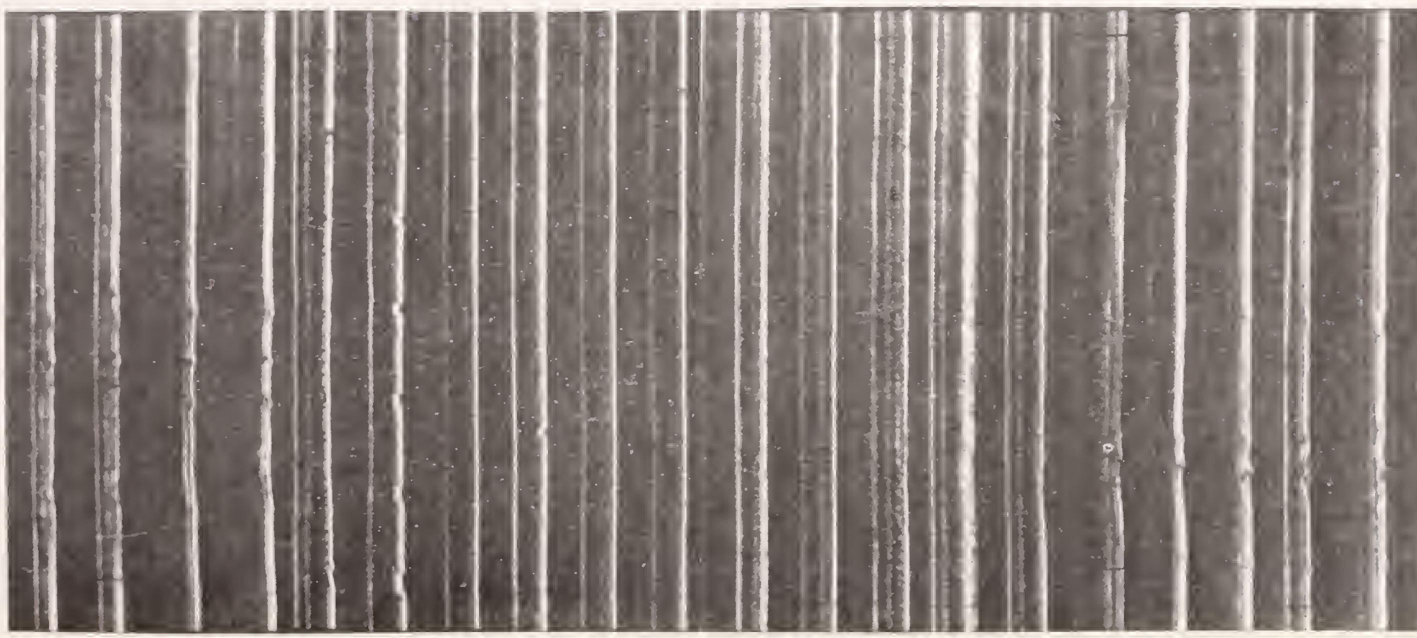


FIGURE 3-3. TIRE T5X 1172R

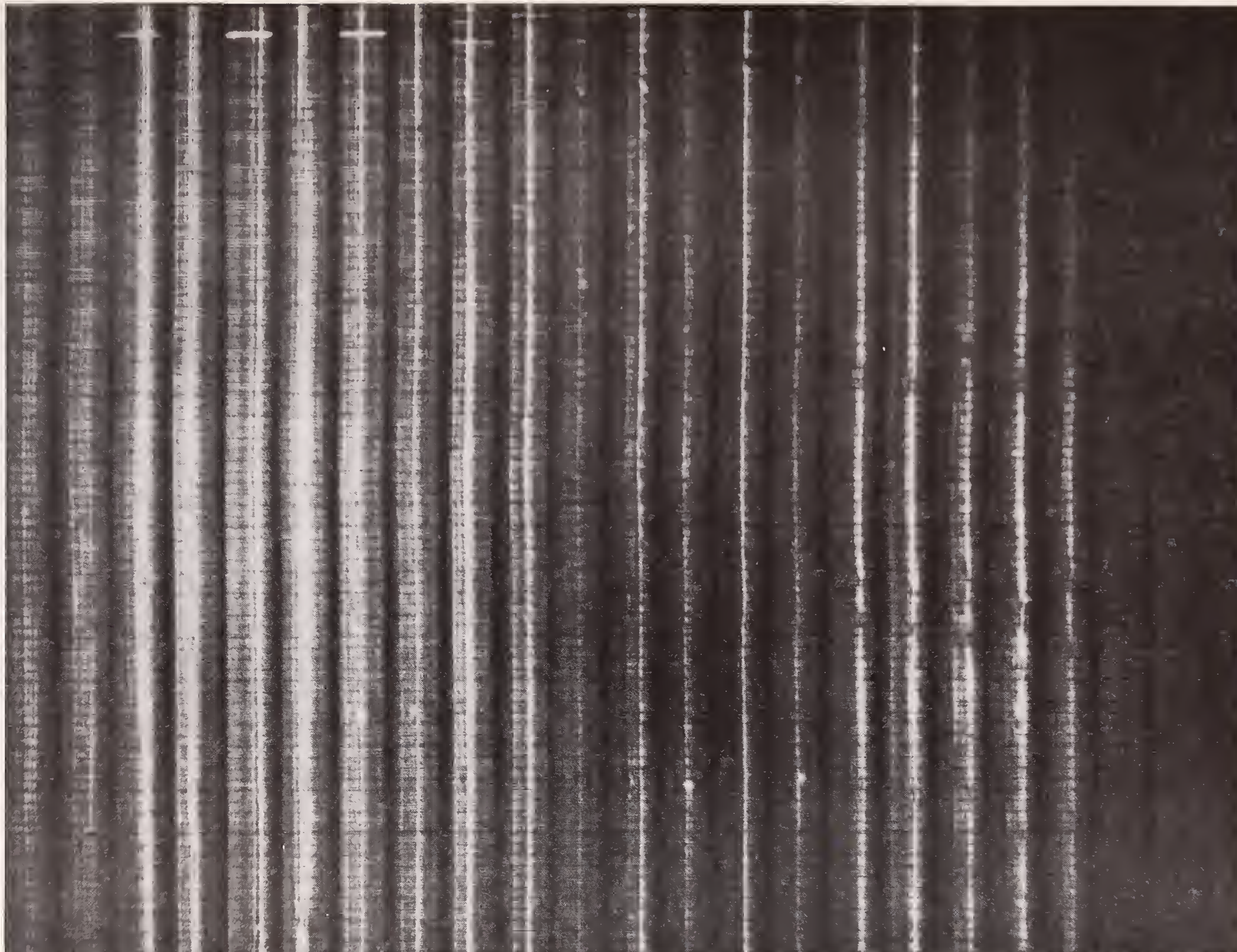


FIGURE 3-4. TIRE T5X 1172R

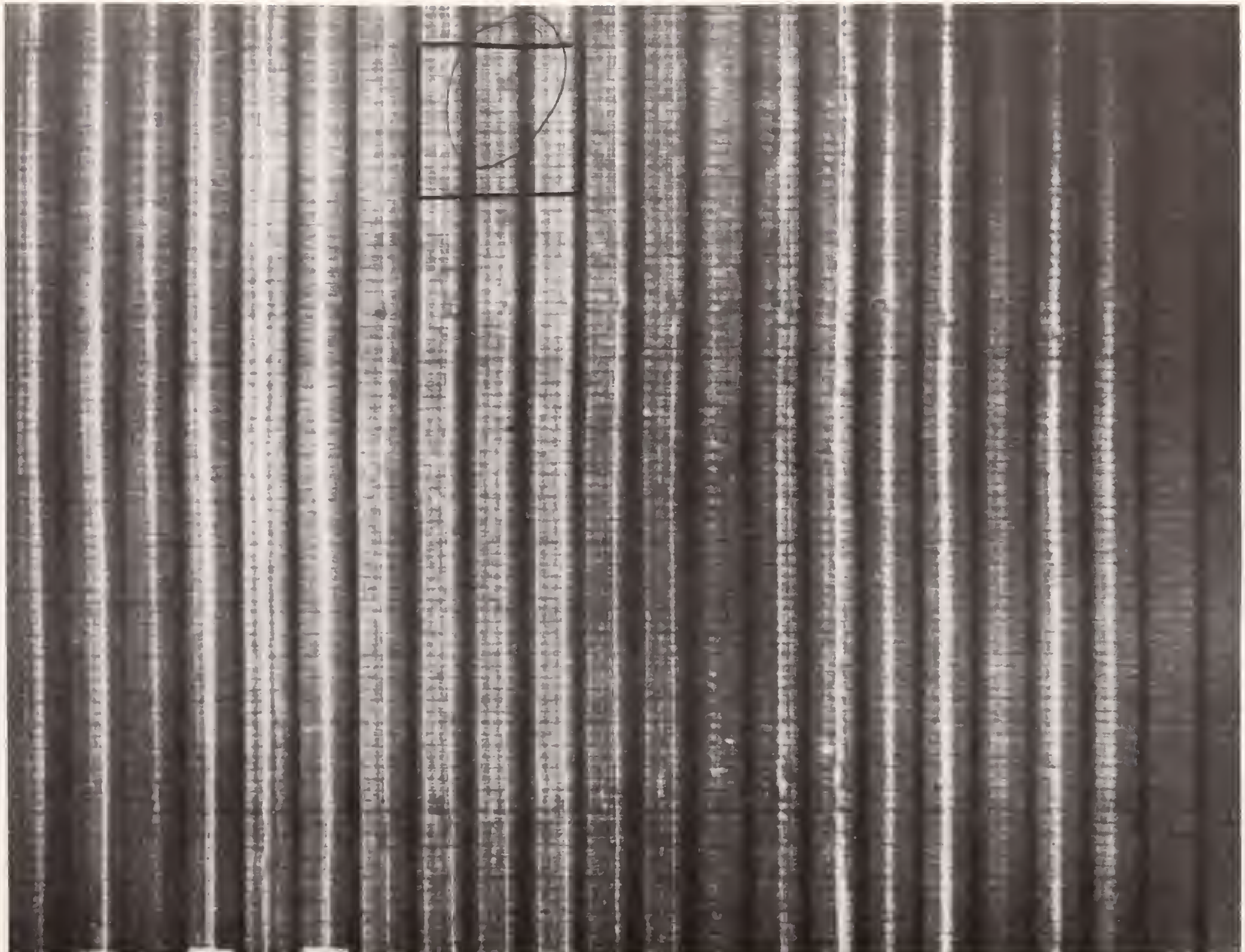


FIGURE 3-5. TIRE T5X 1183R BEFORE RETREADING

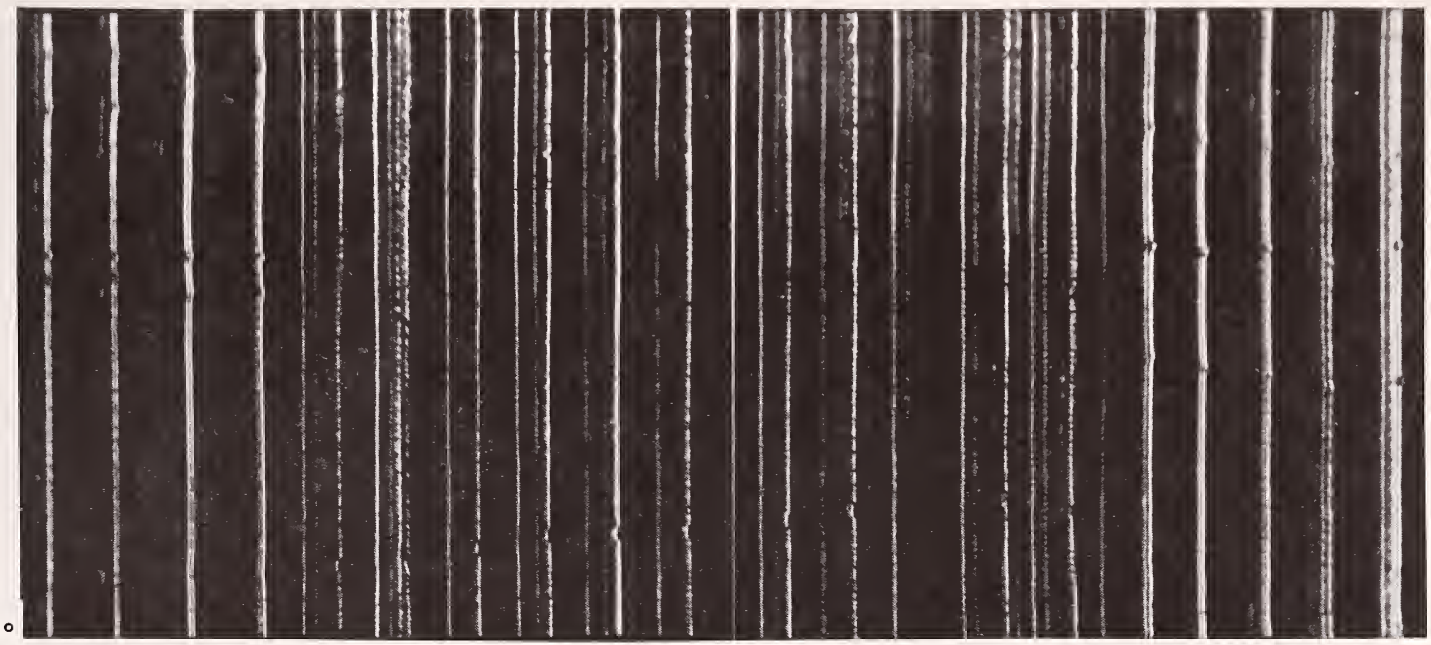


FIGURE 3-6. TIRE T5X 1183R AFTER RETREADING

3.6 TIRE T5X 1204R

If any of the vertical lines in an ultrasonic trace are not straight, they define runout of the tire in some form. Figure 3-7 is an example of this. The distance of tread surface reflection as measured from the liner reflection is proportional to the thickness of the tire at the point of measurement. This value varies as much as 20 percent in this tire. The tire would therefore be particularly difficult to balance. But the cause of failure in this tire is the separation shown in channel 8.

3.7 TIRE T5X 1223R

Figure 3-8 is the ultrasonic trace from this tire. Channel 4 shows a heavy reflection with a characteristic shadow behind it and channel 6 shows modulation representative of belt edge nonuniformity.

The location of the conditions are not, however, the same as those at which failure occurred. There is no valid explanation for this from the data. There is a slight possibility that the tire could have been placed backward on the ultrasonic inspection device and this would account for the location difference, but this is conjecture and, therefore, no conclusion can be made.

3.8 TIRE T5X 1239R

It is instructive to review the data from this tire since it is indicative of the types of conditions which can occur. Figure 3-9 is an early reflection trace of the tire prior to retreading. Channels 8,9,10,15 and 16 indicate substantial runout from a heavy splice. This appears only in the liner and

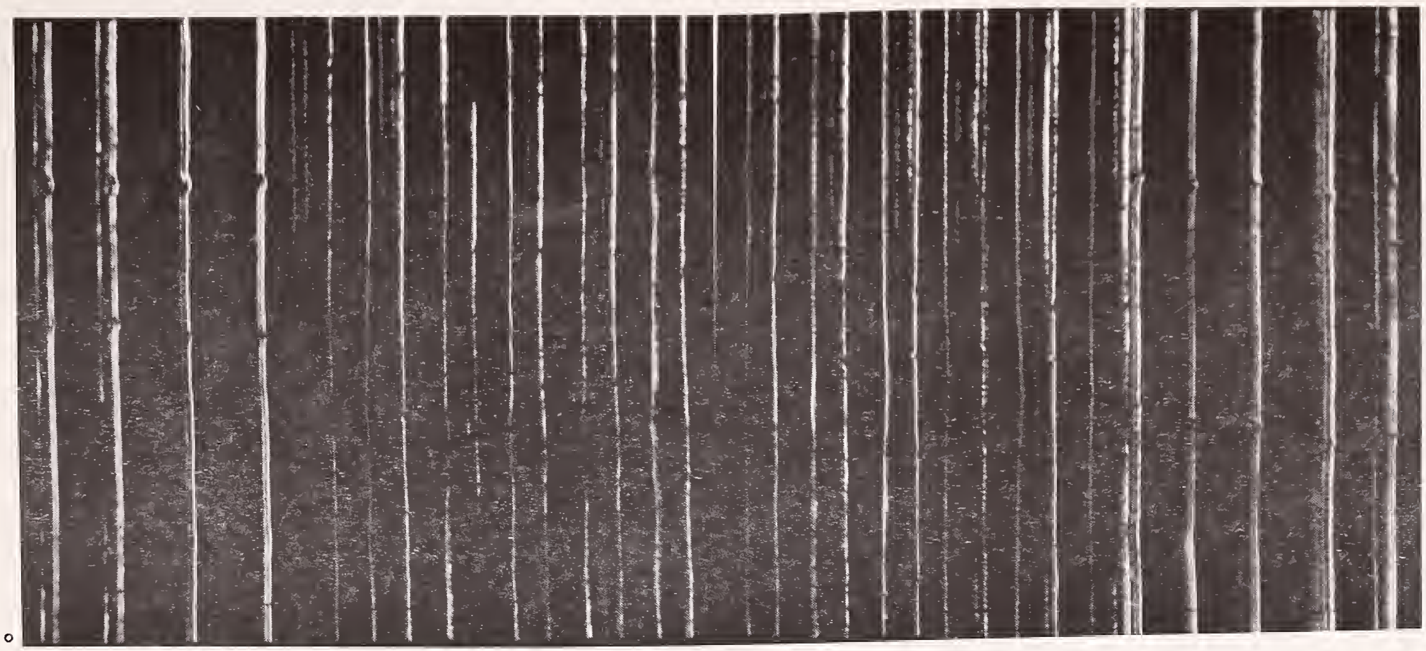


FIGURE 3-7. TIRE T5X 1204

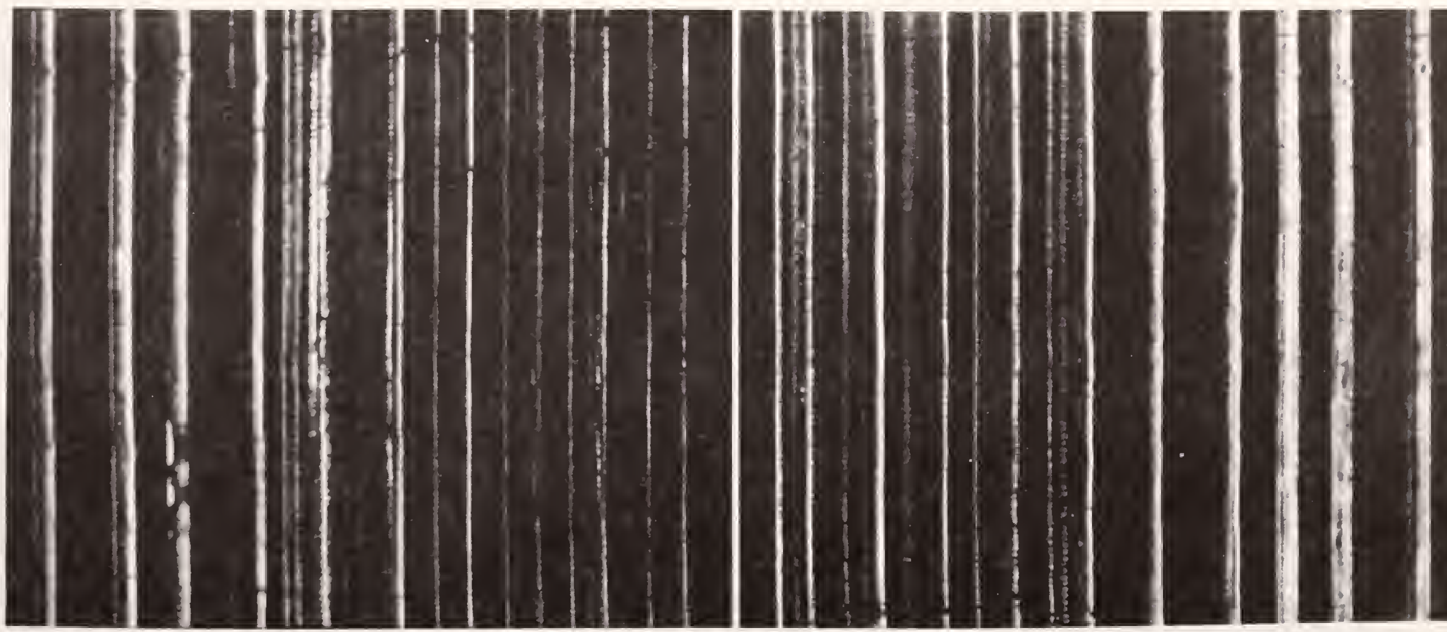


FIGURE 3-8. TIRE T5X 1223R

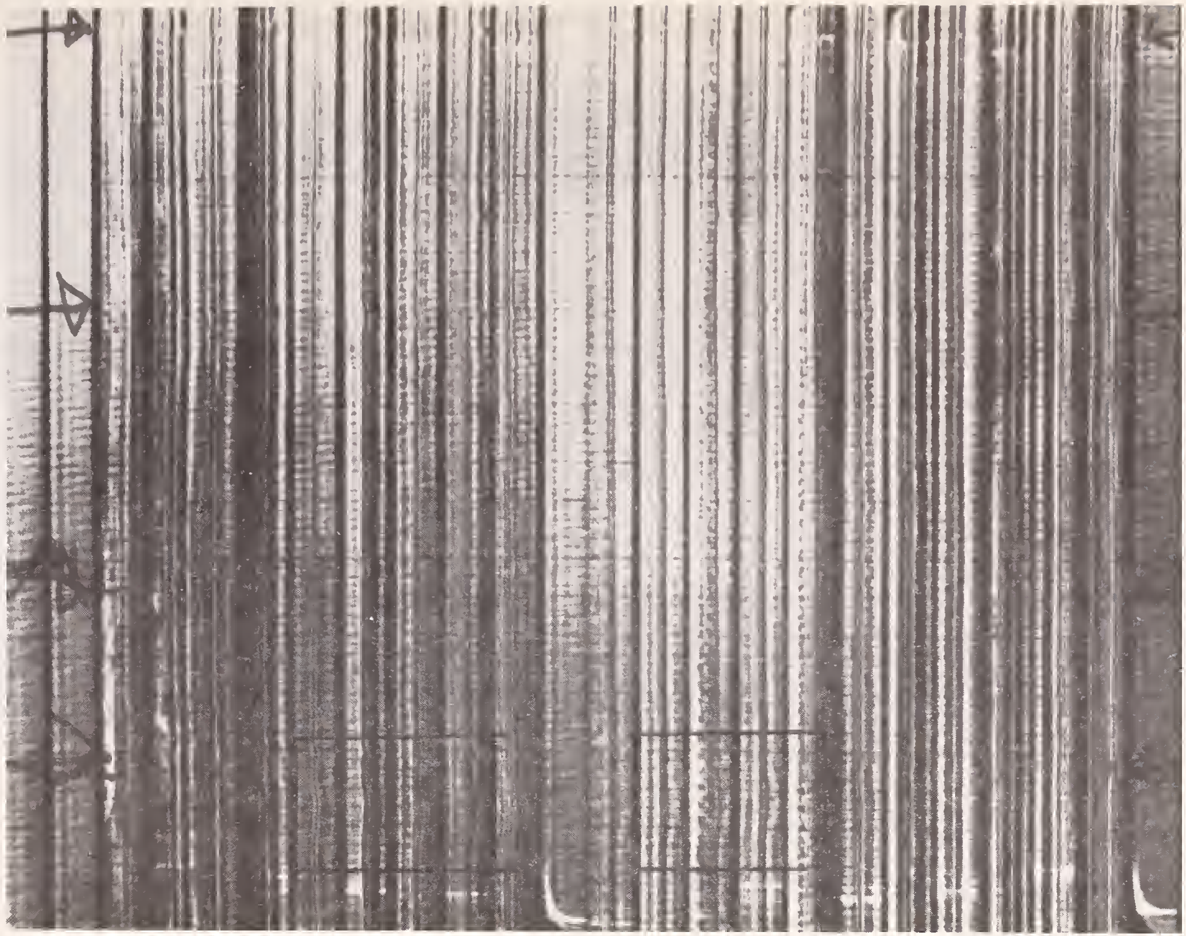


FIGURE 3-9. TIRE T5X 1239 BEFORE RETREADING

not on the tread surface. Figure 3-10 is a trace of the tire after retreading. It shows no evidence of this condition and indicates that, in this tire at least, the retreading has helped the balance situation.

3.9 TIRE T5X 1245R

In this tire, holography indicated a number of belt edge separations. The ultrasonic trace of this tire was of poor quality. It indicated some evidence of belt edge irregularity but the evidence was not conclusive. As in the previous tire a heavy splice condition was also apparent. There is also evidence that channels were transposed in this trace, Figure 3-11, with the result that it is difficult to identify the location of the shoulder.

3.10 TIRE T5X 1259R

Although the tire did not fail, there is definite evidence of a small separation at Θ=190 on channel 11, at tread center (Figure 3-12). There is also some evidence of irregularity at the shoulders in channel 16 and 5.

3.11 TIRE T6X 2084R

This tire, Figure 3-13, appears to be quite uniform and of good quality. Unfortunately, at one point it had an inclusion or separation in the shoulder. Although this was the site of failure, failure analysis of this tire indicated another reason for failure - poor adhesion in the tread rubber bond line as a result of too much mold heat. It appears that detection of the failure site in this case may have been coincidence.

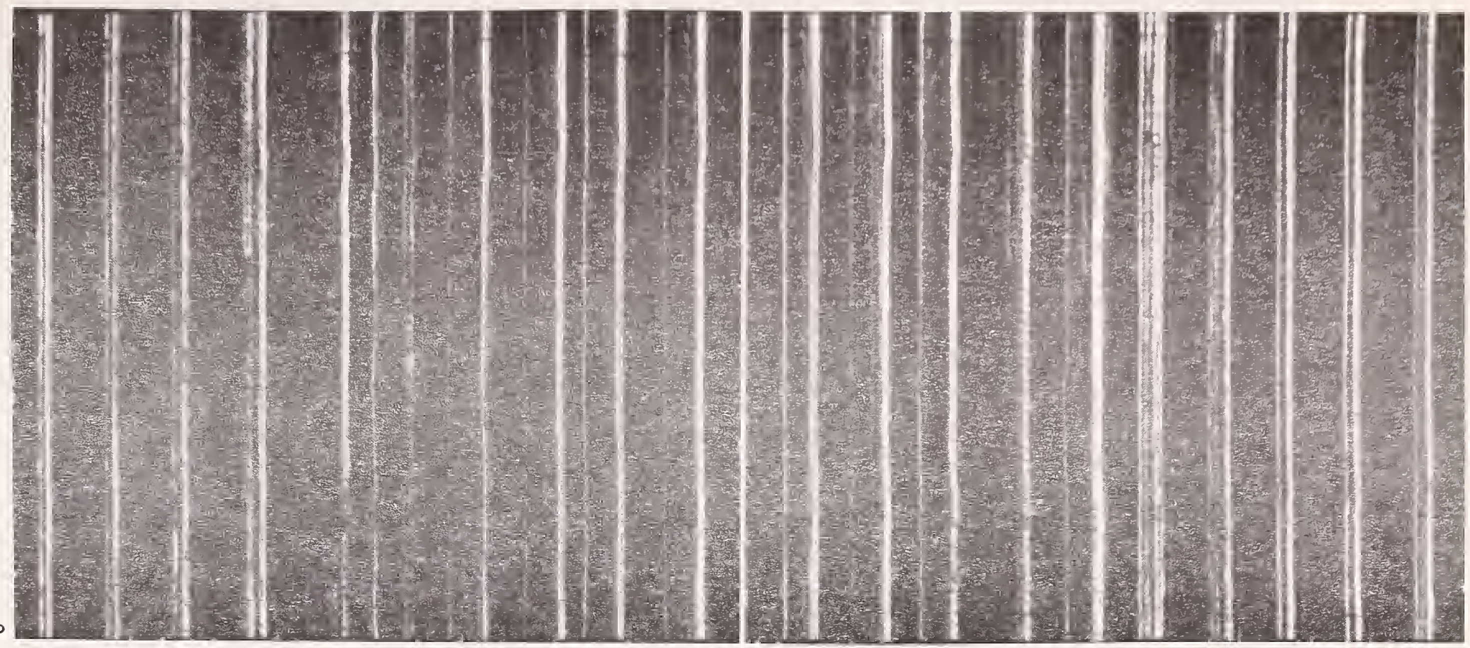


FIGURE 3-10. TIRE T5X 1239R AFTER RETREADING

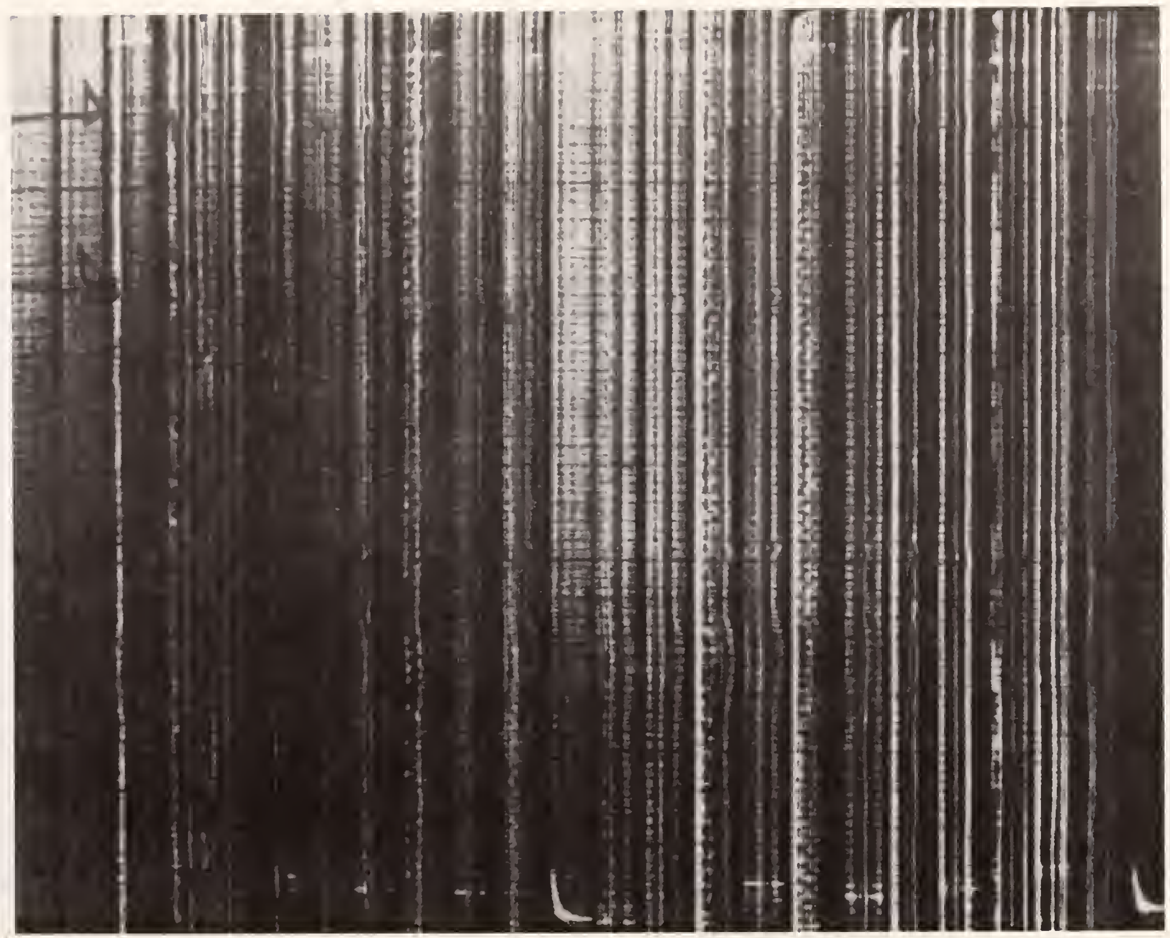


FIGURE 3-11. TIRE T5X 1245R

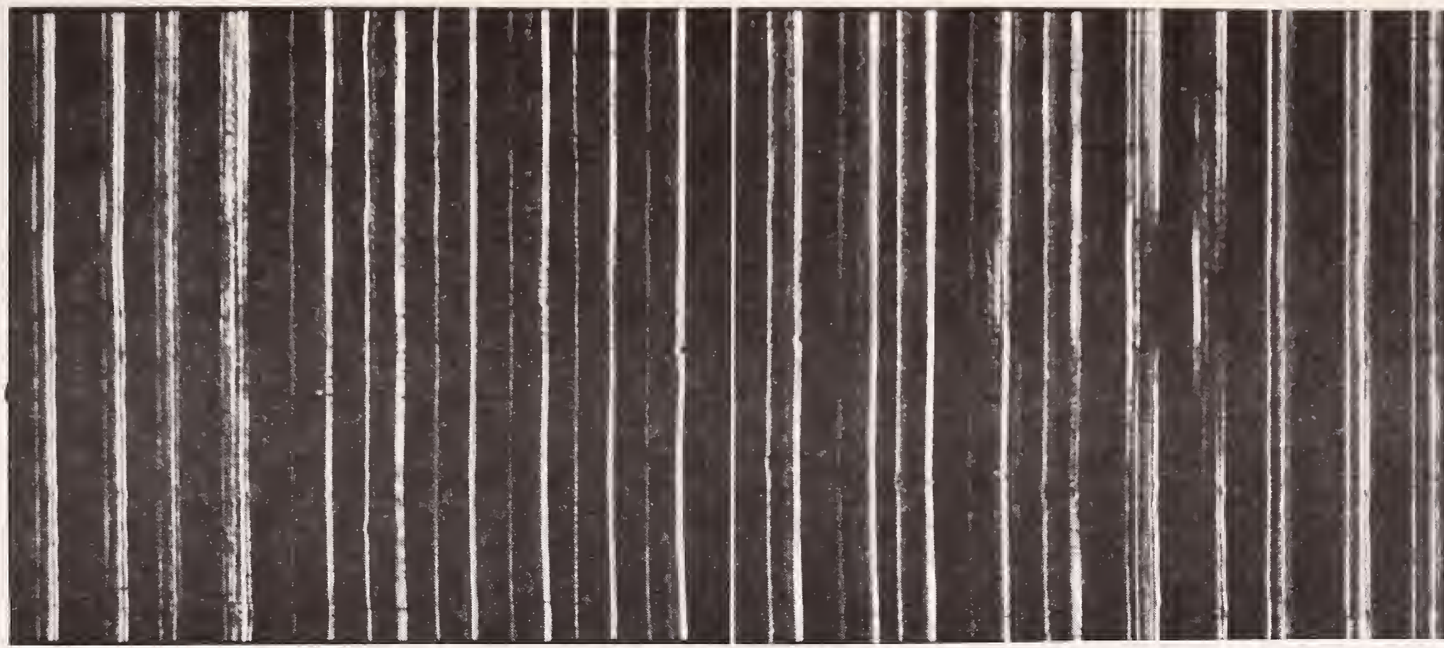


FIGURE 3-12. TIRE T5X 1259R

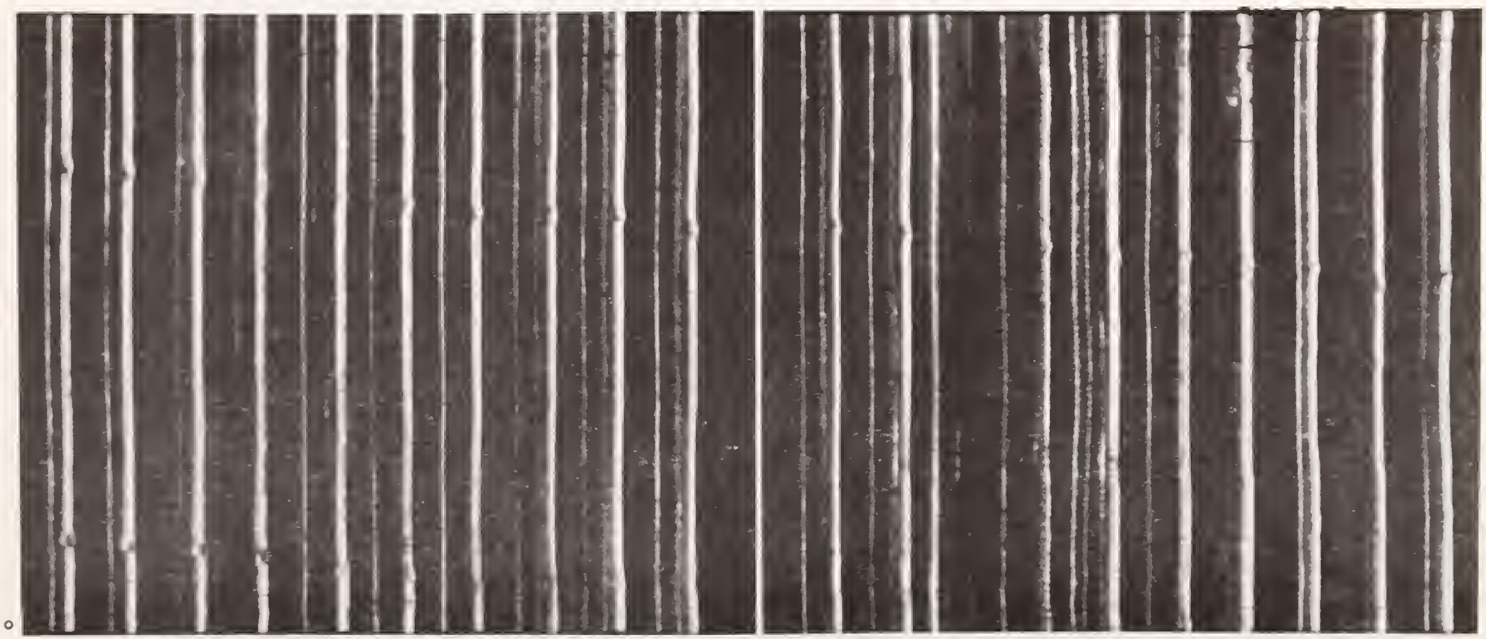


FIGURE 3-13. TIRE T6X 2084R

3.12 TIRE T7X 2169R

Channel 11 (Figure 3-14) indicated an area of insufficient rubber. This, coupled with the failure analysis report of insufficient stitching might tend to indicate a short section of camelback. These tires, however, were prepared using an orbitread machine and, barring malfunction, the condition could not have occurred in that way. The difference in tread thickness at this point and at any other point on the tire is .200 of an inch, enough to cause the tire to encounter severe stresses during wheel test. This undoubtedly was a major contributor to failure.

FIGURE 3-14. TIRE T7X 2169R

4. TEST RESULTS

4.1 WHEEL TEST RESULTS

As cited earlier, the wheel test consisted of a 55 miles-per-hour, 100 percent full-load test for a period of eight hours. During this time six tires failed. Comments at the time of failure for the six tires are shown in Table 4-1.

4.2 FAILURE ANALYSIS RESULTS

As stated earlier, analysis of the six failed tires was carried out by FRL, an independent laboratory under contract to DOT. Sections of their report have been discussed previously and some results of the analysis shown in Table 3-1. In the discussion of flaw characteristics and failure modes, the illustrations were taken from the FRL report. The complete FRL report is included in the Appendix.

TABLE 4-1. WHEEL TEST FAILURE ANALYSIS

Tire	Failure Mode
T5X 1161	Bubble On Sidewall 5½ Hours
T5X 1183	Large Bubble On Sidewall 2 Hours
T5X 1204	Recap Split At Tread 7 Hours
T5X 1223	Recap Started Coming Off 7½ Hours
T5X 2084	Part of Recap Came Off 1¼ Hours
T5X 2169	Part of Recap Came Off 2½ Hours

5. FLAW FAILURE CORRELATION

Ultrasonic inspection has enhanced the ability of the investigator to connect the existence of a condition within a tire to its failure. It is seldom possible to visually inspect a tire before it is subjected to a wheel test and identify the cause of failure. However, in this study ultrasonic inspection has correctly identified incipient failure conditions existing in tires which actually failed wheel tests at the location at which the conditions were known to exist.

In the case at hand, of 34 tires, six failed. Of the six tires, five had evidence of major separations present prior to wheel test. No other tires in the group had evidence of separations. Of the five failures with separation damage, four had point failure correlation with FRL failure analysis data. One tire had point correlation of another failure mode with failure analysis data. One tire with a separation indicated by nondestructive test was listed by failure analysis as having another mechanism as the cause of failure. Table 5-1 is a tabulation of these results.

TABLE 5-1. FLAW FAILURE CORRELATION

As Determined By:	Analysis	Non-Destructive Inspection	Same Point Correlation	Correlation Coefficient
Failed by Separation or Belt Break	4	5	3	75%
Failed by Poor Retread Procedure	1	1	1	100%
Failed by Other	1	1	1	100%

In tires which did not fail, there was 100 percent agreement between ultrasonic and holographic inspection and agreement in four out of six cases with transmission ultrasound. In some cases the transmission ultrasound indicated a condition that reflection ultrasound could explain. These results are listed in Table 3-1.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

Essentially, the data has provided a clear picture of the capability of reflection ultrasound to identify the potential cause of failure in retreads. The specific conclusions are: 1) anomalies as found by ultrasound can be related to tire failure; and 2) the major failure modes of retreads can be characterized from what has been found in this study and they do differ from new tire failure modes.

Failures in retreads observed appear in large part to be from separations and poor tread rubber adhesion. While adhesion may play a part in new tire failure over the long term there is little evidence that it is a major early problem in new tires. On the other hand separations, particularly belt edge separations, are heavy contributors to early new tire failure. They are certainly a major contributor to retread failure. If one considers that most separations which cause retread failure start in the later life of new tires, then they can be considered to originate from the same cause. A detailed analysis of the cause and rate of fatigue degradation in tires is given by S.K. Clark [Reference 5]. Summarized, it indicates that tire cords fatigue slowly up to a point at which little tread remains and then the rate accelerates radically. If retreads are built on casings where the fatigue rate is still slow they have a good chance of survival through a second service life. Ultrasonics can detect where in the failure cycle a given tire carcass lies. It is therefore possible to determine whether or not a casing is a good retread risk.

Ultrasonic nondestructive inspection as demonstrated in this study may have a heavy impact on the ability of the retreader to improve his product to a point where it may become as reliable and safe as new tires. This study indicates that the cause of retread failure stems largely from the inability of the retreader to find latent defects in a carcass which will cause the retreaded finished product to fail in service. From the standpoint of conservation of resources it is important to retread as many tires as possible. In order to accomplish this desirable goal it will be necessary to determine precisely the difference in quality between retreads and new tires. Ultrasonic inspection has a demonstrated capability to accomplish this.

6.2 RECOMMENDATIONS

As a result of the work described in this report, ultrasound is shown to be a useful working tool which can be used to further the objectives of the National Highway Traffic Safety Administration. It is therefore recommended that this technique be used to support NHTSA's ongoing rule enforcement activities particularly in the area of identifying and defining separations as cited in FMVSS 109 and buff damage as cited in FMVSS 117.

If retreads do not have service life or safety equivalent to new tires, ultrasonics can provide a tool to make a judgment of just what degree of safety these tires have. It is therefore further recommended that consideration be given to using ultrasonics to grade retreads for safety and performance as compared to their new tire counterparts. Specifically, a retread research program is proposed, the purpose of which will be to determine how safe retread tires are. The program will consist of three elements:

1) A study to find what proportion of retreads show anomalies likely to lead to failure.
2) An analysis of the principal failure modes of retreads and their causes.
3) Development of a low cost liquid-coupled inspection system which will identify those casings and finished retreads which represent a safety risk for the consumer.

APPENDIX

DEFECT CHARACTERIZATION OF A SERIES OF RE-CAPPED TIRES PREVIOUSLY WHEEL TESTED

REPORT

CLIENT	CASE NUMBER
U. S. Department of Transportation Transportation Systems Center 55 Broadway Cambridge, Massachusetts 02142	G71673
	DATE
Attention: Mr. Stephen N. Bobo Contract DOT-TSC-317	21 November 1977

Subject: Defect Characterization of a Series of Re-Capped Tires Previously Wheel Tested - Report No. 16

Samples Submitted

Six re-capped tires were received from DOT/TSC that had failed during wheel testing. The tires were from a test lot of re-capped tires obtained from Yudy Tire Company of Maine.

The tire identification is listed in Table 1. All the tires were marked YUDY'S SUPER TREDS.

Introduction

DOT/TSC had examined the tires prior to wheel testing using a water-coupled, ultra-sonic, NDT technique. Of all the abnormalities noted, only the separations appeared to have a bearing on tire failure.

From the re-cap numbers all the tires were re-capped in mid 1976 (assuming the missing numbered tire was from the same lot) and the original tires were made in mid 1972 to early 1973 with the exception of T5X 1161 which was made during early 1967, making this tire 9 1/2 years old at the time of re-capping.

The six tires failed during wheel testing from a tread-shoulder separation which resulted in a severe bump or chunk-out.

DEFECT CHARACTERIZATION OF A SERIES OF RE-CAPPED TIRES PREVIOUSLY WHEEL TESTED

performed by

Fabric Research Laboratories
1000 Providence Highway
Dedham, Massachusetts 02026

21 November 1977

Report No. 16

prepared for

U. S. Department of Transportation
Transportation Systems Center
Cambridge, Massachusetts 02142

TABLE 1

TIRE IDENTIFICATION

DOT Sample No.	T5X 1161	T5X 1183	T5X 1204	T5X 1223	T5X 2084	T5X 2169
Re-Cap No.	← DOT R BHD AN →					
	296	286	306	306	316	missing
Original						
Name	Atlas Plycron (UniRoyal)	UniRoyal Fastrak	Firestone Sup-R-Belt	Firestone Sup-R-Belt	Kelly Springfield Explorer 78	Firestone Sup-R-Belt
Type	8.25-15	G78-15	G78-15	G78-15	G78-15	G78-15
Carcass Cord	4 ply rayon	2 ply PET	2 ply PET	2 ply rayon	4 ply PET	2 ply PET
Belt	none	2 fiberglass	2 fiberglass	2 rayon	none	2 fiberglass
Manufacturer's No.	DOT 127 02027	AKVV DD0133	VJVV DD4013	VFVV DDD402	PKVW KBE242	VFVV DD1013

Table 2 lists the first (or liner) ply-cord adhesion values and Table 3 gives the cord tensile properties.

TABLE 2

CARCASS PLY CORD, PEEL ADHESION (POUNDS PEEL PER CORD)

Sample No.	Sample Cord	Inside Wall	Shoulder	Tread	Tread	Shoulder	Outside Wall	Average
T5X 1161	4000 d. rayon	8.0	7.0	7.8	8.2	5.8	8.2	7.5
1183	3600 d. PET	9.9	7.9	7.6	8.6	8.7	11.6	9.0
1204	3600 d. PET	5.0	4.4	4.4	4.0	3.7	4.5	4.3
1223	6000 d. rayon	12.1	10.1	9.3	8.5	8.2	11.3	9.9
2084	2200 d. PET	3.5	3.0	2.4	2.7	3.5	4.5	3.3
2169	3600 d.	5.8	3.4	3.0	4.2	3.8	4.0	4.0
2nd ply		2.1	1.4	2.6	1.5	1.3	2.3	2.0

TABLE 3

CARCASS CORD TENSILE PROPERTIES

Sample No.	Sample Cord	Strength (lbs) New*	Strength (lbs) Actual	% Elongation New*	% Elongation Actual
T5X 1161	4000 d. rayon	26	26.2	12	10.2
1183	3600 d. PET	47	42.4	15	12.9
1204	3600 d. PET	47	45.2	15	14.5
1223	6000 d. rayon	37	36.5	15	10.8
2084	2200 d. PET	30	30.2	15	12.4
2169	3600 d. PET	47	43.8	15	15.2
2nd ply		47	40.9	15	13.9

*Data obtained from testing actual new tire cord of similar size and construction.

Summary of Conclusions

Three tires (T5X 1161, 1183, 1204) should not have been re-capped because of severe faults with the original carcass; two tires failed because of poor re-capping; one tire failed most likely from over-heating in the re-cap mold although the tire cord and cord/rubber adhesion was in such a state of degradation that the cause of degradation might not have been from mold over-heating but might have occurred prior to re-capping.

T5X 1161, a 9 1/2 year carcass appeared to be over-age. In addition, the 83% aspect ratio tire was re-cap molded in a 78% aspect ratio mold, and would be distorted during molding. This would likely cause a sidewall/shoulder bubble at any limited adhesion area.

T5X 1183 and 1204 both contained massive glass belt breakage and separations and should not have been re-capped.

T5X 1223 and 2084 failed primarily from a poor re-capping technique which allowed solvent to be present under the re-cap tread, mold hot-spots and/or mold over-heating.

T5X 2169 cause of failure was not obvious in that it could be a combination of mold over-heating and to the general deteriorated state of the ply-cord adhesion. Also one belt edge shoulder separation developed when the tire was re-capped and this could have been the failure site.

1. Tire Analysis T5X 1161 - A large separation and bubble centering at θ=300, φ=190-280 (NDT ultra-sonic inspection had shown separations at both θ=270 and 300 and φ=270) was the immediate cause of failure. Figure 1 shows the separation area at θ=300°, and especially an area of no rubber adhesion to the sidewall. The ply-cords in this area also contained detritus (black) between individual yarn plies and no cord adhesive remained on the surface of each yarn. The ply-cord surface was not abraded to any degree; thus indicating that the separation or an area of no adhesion was present prior to re-capping. Also the original tire has an aspect ratio of about 83% and was molded in a G78-15 (or 78% aspect ratio) re-cap mold. This situation would cause abnormal sidewall and shoulder distortion in a tire to the point where sidewall buckling is promoted which would very likely cause a separation at any area of weak adhesion between cord ply and carcass rubber.

The separation area at the buffed interface under the re-cap tread is caused from the heat generated from the original separation bubble having been pressurized.

Figure 1 Sidewall Separation and Area of Poor Rubber Adhesion T5X 1161

Examination of the carcass ply-cord themselves showed good adhesion (away from the separation) averaging 7 pounds per cord peel in the inside ply. The rayon carcass cords average 26.2 lbs breaking strength at 10.2% elongation which is normal for a rayon cord of this age and size (4,000 denier cord).

IR analysis of a pyrolyzed sample of liner rubber did not show any unusual aging, reversion, or deterioration of the liner rubber. The tread rubber in the burnt area did show reversion which was expected; but the remaining tread rubber appeared normal for the SBR tread stock. Appendix A describes the IR and pyrolysis method.

Also from Figure 1, note how the buffing appears to have been done in the radial direction as opposed to longitudinal buffing which is normally employed.

Conclusions - T5X 1161

1. The tire was really too old to be subject to re-capping.

2. The tire had a severe separation or area of poor carcass-rubber adhesion that became distorted when the 83% aspect carcass was re-capped and molded in a 78% aspect mold.

3. Failure occurred when the separation became pressurized, bubbled and then generated high heat levels which failed the carcass rubber.

2. Tire Analysis T5X 1183 - This glass belted tire had failed when parts of the tread separated. Inspection of the tire under the tread showed massive belt breakage throughout the tire. Actual tire failure was initiated primarily at $\theta=80°$, $\varphi=180°$ where there was a large separation in the carcass directly under an area of severe glass belt breakage. Figure 2 shows the area of severe glass belt breakage and the failure separation beneath the belt. Also a larger sidewall separation was found at $\theta=45°$, $\varphi=250°$. The sidewall/shoulder rubber had separated from the carcass fabric and the carcass fabric had buckled (reverse curvature). Figure 3 shows this separation and buckle. This buckling is an artifact occurring during the re-capping operation when the tire does not fit the mold very well. With the severe glass belt breakage, the tire was probably considerably over-size in circumference which would cause the sidewall to buckle when the tire was placed in the re-cap mold and there is an area of poor adhesion. The sidewall separation at $\theta=45°$, $\varphi=250°$ extends from the bead to well into the shoulder. Also there is another sidewall ply separation at $\theta=50°$. Both glass belts are essentially completely disintergrated from $\theta=70°$ to $120°$. There was no evidence that the carcass buffing prior to re-capping had touched or otherwise

Figure 2. Severe Belt Breakage and Failure Area T5X 1183

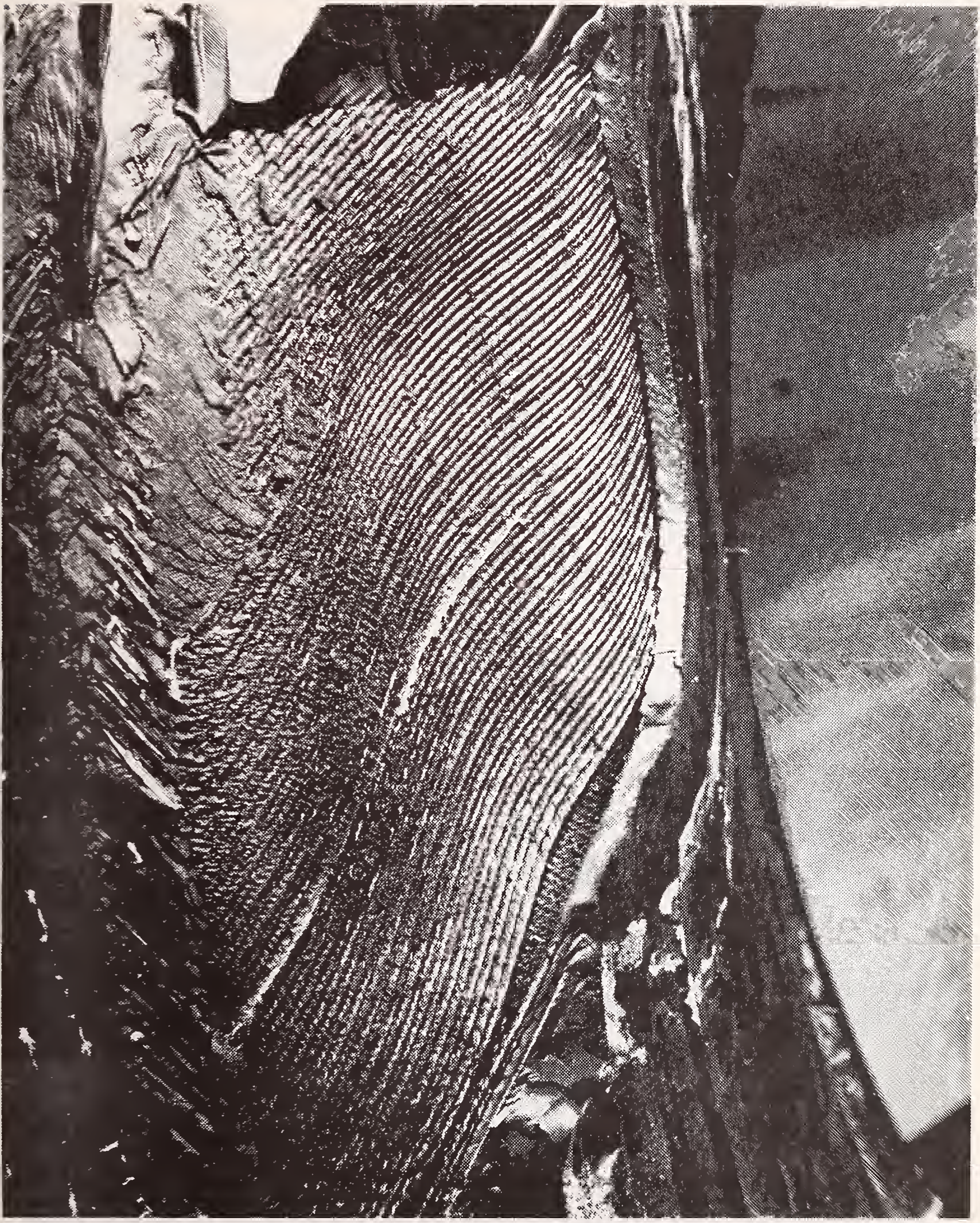


Figure 3. Sidewall Separation and Buckling T5X 1183

damaged the glass belts. Also the broken ends of glass were completely blackened and in some cases covered with burnt rubber, definitely indicating that the tire had been running for a relatively long time with broken glass belt cords.

Ultra-sonic NDT inspection by DOT/TSC prior to wheel testing had shown a separation at θ=100° and a heavy splice at θ=270°, θ=300°. The separation was probably directly involved in the tire failure.

Evaluation of ply-cord adhesion was 9 lbs/cord peel and cord tensile strength of 42.8 lbs indicates that the 3 ply, 3600 denier cord used in this tire carcass is in good condition.

Conclusions - T5X 1183 - This tire had developed massive belt breakage during its operational life and would become over-size in circumference from its normal shape. Therefore during re-capping, sidewall/shoulder buckling was likely to occur.

It is also likely that glass-belted tires should not ever be re-capped, since the odds that the tire has a badly broken glass-belt are quite high.

3. Tire Analysis T5X 1204 - This Firestone glass belted, polyester cord tire failed when a severe tread bump with tread spitting occurred. The failure location at θ=240°, φ=180-190 does correspond to a heavy bump splice detected by ultra-sonic NDT inspection by DOT/TSC prior to wheel testing. This NDT inspection showed a shoulder separation at θ=220°, φ=250 and the bump splice at θ=230° in the middle of the tread.

Dissection and inspection of the glass belt showed the glass yarns to be badly broken. Figure 4 is a photo of the failure area showing the severe glass breakage and the separation. The separation also shows a heavy loss of carcass rubber with black detritus having penetrated into the carcass cord, indicating the separation had been present for a long time. The glass belt was badly broken throughout and especially severe breakage was noted at θ=200-210° and θ=270°, and another belt separation was found at θ=270°. Also a belt edge separation was found at θ=220°, φ=250°. IR scans were made of the pyrolysis products of the tread and liner rubber. Both the tread and liner rubber outside the failure area showed little degradation from either age or heat. The rubber from the failure area was burnt and was oxidized (according to IR analysis) indicating that the tread splitting was caused by excessive heat buildup when the separation became pressurized. Ply-cord adhesion averaged about 4.3 lbs/cord. This adhesion is low for the 3 ply, 3600 denier polyester cord used in this tire. Cord strength was 45.2 lbs which is normal for this cord. The low cord adhesion is probably an accelerated aging effect caused by the tire having been overloaded or underinflated during its earlier life.

Figure 4. Severe Belt Breakage and Separation in Failure Area T5X 1204

Conclusions - T5X 1204 - This tire had severe belt breakage and at least two belt separations at the time of re-capping and was essentially a failed tire prior to re-capping.

4. Tire Analysis T5X 1223 is a re-capped belted Firestone tire with rayon belt and rayon carcass cord and is of somewhat older vintage than the preceding Firestone tire. The tire had failed during wheel testing when a large section of the tread separated from the carcass. This separation was at the buffed interface of the tire and was on the outside of the tire centering at the shoulder (φ=250°) and extended from θ=240° to 290°. The separation extended well under the tread reaching to φ=190° at θ=250°. Also at θ=270°, φ=250° starting at the belt edge a carcass separation was found and the belt edge was both burnt and aged, showing frayed cord ends. This separation had been present a long time prior to re-capping.

Also the re-cap buffing interface was burnt over a large area as shown in Figure 5. Since the buffed interface, when dissected, showed clear and sharp buffing lines, there was no re-cap tread adhesion obtained when the tire was re-capped and vulcanized. This is usually caused from residual solvent held in the interface followed by too much heat and/or too fast a heat cycle. Figure 6 shows a tread groove impression burnt into the re-cap/carcass interface which definitely indicates mold over-heating and/or a mold hot spot. Re-cap tread adhesion, outside the failure area was quite variable. There is no question that there was a tread separation right after the tire was re-capped and that a poor re-cap job had been accomplished.

Inside the tire, a tire plug was found at θ=60°, φ=180°; the plug was well bonded to both liner and carcass. At θ=190°270°, φ=270° an area of burnt liner showing rubber reversion was found, which corresponds in position to the sidewall separation. IR analysis of pyrolyzed liner rubber indicated generally an aged butyl rubber liner with some reversion. The SBR tread rubber was also checked in both good and failed areas and it was found that the tread rubber was partially oxidized and degraded over a large area. The fact that this tire was over-cooked was probably the major reason for tire failure.

Carcass cord strength was normal at 36.5 lbs for the 6000 denier, 3 ply cord rayon cord but the elongation of 10.8% is low but consistent with the apparent heat history of the tire. First ply cord peel strength was good for this three ply rayon cord averaging 9.9 lbs/cord peel. Thus the over-heating noted before must have been of short duration not to have adversely affected cord/rubber adhesion.

The re-capping was also of poor quality especially along the edges of the re-cap when the stitching was poorly done with many areas of loose edges, one of which was next to the separation at θ=270°.

Figure 5. Buffed Interface and Belt Edge Separation T5X 1223

Figure 6. Burnt Mold Groove Line T5X 1223

Conclusions - T5X 1223 - This tire failed because of a re-cap separation present in the tire right after the re-capping. Also the tire became over-heated in the re-cap mold which promoted deterioration. The presence of the belt edge separation at this point also caused local over-heating and a bump in the tire during the wheel testing. Again the tire should not have been re-capped. However, the poor re-capping job and a hot spot in the mold were the immediate cause of failure.

5. Tire Analysis T5X 2084 - The carcass for this re-capped tire was a 4 ply polyester cord tire of conventional bias ply construction made by Kelly Springfield. The tire had failed when a section of the re-cap came off during wheel testing. The break-out section was at θ=90°, φ=220°; however, the outside tread was found to be essentially separated from θ=60° to θ=240°. The massive separation was at the buffed interface between the re-cap tread and carcass. Ultra-sonic NDT by DOT/TSC prior to testing the tire showed a shoulder separation at θ=270°, φ=250° which was not found when the tire was dissected. However, a sidewall shoulder separation was found at θ=100°, φ=250°. This separation, of course, was right in the area of tread break-out. Inspection of the tread separation from θ=90° to θ=230° showed that the buffed surface lines were clean and sharply outlined and also contained small bubbles, blisters and burnt spots. The burnt spots were essentially reverted SBR rubber as determined by IR analysis of a pyrolyzed sample of the rubber. This burnt, bubbly and blistered interface indicates solvent entrapment during re-cap vulcanization.

The tread separation extended from shoulder to tread center and tread adhesion outside the separation area was fair.

Additional separations were found at θ=190°, φ=250° (a sidewall separation) and between the 3rd and 4th carcass plies at θ=350°, φ=260°. Ply cords for these separations were dissected and examined and black detritus was found inside the cord yarn indicating the separations were old and present before the tire was re-capped. However, it seems that these separations did not take an active part in the failure.

IR analysis of pyrolyzed samples of tread stock outside the separation area indicated moderate oxidation degradation of the tread stock.

IR analysis of the butyl rubber liner also showed a moderate level of oxidation degradation. Since this tire did not have any heat bands (which are generated when a tire is operated overloaded and/or underinflated), and with the original tire made in mid 1972, it does not seem to be over-aged; it is reasonable to assume that the tire was over-heated or heated too rapidly during re-capping vulcanization.

Inspection and testing of the ply cord showed that the 2200 denier 2 ply polyester cord had a 30.2 lbs strength and 12.4% elongation which is about normal for this cord. The cord peel adhesion, which averaged 3.3 lbs/cord is low, indicating marked deterioration of cord/rubber adhesion. This is consistent with the over-heated tire condition.

Conclusions - T5X 2084 - The tire failed because of a poor re-capping procedure related to the presence of solvent at the buffed interface between the tire carcass and re-cap tread stock and to over-heating (or too rapid a heat cycle) in the re-cap mold.

6. Tire Analysis T5X 2169 - Part of the re-cap tread separated from this tire during wheel testing. In the area of the break-out a large sidewall/shoulder separation at θ=300°-340°, φ=260° (whitewall side) was noted. Inspection and dissection of ply cords from the separation showed that there was no loss of cord adhesive and that there was no penetration of detritus into the yarn. This separation was an area of poor adhesion and therefore the separation was initiated during the re-capping vulcanization or wheel testing.

DOT/TSC ultra-sonic NDT inspection indicated over-buffing at θ=340°, φ=150° (blackwall side) and at θ=60°, φ=240° (whitewall shoulder); an over-buffing of a splice at θ=160°, φ=240°.

The original tire was a Firestone glass belted tire with a two ply polyester carcass.

Tread adhesion was variable and near the break-out was very poor easily peeling at the buffed carcass interface. However, the buff lines were not present indicating some adhesion was obtained.

In general tread adhesion on the whitewall (outside) was inferior to adhesion on the blackwall (inside).

Tread stitching on the whitewall side is poor with many areas of a loose rubber flap. On both sides of the break-out, the buffed interface showed a burnt surface indicating that this area of tread had separated and had become pressurized during the wheel test. The separation did not occur when the tire was re-capped since the buff lines are not present, although a poor bond could have been achieved. Removing the tread and inspecting the glass belt indicated that there were numerous areas of belt breakage throughout the tire. Overall glass yarn breakage was estimated to be at 20%.

Inspection and dissection of the carcass first ply cords gave an average adhesion value of 4.0 lbs/cord and a strength of 43.8 lbs at 15.2% elongation. The cord is a 3 ply polyester cord, 3600 denier and should have a strength of from 45-

48 lbs. Since there was evidence of cord degradation, the second ply cord was also dissected and tested. The adhesion was only 2.2 lbs/cord and the strength was 40.9 lbs at 13.9% elongation. Carcass cord degradation is therefore quite pronounced.

IR analysis of pyrolyzed rubber samples taken from undamaged areas of the liner carcass and tread rubber showed only a moderate level of rubber oxidation and degradation. The burnt area tread showed severe degradation.

Conclusions - T5X 2169 - A large area of poor re-cap adhesion occurred during vulcanization. The presence of poor stitching suggest that the re-capping was poorly done. Although the glass belt was badly broken it does not seem to have been the source of failure although the tire was probably over-size in circumference and would not fit the mold very well. The general degradation of the ply cords suggests that the re-cap vulcanization was too severe for the polyester cord present in the tire. Therefore, the cause of failure was not that definite but might well have been from the combination of a rather poor stitching/re-capping job, the relatively deteriorated condition of the original carcass, the presence of a relatively large sidewall area of poor adhesion and the likely excessive heat levels used during re-cap vulcanization.

APPENDIX A

Infrared Analysis and Pyrolysis Technique

1. Sample Preparation

A sample of rubber to be analyzed is first extracted in acetone and then toluene to remove any oils and residual rubber chemicals from the rubber material. The sample is then dried at 95°C for one hour. From the dried sample material, prepare two test specimens for pyrolysis.

Twenty-five (25) milligrams of sample, no more than 1 mm thick, is wrapped in aluminum foil; the package is perforated with small holes on one side and then placed in a Barnes Model PY-2 pyrolyzer fitted with an ATR Condensate Chamber.

2. Pyrolysis

The foil-wrapped specimen is placed on the electrode ribbon, perforated side up. Insert ATR crystal gasket, place a 2x18x52 mm KRS-5, 45°, ATR crystal on top of gasket and close shield into position.

Evacuate the test chamber for 2 minutes using a water asperator, or for 1 minute using a mechanical vacuum pump, then seal test chamber.

Immediately fire the electrode ribbon for 30 seconds at a setting of 650°C. Wait 30 seconds then release the vacuum. Carefully remove the ATR crystal.

Place the second foil wrapped specimen in pyrolyzer, turn over the ATR crystal and place it on top of the gasket on the condensate chamber. Repeat the pyrolysis procedure as before.

The ATR crystal now as a condensate coating on both major faces.

3. IR Scan

Place KRS-5, ATR crystal in the MIRA (multiple internal reflectance accessory) and place in the sample beam of a dual beam, grating type infrared spectrophotometer. [The KRS-5 ATR crystal, itself, shall have a 40% transmittance or better at a wave number of 4000 cm^{-1} with the reference beam open.] Attenuate the reference beam until 80% transmittance is achieved, then commence IR scanning from a wave number of 4000 cm^{-1} to at least 600 cm^{-1}. The scan made should be done at a medium, speed, using a normal slit and a time constant of 1. If the pyrolyzed condensate concentration on the ATR crystal is of sufficient quantity, the absorbance at 2920 cm^{-1} will be at least 1 (or the transmittance less than 10%).

4. IR Analysis - SBR Rubber

In the case of tread stock the subject tires all used an SBR base rubber. In analyzing for oxidative-degradation (i.e., exposure of the rubber especially to excessive heat), the IR absorbances at 962 cm^{-1} and 698 cm^{-1} are carefully analyzed. Figures 7 and 8 are IR scans of SBR tread stock showing the effect of oxidative-degradation.

First construct a zero baseline by drawing a straight line on the IR trace from 1540 cm^{-1} to 660 cm^{-1}. Measure the absorbances based on the zero baseline of the two IR bands and calculate the ratio of 962 cm^{-1} to the 698 cm^{-1} IR absorbances.

For most normal SBR rubbers this ratio will range from about 0.3 to 0.4. As aging or oxidation-degradation occurs this ratio will exceed 0.6 and under severe reversion will approach 1.

The IR absorption band at 698 cm^{-1} is associated with the styrene-aromatic molecule vibration and essentially remains nearly constant when degraded SRR is pyrolyzed. However, the band at 962 cm^{-1} is associated with the carbon to carbon, trans, double bond vibration. As the SBR rubber molecule breaks down due to oxidation and reverts, alkene and vimyls are formed and this absorption increases in intensity relative to the styrene vibration when the degraded SBR is pyrolyzed.

5. IR Analysis - Liner Rubber

Liner rubber is usually a blend of rubbers of which butyl rubber tends to predominate. The subject tires all contain liners made from blends of butyl rubber. The key characteristic IR absorption band for butyl is a doublet at 1375 and 1365 cm^{-1} which is the deformation of the CH_3-C and $(CH_3)_2$-C parts of the polymer chain. Figure 9 illustrates the normal butyl rubber IR scan. Although butyl has good heat resistance, butyl will break down with heat and an oxidizing atmosphere and the band at 1365 cm^{-1} will gradually disappear when the degraded butyl is pyrolyzed. Figure 10 is an IR scan of degraded butyl rubber. The skeletal vibration of the $(CH_3)_2$-C occurs at about 1230 cm^{-1} and also gradually disappears as the butyl polymer degrades and is pyrolyzed. The ratio of the absorbances at 1375 and 1365 cm^{-1} will run between 0.9-1.1 for a normal butyl polymer but as degradation occurs the ratio will increase to about 1.5 or the band at 1365 cm^{-1} will almost disappear after pyrolyzing the degraded butyl.

The zero baseline used to obtain absorbance is constructed in the same manor as with the SBR analysis method.

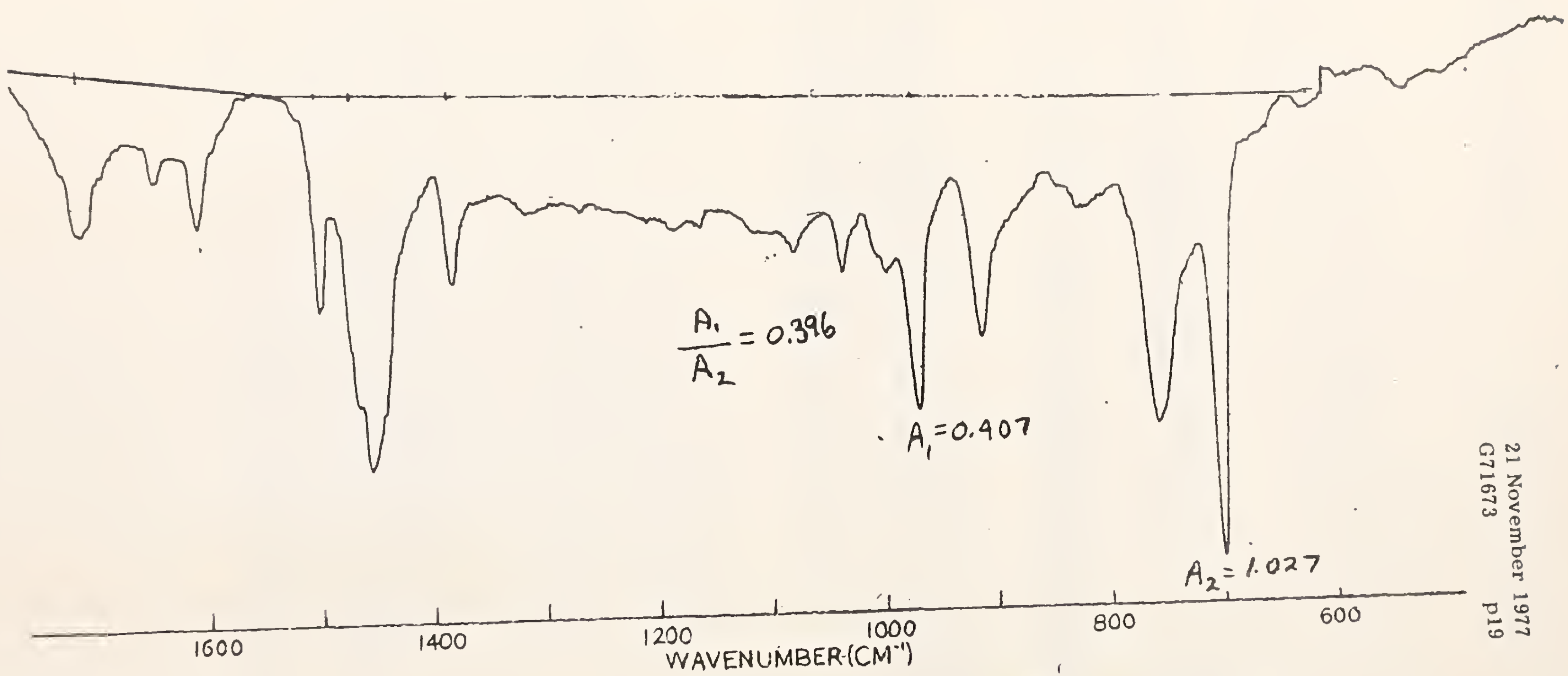


Figure 7. IR Scan - Pyrolyzed SBR Tread Rubber - Little Oxidation-Degradation T5X 1161

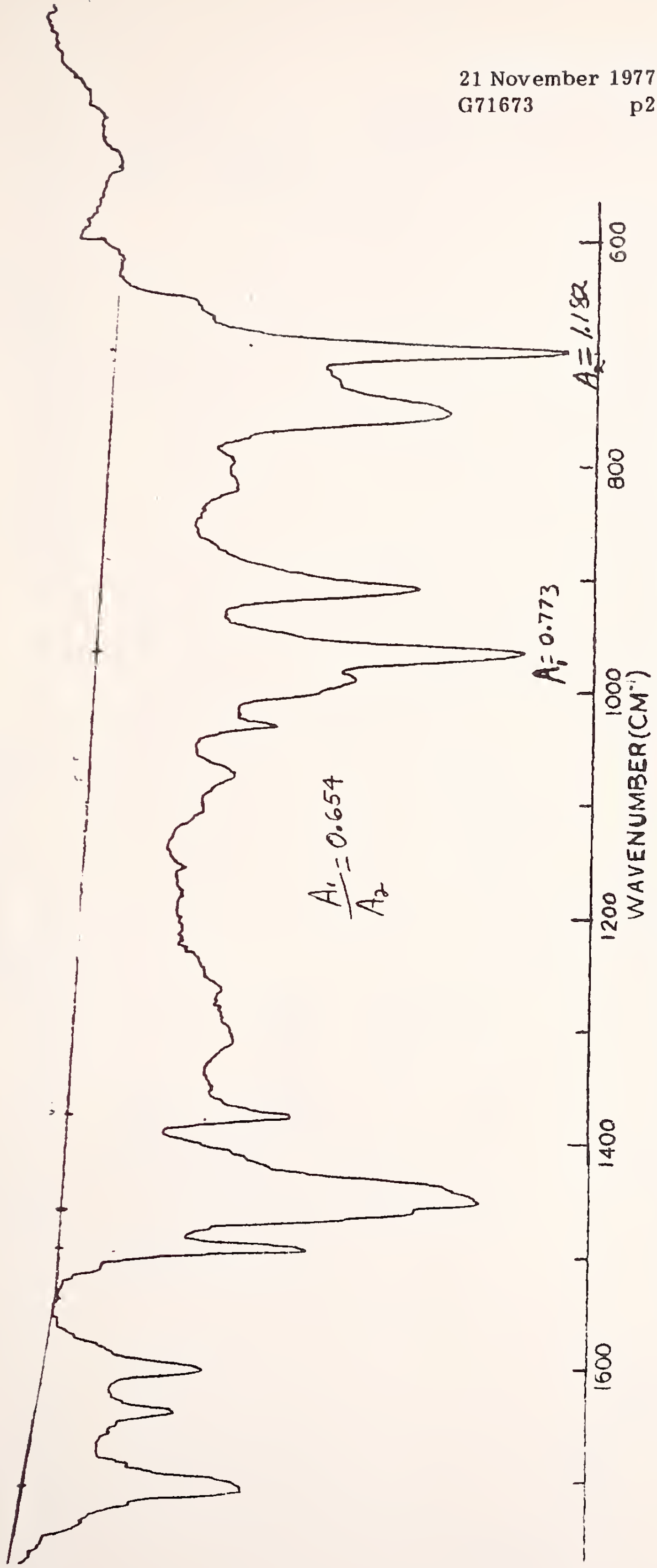


Figure 8. IR Scan - Pyrolzed SBR Tread Rubber - High Oxidation-Degradation T5X 1223

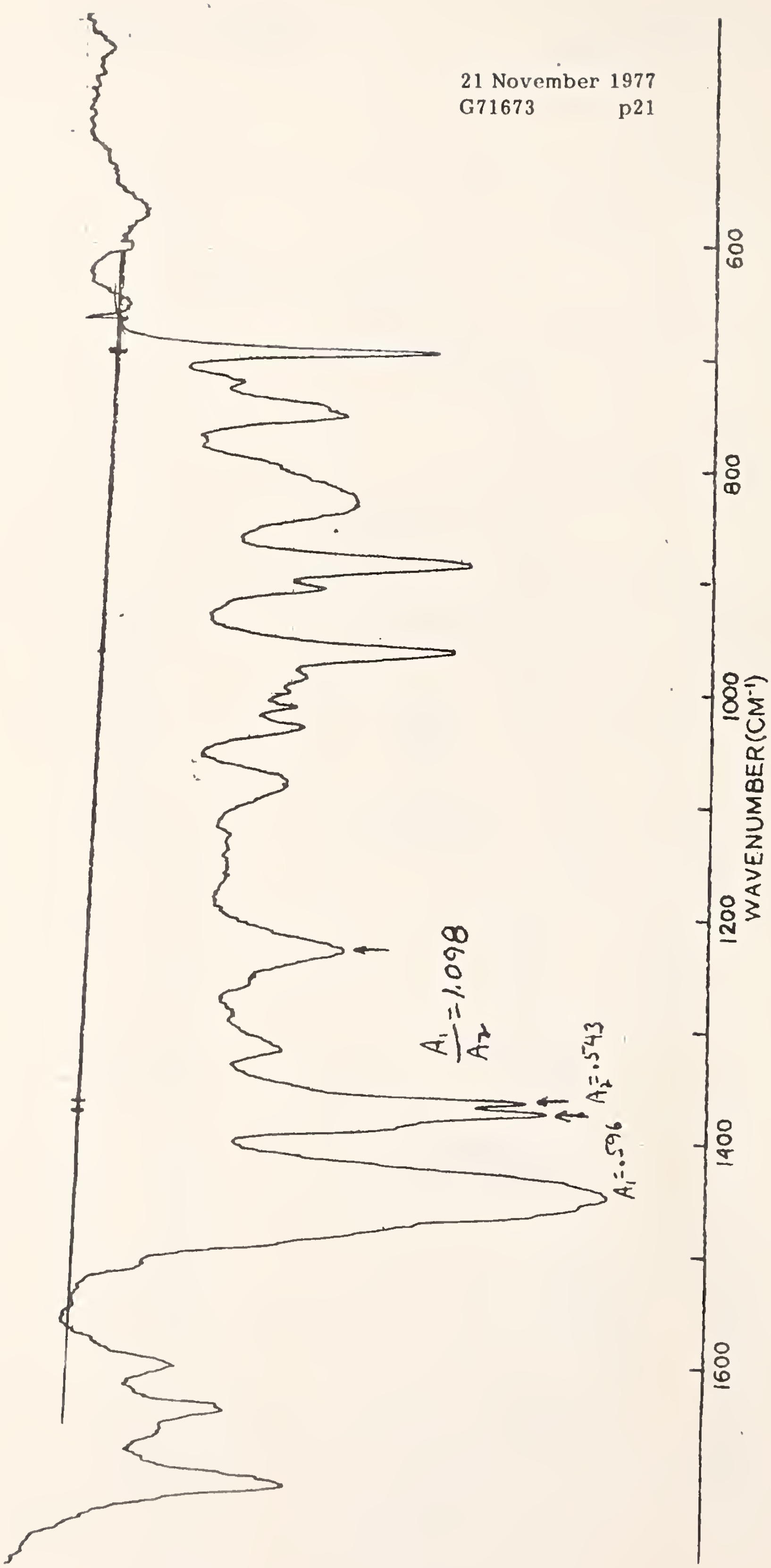


Figure 9. IR Scan - Pyrolyzed Liner Rubber - Little Oxidation-Degradation (Butyl) T5X 1204

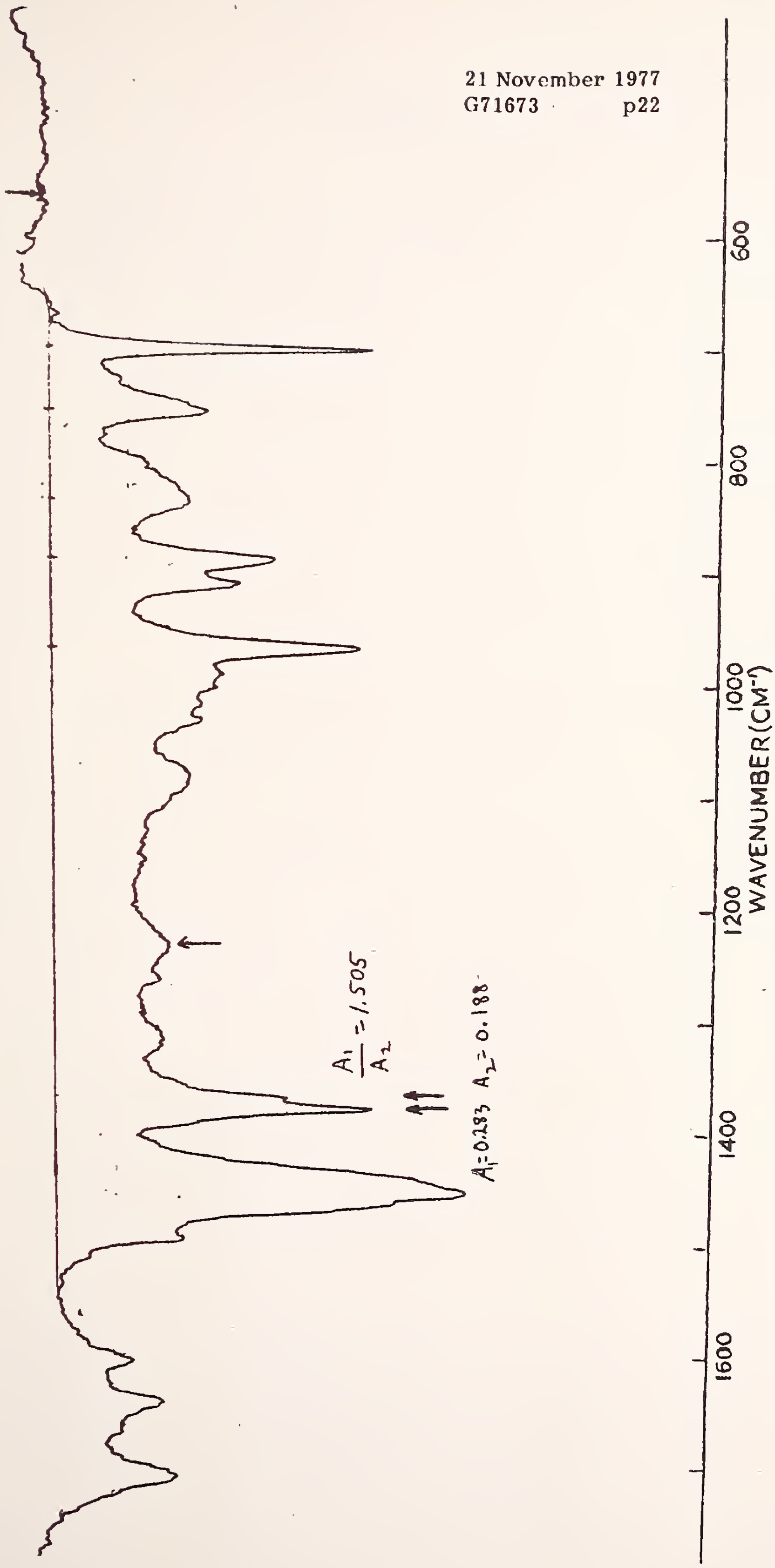


Figure 10. IR Scan - Pyrolyzed Liner Rubber - High Oxidation-Degradation (Butyl) T5X 1223

GLOSSARY

<u>Anomaly</u>: Departure from a regular condition. Specifically, in Ultrasonic Nondestructive inspection a deviation from the regular pattern of ultrasonic traces appearing in the hard copy trace of the ultrasonic tire inspection system.

<u>Analysis</u>: The act of inspecting the ultrasonic hard copy printout, listing the location and severity of any anomalies as a function of their probable impact on five discrete parts of the tire: tread, belt, sidewall, carcass, liner.

<u>Defect</u>: A latent condition within a failed tire found by non-destructive inspection or failure analysis as the cause of a specific failure.

<u>Failure</u>: A tire which has been considered to have failed MVSS 109. Specifically, one having any of the defects called out in the regulation; cord separation, groove or liner cracks, loss of air. A tire can be considered a failure even if it was not identified as such if the above defects can be proved to exist by nondestructive means.

<u>Failure Analysis</u>: The act of sectioning and inspection of a tire in an attempt to understand what condition led to failure of the tire.

<u>Failure Mechanism</u>: The detection and logical connection between a condition judged to exist within a tire prior to its failure and the subsequent failure of that tire.

Faying Surface: The surface at which bonding occurs between two components within the tire.

Flaw: A characteristic within a tire which could be expected to lead to its degradation and possible failure.

Singularities: An anomalous condition observed within the tire either during visual inspection or during sectioning and analysis. It is a condition in which there is no known link to degradation and failure.

REFERENCES

1. Ryan, R.P., "A Semi-Automated Pulse-Echo Ultrasonic System for Inspecting Tires," Report DOT-TSC-NHTSA-76-3/HS-802-104/ PB-272 323 July 1977.

2. Lavery, A.L., Nondestructive Tire Testing; Material on file at DOT/TSC.

3. Ceccon, H.L., "Holographic Techniques for Nondestructive Testing of Tires," Report DOT-TSC-NHTSA-72-4/HS-820-227/ PB-214 258, April 1972.

4. Bobo, S.N., Detection of Overbuff in Retreaded Tires; Material on file at DOT/TSC.

5. Clark S.K., "Mechanics of Pneumatic Tires," NBS Monograph 122, July 1972.

6. Clark, S.K., "Inspection Techniques for Passenger Car Tire Beads," DOT/TSC. In preparation.

220 copies

U.S. DEPARTMENT OF TRANSPORTATION
RESEARCH AND SPECIAL PROGRAMS ADMINISTRATION
TRANSPORTATION SYSTEMS CENTER
KENDALL SQUARE, CAMBRIDGE, MA. 02142

OFFICIAL BUSINESS
PENALTY FOR PRIVATE USE, $300

POSTAGE AND FEES PAID
U.S. DEPARTMENT OF TRANSPORTATION
613

U.S. MAIL