

**Elastomers for Tracked Vehicles:
1980–1997 Program to Improve Durability
of Rubber Tank Pads for Army Tracked Vehicles**

by David P Flanagan, Paul Touchet, and Henry O Feuer

ARL-TR-7331

June 2015

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Elastomers for Tracked Vehicles: 1980–1997 Program to Improve Durability of Rubber Tank Pads for Army Tracked Vehicles

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REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
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1. REPORT DATE (DD-MM-YYYY) June 2015		2. REPORT TYPE Final		3. DATES COVERED (From - To) September 1980–September 1997	
4. TITLE AND SUBTITLE Elastomers for Tracked Vehicles: 1980–1997 Program to Improve Durability of Rubber Tank Pads for Army Tracked Vehicles				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) David P Flanagan, Paul Touchet, and Henry O Feuer				5d. PROJECT NUMBER AH80	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) US Army Research Laboratory ATTN: RDRL-WMM-C Aberdeen Proving Ground, MD 21005-5069				8. PERFORMING ORGANIZATION REPORT NUMBER ARL-TR-7331	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) US Army Tank Automotive Research, Development and Engineering Center 6305 East 11 Mile Road Warren, MI 48092				10. SPONSOR/MONITOR'S ACRONYM(S) TARDEC	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT Military tracked vehicles are equipped with rubber track pads or endless-band rubber track to reduce noise and wear, improve traction, and reduce damage to road surfaces. Historically, field performance of the rubber components has been poor. ARL initiated an effort to develop improved rubber compounds for the track pads on military tracked vehicles. Following an extensive series of rubber formulating, mixing, laboratory testing, and field testing, an elastomeric compound coded NBR-12 was developed. This compound was based on a highly saturated nitrile rubber or hydrogenated acrylonitrile-butadiene rubber (HNBR) reinforced with a small particle size carbon black, grafted with zinc methyl methacrylate domains, and vulcanized with a peroxide. The NBR-12 material provided more resistance to heat, abrasion, cutting, chipping, and flex fatigue compared to all other commercial track pad materials evaluated in this program. This material provided a 2- to 3-fold increase in service life of pads on the M-60, M-1, and Counter Obstacle Vehicle. During the late 1990s, 2 of the critical ingredients for NBR-12 (Z Max MA and MPC black) became unavailable. Additional work is needed to replace these ingredients. Natural rubber compounds provided excellent tear properties but lacked the necessary abrasion resistance needed for track pad applications, and were better suited for bushing and road wheel applications. Tri-blends of the polymers styrene butadiene rubber, natural rubber, and polybutadiene rubber exhibited potential for future consideration as candidate track pad compounds.					
15. SUBJECT TERMS elastomer, track vehicles, formulations, physical properties					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UU	18. NUMBER OF PAGES 84	19a. NAME OF RESPONSIBLE PERSON David Flanagan
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified			19b. TELEPHONE NUMBER (Include area code) (410) 306-0691

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1. Introduction

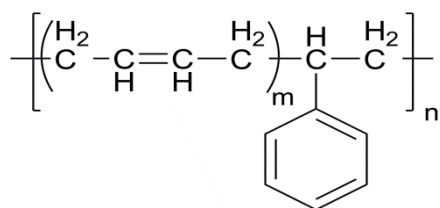
Military tracked vehicles are equipped with rubber track pads or endless-band rubber track to reduce noise and wear, improve traction, and reduce damage to road surfaces. Historically, field performance of the rubber components of such US Army tracked vehicles as the M-60, M-1, and Bradley has been poor. The problem is further complicated with off-the-road service conditions where rubber pads fail at a faster rate. The severity of the wear is more pronounced on the latest M-1 main battle tanks and the Bradley vehicles than the previous M-60 tanks because of increased weight and speed, coupled with smaller rubber footprints, which produce much higher stresses and greater heat buildup. Therefore, to keep the tanks operational, costly and frequent rubber track pad replacement is needed, resulting in increased down time.

The Army has identified the tank track's elastomeric components as a major generic cost driver in military tracked vehicles. As an initial step in efforts to reduce the operational costs, the US Army Tank Automotive Command provided funding to many university, industry, and government laboratories in the 1980s to develop new and improved track pads that have a longer service life, thereby reducing downtime and replacement costs. The Rubber Research Group of the Belvoir Research, Development and Engineering Center (BRDEC) of Ft. Belvoir, VA, which moved in 1997 to the Polymers Engineering Team within the US Army Research Laboratory (ARL) at Aberdeen Proving Ground, MD, has been a central contributor to the technological base for new track and suspension elastomeric materials. Initially the physical and mechanical characteristics of various vendors' elastomeric compounds for tank pads were measured to assemble a database and draft target performance requirements for the tank pads. A great number of compound formulations were then prepared and tested to investigate the effect of different base polymer, vulcanization, filler, and antioxidant systems on the mechanical and performance properties.

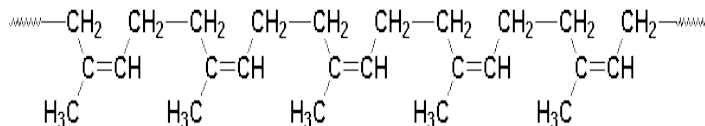
The efforts of the Rubber Research Group, then at Fort Belvoir, VA, produced a patented rubber formulation (NBR-12) based on hydrogenated nitrile rubber (HNBR)^{1,2} with a novel curing and filler system that was found to offer unique properties for pad applications. The HNBR compound demonstrated substantially improved performance on the M-60 tank over commercial materials and the conventional compounds under MIL-T-11891.³ This compound demonstrated a 2- to 3-time service life performance of standard MIL-T-11891 track pad elastomers. Much has been said about the performance of this compound, and much work still needs to be done to optimize and elucidate the mechanisms involved that make this compound outrank all other standard production materials.⁴⁻⁹

ARL initiated an effort to develop improved rubber compounds for the track pads on military tracked vehicles. The project encompassed a broad range of research in new emerging materials and processing techniques to provide rubber formulations for roadside track pad materials with increased service life. The polymers used in this study are described below:

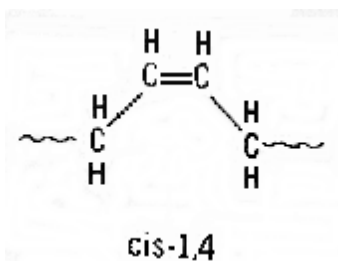
- **Styrene butadiene rubber (SBR)¹⁰:** SBR, a copolymer of styrene and butadiene, is the most important and widely used synthetic rubber in the world. Polymerization of butadiene ($\text{CH}_2=\text{CH}-\text{CH}=\text{CH}_2$) occurs by adding one butadiene unit to another, repeated several thousand times over. The SBR chemical structure is shown here:



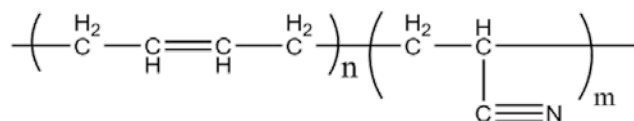
- **Natural rubber (NR)¹⁰:** NR is produced commercially from the latex obtained from the Hevea rubber trees. NR is classified into 8 types, which are broadly differentiated by the method of processing and source of the raw materials used. Within each type the visual quality is differentiated into 35 grades. NR is a linear, long chain polymer known chemically as cis-1,4 polyisoprene, and its chemical structure is shown here:



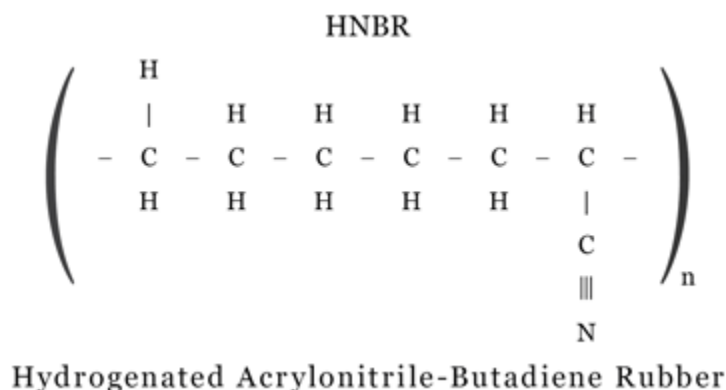
- **Polybutadiene rubber (BR)¹⁰:** BR can be prepared in either emulsions or solution systems. Most is produced by solution polymerization. BR is widely used in tires to produce the better and longer-wearing tires required by heavy high-performance vehicles.



- **Acrylonitrile butadiene or nitrile rubber (NBR)¹⁰:** NBR is the generic name given to emulsion polymerized copolymers of acrylonitrile and butadiene:

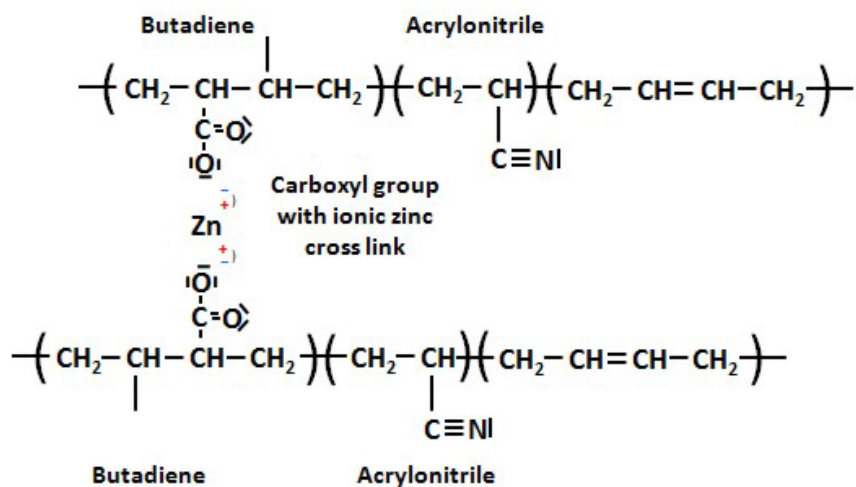


- **Highly saturated or hydrogenated nitrile rubber (HNBR):** HNBR is a new group of specialty rubbers manufactured by the catalytic hydrogenation of NBR.



During this process the nitrile groups remain unchanged while the carbon-carbon double bonds in NBR convert into more stable single bonds. Because of the reduction in double bonds, HNBR provides superior resistance to ozone, weathering, and heat when compared to SBR, NR, BR, and NBR. HNBRs are vulcanized with peroxides and the latter with sulfur/sulfur donor and accelerator or with peroxides.

- **Carboxylated nitrile rubber (XNBR):** XNBRs are made by copolymerizing butadiene, acrylonitrile, and an organic acid monomer in an emulsion system, and adding a stabilizer. XNBR provides much better resistance to heat and abrasion when compared to NBR.



2. Laboratory Investigation

Traditionally, roadside track pads are based on SBR/NR blends or SBR/NR/BR tri-blend rubber formulations with conventional curing systems. These materials usually fail prematurely in service because of poor chunking and chipping resistance, excessive wear from poor abrasion resistance, blowout, or rubber-to-metal bond failure (Figs. 1 and 2). In many cases these compounds undergo anaerobic thermal degradation or reversion.¹¹ This reversion is due to the thermal degradation of the sulfidic cross-links, which are formed during the vulcanization process. This degradation leads to a reduction in cross-link density and changes in the distribution of cross-link types and the introduction of main chain modifications.¹¹ Such changes translate into a decline in the physical properties and performance characteristics of the rubber compound and, eventually, to a reduction in the service life of the tank pads. Obviously, improved service durability of rubber track pads would provide economic, tactical, and logistical advantages for the modern high-speed tracked vehicles.



Fig. 1 Pad failure from blowout



Fig. 2 Typical commercial pad failure mode

In this program we have taken what was being learned in other reported track pad efforts at BRDEC during this same time period and applied it to this program. Previous studies^{1-9,12-15} have identified several desired material properties for optimum track pad performance. These properties are presented in Table 1.

Table 1 Desired properties for candidate track pad material

Original Properties	Measured Value
Tensile strength (PSI)	>3000
Elongation (%)	>500
Hardness, shore A (points)	72-80
Abrasion resistance (Pico rating)	>500
Tear strength, ASTM die C	...
Unaged, lb/inch (tested at room temp.)	>400
After aged 4 h at 250 °F (tested at 250 °F)	>200
De Mattia flex properties	...
Unaged	...
Crack growth rate (mils/min)	<20
After aging 70 h at 212 °F	...
Crack growth rate (mils/min)	<100
Goodrich flex at 50 °C	...
Internal temperature rise (°C)	<100
External temperature rise (°C)	<60
Blowout no. 1 time at 141.6 PSI (min)	<30

The physical properties of commercially available track pad compounds formulated and vulcanized by US manufacturers are presented in Table 2. Rubber formulations from these vendors are considered proprietary and are not reported here. The track pad materials were provided mixed but unvulcanized. The cure time for each compound was determined from the rheometer cure curve at 290, 300, 310 and 320 °F (depending on the particular polymer and curing system). The rheometer curves were run on the Monsanto Oscillating Disk Rheometer according to ASTM D 2084. The vulcanization time for each material was selected by using the time to reach 95% of maximum torque value. The materials were then vulcanized at the selected temperature using the cure time established from the rheometer cure curve. The effect of compounding ingredients on its properties was measured using a wide range of laboratory physical properties. The sample preparation was conducted in-house using ASTM D 3182. The laboratory tests performed on these materials are shown in paragraphs 8–11 of Table 3.

Properties of commercial track pads obtained from foreign companies are presented in Table 4. The track pads were provided molded and vulcanized. The samples were prepared from the pads using ASTM D 3183. The laboratory tests performed on these materials are shown in paragraphs 8–11 of Table 3.

Table 2 Pad materials obtained from industry: properties

Compound ID	TP-A	TP-B	TP-C	TP-D	TP-E	TP-F	TP-G	TP-H	TP-I	TP-J	TP-K	TP-L	TP-M
Supplier	Firestone	Goodyear	Std Product	Std Product	RRAD	Firestone	Firestone	Firestone	Dupont	Dupont	Tel Monarch	Goodyear	Goodyear
Supplier Material ID	NB-907	SM-8622	S-378	S-379	T-97, Mixed by Mohawk	NK-177	TS-934	TS-935	1181	1182	K-14		SM8671
							Cd 14A	Cd 10L	Nat/Neoprene	Nat/Neoprene		Cd 14A	
Month/Year Supplied	4/83	4/83	4/83	4/83	4/83	9/84	9/84	9/84	10/84	10/84	11/84	11/84	11/84
Properties													
Mooney Viscometer													
ML +4 at 212 Deg F	61	74	58	50	45	47	---	72	33	76	78	57	68
T5 @ 250 Deg F, Minutes	57	45	28	27	5	26		83	9	8	6	39	78
Cure Conditions, Minutes/Deg F	35/310	35/310	25/310	25/310	30/310	40/290	35/310	35/320	15/300	15/300	25/290	40/300	40/320
Original Properties													
Tensile Strength, psi	2817	2667	2883	2442	3100	3250	2700	2617	3443	3167	4123	2887	2627
200% Modulus, psi	575	802	1500	883	883	757	1200	1407	1013	1413	1063	500	800
Ultimate Elongation, %	513	500	350	490	507	503	370	323	517	383	500	377	527
Hardness, Shore A	69	80	75	80	78	69	74	76	73	75	66	78	78
Bashore Rebound, %	36	32	33	32	32	36	34	34	23	24	49	35	29
Specific Gravity	1.1559	1.6910	1.1936	1.1705	1.1254	1.1335	1.1554	1.1649	1.2314	1.2333	1.1210	1.1539	1.1592
Abrasion Tests													
Taber, Grams/1000 Cycles	0.0364	0.1415	0.0415	0.2320	0.1816	0.0175	0.0809	0.0136	0.2570	0.0255	0.0338	0.0177	0.1113
Pico, Rating	101	98	134	141	129	87	110	159	120	127	131	73	71
Tear Strength Using ASTM Die C													
Unaged, Lb/in	310	326	335	361	299	270	322	254	535	279	554	271	281
10 Minutes @ 250 Deg F, Lb/in	115	124	109	180	120	171	152	130	345	201	320	175	152
De Mattia Flex Properties													
Unaged Growth Rate, Mils/Minute	24	33	37	26	50	30	31	64	8	13	12	33	21
Unaged Crack Initiation, Kilocycles	18	18	5	21	39	23	24	90	6	65	161	6	38
After 70 Hours @ 212 Deg F, Mils/Minute	103	97	208	89	105	87	76	362	10	30	15	334	35
Goodrich Flex Properties at 50 Deg C													
External Temperature Rise, Deg C	30.0	40.0	29	54.0	33.0	27.0	31.0	31.0	32.0	27.0	15.0	30.0	39

Table 2 Pad materials obtained from industry: properties (continued)

Compound ID	TP-N	TP-O	TP-P	TP-Q	TP-R	TP-S	TP-T	TP-U	TP-V	TP-W	TP-X	TP-Y	TP-Z
Supplier	Goodyear	Armstrong	Armstrong	Gates Rubber	Goodyear	Goodyear	Goodyear	Goodyear	Goodyear	Goodyear	Goodyear	Goodyear	Ames Rubber
Supplier Material ID	XA 28A594	579	580	VXD-1059	S-387	85-47-024.1	85-47-024.1	85-47-024.1	85-47-024.1	GY-NE	SM-8621	SM-8493	7365A
	LAC V 30 Finger				Nat with Novat with Novat w/ Curite 18					Natural Rub			
Month/Year Supplied	12/84	1/85	1/85	2/85	2/85	2/85	2/85	2/85	6/85	6/85	6/85	6/85	6/85
Properties													
Mooney Viscometer													
ML +4 at 212 Deg F	55	31	43	137	59	39	35	29	67	41	60	55	40
T5 @ 250 Deg F, Minutes	79	33	38	69	54	28	45	39	13	10	22	40	16
Cure Conditions, Minutes/Deg F	30/310	30/300	30/300	40/330	35/310	35/300	35/300	35/300	30/300	20/310	25/310	30/310	25/300
Original Properties													
Tensile Strength, psi	3117	3757	3230	2727	2977	2793	3240	3367	3630	3233	3107	3010	3343
200% Modulus, psi	890	730	1370	680	1217	1957	1920	1947	1113	1057	800	777	1120
Ultimate Elongation, %	500	570	433	443	407	277	330	330	503	470	517	520	453
Hardness, Shore A	73	63	62	69	78	85	82	74	68	75	69	69	65
Bashore Rebound, %	36	42	39	44	27	39	34	33	42	32	26	26	37
Specific Gravity	1.1357	1.1210	1.1369	1.1175	1.1719	1.1518	1.1549	1.1531	1.1489	1.1652	1.1642	1.1685	1.1387
Abrasion Tests													
Taber, Grams/1000 Cycles	0.0453	0.0442	0.0435	0.1001	0.0210	0.1443	0.0467	0.0458	0.0795	0.0849	0.0450	0.3080	0.2446
Pico, Rating	212	116	204	107	180	289	328	366	165	126	198	790	241
Tear Strength Using ASTM Die C													
Unaged, Lb/in	437	598	577	209	264	248	317	240	598	520	266	266	563
10 Minutes @ 250 Deg F, Lb/in	273	304	383	102	184	132	185	149	307	269	125	152	290
De Mattia Flex Properties													
Unaged Growth Rate, Mils/Minute	24	4	9	21	29	28	---	---	---	---	---	---	---
Unaged Crack Initiation, Kilocycles	59	289	37	77	47	40	---	---	---	---	---	---	---
After 70 Hours @ 212 Deg F, Mils/Minute	---	5	12	21	37	---	---	---	---	---	---	---	---
Goodrich Flex Properties at 50 Deg C													
External Temperature Rise, Deg C	29.0	22.0	26	42.0	28.0	34.0	---	---	---	---	---	---	---

Table 2 Pad materials obtained from industry: properties (continued)

Compound ID	TP-AA	TP-AG	TP-AH	TP-AI	TP-AJ	TP-AK	TP-AL	TP-AM	TP-AN	TP-AQ	TP-AR	TP-AS
Supplier	Ames Rub	L'Garde	Tel Monarch	TGL Ind.	TGL Ind.	Firestone/RRAD	Firestone/RRAD	Firestone/RRAD	Goodyear/RRAD	Firestone/RRAD	Firestone/RRAD	Firestone/RRAD
Supplier Material ID	7367D	465NR	15Nat-22A	#19	#77	15Nat-22A	15NSP-8	15NSP-11	15Nat-25A	15Nat-1	15NSP-4	15NSP-3
			From Belvoir			From Belvoir	From Belvoir	From Belvoir	From Belvoir	From Belvoir	From Belvoir	From Belvoir
Month/Year Supplied	6/85	7/85	7/85	8/85	8/85	8/85	8/85	8/85	8/85	8/85	8/85	8/85
Properties												
Mooney Viscometer												
ML +4 at 212 Deg F	43	32	62	50	75	78	140	93	35	57	200	50
T5 @ 250 Deg F, Minutes	27	8	9	20	16	6	5	11	7	7	---	11
Cure Conditions, Minutes/Deg F	30/310	25/290	40/300	35/310	35/300	20/310	23/300	40/300	25/300	40/290	40/290	40/290
Original Properties												
Tensile Strength, psi	3127	3913	3950	3380	3467	3127	1678	2090	3913	3917	2230	2410
200% Modulus, psi	1110	1070	737	880	663	407	360	630	700	630	1030	225
Ultimate Elongation, %	450	480	613	177	543	590	433	410	580	607	310	673
Hardness, Shore A	72	71	71	69	64	71	60	---	66	64	77	---
Bashore Rebound, %	30	42	45	29	39	43	32	---	45	41	26	---
Specific Gravity	1.1526	1.1188	1.0957	1.1379	1.1322	1.0910	1.1221	1.1352	1.0904	1.0916	1.1767	1.0533
Abrasion Tests												
Taber, Grams/1000 Cycles	0.0194	0.0319	0.0721	0.0184	0.0124	0.1310	0.0489	0.0662	0.0888	0.1878	0.0294	---
Pico, Rating	363	166	110	160	122	77	100	116	132	145	241	68
Tear Strength Using ASTM Die C												
Unaged, Lb/In	498	593	710	258	305	492	317	289	618	635	413	196
10 Minutes @ 250 Deg F, Lb/In	300	312	287	240	143	217	190	189	262	278	219	100
De Mattia Flex Properties												
Unaged Growth Rate, Mils/Minute	---	14	6.5	31	21	7	7	5	9	19	9	12
Unaged Crack Initiation, Kilocycles	---	---	55	---	---	50	240	28	18	70	47	30
After 70 Hours @ 212 Deg F, Mils/Min	---	25	5	598	40	7	11	11	10	24	153	17
Goodrich Flex Properties at 50 Deg C												
External Temperature Rise, Deg C	---	---	33	28.0	22.0	35	40	27	22	27	12	17

Table 2 Pad materials obtained from industry: properties (continued)

Compound ID	TP-AT	TP-AU	TP-AV	TP-AW	TP-AX	TP-A1	TP-A2	TP-A3	TP-A4	TP-A5	TP-A6	TP-A7
Supplier	Gates Rub	Pirelli	Pirelli	Caterpillar	Caterpillar	Woodville	Polycraft	Polycraft	Polycraft	Brad Ragan	Brad Ragan	Brad Ragan
Supplier Material ID	Cd X-2730	N-10050	N-10053	F 748	F 794	X-143	Item 003	Item 004	Item 005	MSBR + 2.2 parts	ORLE + 1.5 parts	CTA + 2 parts
							SBR/PU	Nat/SBR/PBD	Nat/SBR/PBD	Cellulose Fibers	Cellulose Fibers	Cellulose Fibers
Month/Year Supplied	10/85	12/85	12/85	1/86	1/86	6/86	6/86	6/86	6/86	6/86	6/86	6/86
Properties												
Mooney Viscometer												
ML +4 at 212 Deg F	73	65	30	---	---	63	57	46	55	39	40	40
T5 @ 250 Deg F, Minutes	18	96	19	---	---	19	45	33	25	---	---	---
Cure Conditions, Minutes/Deg F	20/290	50/310	30/300	---	---	40/300	40/350	40/340	55/320	30/300	30/290	35/300
Original Properties												
Tensile Strength, psi	3463	2840	3450	3480	3730	2790	803	2130	2140	3483	3793	2890
200% Modulus, psi	1850	740	690	810	820	1040	---	1610	1397	683	773	583
Ultimate Elongation, %	343	600	550	570	580	380	40	247	270	580	530	583
Hardness, Shore A	80	68	66	74	66	73	91	76	70	68	64	67
Bashore Rebound, %	39	31	53	32	44	37	28	32	36	36	47	33
Specific Gravity	1.1506	1.1650	1.126	1.1685	1.1473	1.1382	1.2216	1.1701	1.1577	1.1324	1.1016	---
Abrasion Tests												
Taber, Grams/1000 Cycles	0.0863	0.4028	0.5054	---	0.1669	0.0332	0.2733	0.0211	0.0300	---	---	---
Pico, Rating	356	118	98	289	278	702	71	163	143	113	146	---
Tear Strength Using ASTM Die C												
Unaged, Lb/in	295	314	303	631	642	298	142	186	180	506	395	259
10 Minutes @ 250 Deg F, Lb/in	239	152	198	321	350	200	50	88	90	264	280	170
De Mattia Flex Properties												
Unaged Growth Rate, Mils/Minute	---	13	12	7	7	20	---	585	527	11	46	---
Unaged Crack Initiation, Kilocycles	---	29	53	---	---	17	---	13	5	---	---	---
After 70 Hours @ 212 Deg F, Mils/Minute	---	33	14	28	14	31	---	599	574	12	25	---
Goodrich Flex Properties at 50 Deg C												
External Temperature Rise, Deg C	---	---	---	---	---	35	67	47	44	36	---	48

Table 3 Processing, properties, and test methods

Test	Test Method
1. Rheometer data and curve to establish cure and processing conditions	ASTM D 2084
2. Mill mixing procedure for natural rubber	ASTM D 3184
3. Mill mixing procedure for SBR rubber	ASTM D 3185
4. Mill mixing procedure for polybutadiene rubber	ASTM D 3189
5. Mill mixing procedure for nitrile, carboxylated nitrile, and HNBR rubber	ASTM D 3187
6. Preparation and vulcanization of rubber samples for laboratory testing	ASTM D 3182
7. Preparation of test samples from tank pads	ASTM D 3183
8. Properties of cured rubber run at room temperature	
• Tensile strength	ASTM D 412, method A
• Elongation	ASTM D 412, method A
• 100% and 200% modulus	ASTM D 412, method A
• Hardness, shore A	ASTM D 2240
• Resilience, Bashore rebound	ASTM D 2632
• Tear strength, die C	ASTM D 624, die C
• Abrasion, Pico	ASTM D 2228
• Abrasion, Taber	ASTM D 3389, using S-35 wheel and 1000-g load
• Cutting and chipping	Goodrich method
• Specific gravity	ASTM D 792, para 15
9. Properties on cure materials run at 250 °F	ASTM D 573
• Tear strength, die C	ASTM D 624, die C
10. Flex fatigue tests	
• De Mattia cut growth, unaged and tested at room temperature	ASTM D 813
• De Mattia crack initiation tested at room temperature	ASTM D 430
• De Mattia cut growth after aged 20 h at 212 °F	ASTM D 813
• Goodrich flex at 122 °F	ASTM D 623, method A using a 0.175-inch stroke and 141.6 PSI for heat buildup and using a 0.30-inch stroke with 141.6 PSI pressure for blowout test
• Ross flex, crack growth unaged and after aging at 212 °F	ASTM D 1052
11. Compression set after 22 h at 160 °F	ASTM D 395, method B

Table 4 Commercial pads obtained from foreign countries: properties

Compound ID	NBR-12	TP-AF	TR-543	TR-129	TR-131	TR-132	TR-133	TR-134	TR-135	TR-136
Supplier	Belvoir	Std Produc	Diehl	??	TRACKS	??	Kuerossier	Skego	Avon	??
Supplier Material ID	NBR-12	S-379	??	??	??	??	??	??	??	??
Track Vehicle Used On	M-1	M1 & M60	Leopard	Vickers	74MBT	ANX-30	??	??	Chieftain	AMX-13
Country	USA	USA	Germany	England	Japan	France	Austria	Sweden	England	France
Properties										
Original Properties										
Tensile Strength, psi	3960	3070	3970	2975	3840	3460	2900	3410	3360	3350
200% Modulus, psi	843	1100	1500	1300	900	1110	1360	1210	1760	1055
Ultimate Elongation, %	570	460	450	385	530	450	340	470	340	490
Hardness, Shore A	78	74	73	74	65	72	72	77	74	77
Bashore Rebound, %	30	30	45	39	42	40	44	30	41	36
Specific Gravity	1.1373	1.1188	1.1236	1.1464	1.1094	1.1248	1.1262	1.1688	1.1459	1.1490
Abrasion Tests										
Taber, Grams/1000 Cycles	0.0015	0.0434	0.0744	0.0228	0.1688	0.0132	0.1263	---	0.1361	---
Pico, Rating	691	179	136	142	122	255	139	166	143	180
Tear Strength using ASTM Die C										
Unaged, Lb/in	449	268	315	368	373	433	475	315	315	478
10 Minutes @ 250 Deg F, Lb/in	234	141	294	301	306	302	357	190	318	313
Goodrich Cutting and Chipping										
Diameter Loss, Inches	0.05	0.16	0.126	---	---	---	---	---	---	---
Weight Loss, Grams	0.75	2.28	1.7336	---	---	---	---	---	---	---
Ross Flex, 250,000 Cycles										
Unaged Growth, %	6	600	142	167	100	117	250	533	250	117
After 70 Hours @ 212 Deg F, Crack Growth,	6	967	100	400	117	FAILED	267	483	FAILED	Failed
Goodrich Flex Properties at 50 Deg C										
External Temperature Rise, Deg C	58	28	18	21	17	18	19	29	21	29
Internal Temperature Rise, Deg C	84	---	33	---	---	---	---	---	---	---
Blowout Time @141.6 psi, Minutes	8	21	>120	>120	>120	>120	>120	>120	>120	>120
Heat Resistance, Aged 70 Hours @ 250 °F										
Elongation Retention, %	81	33	18	16	16	12	18	35	10	10
Tensile Retention, %	100	22	13	17	12	21	15	68	16	18

Table 4 Commercial pads obtained from foreign countries: properties (continued)

Compound ID	NBR-12	TP-AF	TP-AI	TP-AJ	TP-AU	TP-AV	TP-AY	TP-AZ	TP-A1	TR-534
Supplier	Belvoir	Std Product	TGL	TGL	Pirelli	Pirelli	Forsheda	ong & Hambl	Woodville	??
Supplier Material ID	NBR-12	S-379	#19	#77	#10050	#10053	??	#10413	#X-143	??
Track Vehicle Used On	M-1	M1 & M60	Bradley	Bradley	??	??	??	??	??	??
Country	USA	USA	Israel	Israel	Italy	Italy	Sweden	England	England	Switzerland
Properties										
Original Properties										
Tensile Strength, psi	3960	3070	3380	3470	2840	3450	3920	3180	2790	3200
200% Modulus, psi	843	1100	880	660	740	690	1700	1510	1040	900
Ultimate Elongation, %	570	460	477	540	600	550	360	340	380	510
Hardness, Shore A	78	74	71	65	69	66	75	75	74	69
Bashore Rebound, %	30	30	29	39	31	53	34	45	37	24
Specific Gravity	1.1373	1.1188	1.1379	1.1322	1.1650	1.1260	1.1847	1.1668	1.1382	1.1810
Abrasion Tests										
Taber, Grams/1000 Cycles	0.0015	0.0434	0.0184	0.0124	0.4028	0.5054	0.0232	0.3662	0.0333	0.0246
Pico, Rating	691	179	160	122	118	98	367	275	148	474
Tear Strength using ASTM Die C										
Unaged, Lb/In	449	268	258	305	314	303	231	207	298	309
10 Minutes @ 250 Deg F, Lb/In	234	141	240	143	152	198	156	171	203	162
Goodrich Cutting and Chipping										
Diameter Loss, Inches	0.050	0.160	0.209	0.284	0.185	0.347	0.249	0.424	0.183	0.071
Weight Loss, Grams	0.750	2.280	3.208	3.720	2.622	4.424	3.336	5.124	2.551	1.050
Ross Flex, 250,000 Cycles										
Unaged Growth, %	6	600	125	150	317	94	656	108	322	125
After 70 Hours @ 212 Deg F, Crack Growth	6	967	FAIL	183	378	111	FAIL	Fail	372	133
Goodrich Flex Properties at 50 Deg C										
External Temperature Rise, Deg C	58	28	28	22	30	16	26	40	35	38
Internal Temperature Rise, Deg C	84	---	---	---	---	---	---	60	83	79
Blowout Time @141.6 psi, Minutes	8	21	13	23	15	>120	19	>120	>120	25
Heat Resistance, Aged 70 Hours @ 250 °F										
Elongation Retention, %	81	33	11	42	36	13	27	5	53	48
Tensile Retention, %	100	22	27	69	85	12	63	16	36	86

Fifteen-hundred-gram batches of ingredients for SBR, NR, BR, NBR, HNBR, and XNBR rubber formulations were mixed on a laboratory 6-inch-diameter rubber mill according to ASTM D 3185 for SBR, ASTM D 3184 for NR, ASTM D 3189 for BR, and ASTM D 3187 for nitrile, HNBR, and XNBR rubbers. The formulated compounds were processed as previously described for the commercially supplied materials. The effect of compounding ingredients on the properties was measured using a wide range of laboratory physical tests. The rubber formulating, mixing, and sample preparation were all conducted in-house, as presented in paragraphs 1–7 of Table 3. The laboratory tests performed on these materials are shown in paragraphs 8–11 of Table 3.

Formulations and properties of rubber compounds developed at BRDEC are presented in the Results and Discussion section. Additional information on the rubber polymers and compounding ingredients used in this study may be found in editions 1985–1997 of *The Blue Book: Materials, Compounding Ingredients, Machinery and Services for the Rubber Industry*.¹⁶

3. Results and Discussion

The task of assembling a definitive set of target performance requirements for a given application was by no means a trivial one. The pads of an endless track are affected in several ways during service. Directly, they are subjected to cuts, tears, chunking, blowouts, and abrasive wear. Indirectly, the damage can be caused by hysteretic heating, environmental convection, and surface/terrain heating. To achieve improved field performance, the rubber compounder was faced with the tremendous task of optimizing all the properties affected by these conditions.

Apart from specific requirements, many times we must rely upon our detailed knowledge of the application, and our experience and intuition. Therefore, Table 1 is a compendium of all the above, along with years of experience in compounding and testing rubber for dynamic applications, observations, and analysis of test results. However, they are not meant to be interpreted as a hard and fast set of unbreakable rules. Previous compounding studies, field testing of track pads, and attempts to correlate lab data with field test results during the 1980s^{4,8,9} led to the desired properties listed in Table 1. The 4 highlighted properties (Elongation, Tear at 250 °F, De Mattia Crack Growth, and Pico Abrasion Resistance) from a total of 35 laboratory tests on 11 pad materials (6 government experimental materials and 5 commercial) served as the best predictors of field performance. The statistical analysis was performed using T142 pads on an M60 tank during the mid 1980s. Funding was not available in later years to perform this analysis on T158 or T157 pads for the M-1.

The laboratory properties of 50 rubber track pad materials from 16 companies are presented in Table 2. In Table 4 the properties of 16 commercial pad materials from 9 foreign countries are compared to the properties of one commercial US pad supplier and an experimental material

(NBR-12) developed at BRDEC. The NBR-12 material provides far more resistance to heat, abrasion, cutting, chipping, and flex fatigue compared to all other commercial materials.

SBR formulations using the same SBR 1500 polymer with various curing systems are provided in Table 5a, and their laboratory properties are shown in Table 5b. The SBR 1500 rubber provided better abrasion resistance but lower tear resistance than NR. The hardness of formulations SBR-23 through 25 (Table 5b) were lower than required by Table 1. The elongation (233%) for SBR-15 was much too low, while all the other materials exhibited acceptable hardness. Not all of the materials provided adequate resistance to abrasion or tear. The formulations with low sulfur curing systems (SBR-22 through 25) provided the best De Mattia flex fatigue, and all materials except SBR-15 provided poor blowout resistance. Formulation SBR-22, with the Novor 924 curing system, provided the best heat resistance but exhibited the worst abrasion resistance and the highest rate of heat buildup.

Table 5a SBR formulations: cure systems

Compound ID	SBR-1	SBR-9	SBR-11	SBR-12	SBR-13	SBR-14	SBR-15	SBR-22	SBR-23	SBR-24	SBR-25
INGREDIENTS											
Firestone FRS 1500 SBR Rubber	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Zinc Oxide	4.00	---	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00
Stearic Acid	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
N-121, SAF-HS Black	45.00	45.00	45.00	45.00	45.00	45.00	45.00	45.00	45.00	45.00	45.00
Antiox. DQ, Agerite Resin D	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Agerite White	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Antozite 2	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00
Sulfur, Rubber Makers	2.00	2.00	---	---	2.00	1.50	5.00	0.40	0.60	1.00	0.75
Santocure	1.50	1.50	1.50	---	1.00	1.50	1.50				
Sulfur Spider Brand	---	---	2.00	---	---	---	---	---	---	---	---
Polydox S (SS-75)	---	---	---	2.67	---	---	---	---	---	---	---
Polydox S (SA-75))	---	---	---	2.00	---	---	---	---	---	---	---
Novor 924	---	---	---	---	---	---	---	4.20	---	---	---
TMTM, Monex	---	---	---	---	---	---	---	1.50	---	---	---
Santocure NS	---	---	---	---	---	---	---	0.08	---	---	---
Morfax	---	---	---	---	---	---	---	---	1.88	---	---
Octoate Z	---	---	---	---	---	---	---	---	1.50	1.50	1.50
Amyl Ledate	---	---	---	---	---	---	---	---	0.75	0.75	1.00
Amax	---	---	---	---	---	---	---	---	---	1.75	1.88
Formula Weight	158.50	154.50	156.50	155.00	158.00	158.00	161.50	155.40	155.60	156.00	155.75

Table 5b SBR properties: cure systems

Compound ID	SBR-1	SBR-9	SBR-11	SBR-12	SBR-13	SBR-14	SBR-15	SBR-22	SBR-23	SBR-24	SBR-25
Properties											
Mooney Viscometer											
Mooney, ML +4 at 212 Deg F	63.4	62.7	64.3	65.3	65.6	61.7	63.7	63.1	57.3	57.5	56.3
Scorch Safety, T5 @ 250 Deg F, Minutes	10.0	11.0	10.0	9.5	12.9	12.4	6.1	14.6	10.9	9.2	9.9
Cure Conditions, Minutes at 310 Deg F	30	30	30	30	30	30	30	35	20	20	20
Original Properties											
Tensile Strength, psi	3911	3629	3557	3367	3580	3642	2498	3028	2782	3583	3782
200% Modulus, psi	667	712	728	635	542	440	1911	340	443	415	347
Ultimate Elongation, %	493	471	467	466	520	566	233	680	517	603	687
Hardness, Shore A	67	70	72	70	70	67	78	68	60	60	58
Bashore Rebound, %	39	37	37	35	38	37	34	41	41	41	42
Specific Gravity	1.1319	1.1216	1.1177	1.1172	1.1204	1.1235	1.1389	1.1131	1.1171	1.1171	1.1161
Abrasion Tests											
Taber, Grams/1000 Cycles	0.1844	0.1499	0.0993	0.1662	0.1445	0.0993	0.0743	0.1213	0.0603	0.0503	0.0801
Pico, Rating	143	134	131	123	132	126	175	100	129	122	117
Tear Strength Using ASTM Die C											
Unaged, Lb/In	304	319	318	330	298	315	239	310	320	301	300
10 Minutes @ 250 Deg F, Lb/In	165	133	146	151	151	150	104	157	132	119	157
De Mattia Flex Properties											
Unaged Growth Rate, Mils/Minute	26.1	34.4	33.8	25.0	20.3	13.3	>64	12.5	14.8	16.4	12.5
After 70 Hours @ 212 Deg F, Mils/Minute	240	432	414	430	247	35	41	10	24	34	14
Goodrich Flex Properties at 50 Deg C											
External Temperature Rise Rate, Deg C/Mi	6.4	6.6	5.6	6.2	6.9	6.8	5.1	8.0	6.3	6.3	7.2
Blow Out Time at 141.6 psi, Minutes	25	26	14	19	17	13	>120	14	15	20	17
Heat Resistance at 250 Deg F											
Stress Relaxation, F/F0 at 250 Deg F = 70%	500	---	543	340	305	260	---	998	765	930	1060
After Heat Aging for 70 Hrs at 250 Deg F											
Elongation Retention, %	33	---	34	36	28	25	9	80	38	65	64
Tensile Retention, %	59	---	61	68	56	51	36	100	43	67	45

Formulations of SBR 1500 from 7 suppliers are provided in Table 6a, and their properties are compared in Table 6b. All of the formulations used identical filler, antioxidant, and curing systems. Formulation SBR-26, which used the copolymer SBR 1500 polymer, provided the best balance of properties and excelled in flex fatigue and heat resistance. This material, however, exhibited the worst blowout resistance, followed by SBR-36 (with Synpol 1500) and SBR-35 (with Ameripol 1500). The formulation containing the Gentro SBR 1500 provided the best abrasion resistance. Formulations SBR-26, 34, 42, and 43 provided the highest resistance to blowout. SBR-35 and 36 exhibited the lowest Pico abrasion resistance. All materials provided essentially the same resistance to tear. SBR-26 (with Copo 1500) provided the highest crack growth rate at 212 °F, while all other materials provided similar crack growth values.

Various formulations using 5 SBR 1502, 4 SBR 1503, and 1 SBR 1500 polymers are presented in Table 7a. Their properties are compared with the FRS 1500 SBR (SBR-1) in Table 7b. Formulation SBR-49 (Copo SBR 1502) provided very low original tensile and elongation values. Pico abrasion was run on only 2 materials (SBR-44 and 47), and both materials provided substantially better abrasion resistance than the SBR-1 containing the SBR-1500 polymer. All of the formulations provided similar resistance to tear. The blowout test was only run on the SBR-47 material (with the Ameripol 1502 polymer), and its resistance to blowout was much better than for the SBR-1 material with the SBR-1500 polymer.

Formulations for 8 Hevea NR types, 1 synthetic NR (NR-27), and 1 Guayule NR (NR-65) are presented in Table 8a, and their properties are compared in Table 8b. In Table 8c all the properties for track pad potential are ranked individually from 1 (most desirable) to 10 (least desirable) and totaled for each material. The average ranking for each material is provided in the bottom row, with NR-68 (using SMR-5) providing the best potential and NR-27 (using the synthetic polymer) providing the lowest potential for use in track pads. Formulation NR-68 (containing the Guayule rubber) provided the best tear strength at 250 °F and least resistance to blowout. Formulations NR-87 (SIR-20), NR-21 (Pale Crepe no. 1), and NR-69 (SMR-WF) provided the best tear strength at room temperature (all over 600 lb/inch). Formulations NR-68 (SMR-5), NR-21 (Pale Crepe no. 1), and NR-20 (SMR-GP) provided the best tear strength at 250 °F (all over 300 lb/inch). Formulations NR-70 (SMR-CV), NR-87 (SIR-20), and NR-69 (SMR-WF) provided the best Pico abrasion resistance with rating values over 160, while NR-19 (SMR-CV), NR-20 (SMR-GP), and NR-65 (Guayule) provided the lowest rating (all below 122). All the materials exhibited similar unaged cut growth values, and formulations NR-19 (SMR-CV), NR-68 (SMR-5), and NR-27 (synthetic) provided the best crack initiation values of over 94 kilocycles for the first sign of cracking.

Table 6a SBR formulations: SBR 1500 from various suppliers

Compound ID	SBR-1	SBR-26	SBR-34	SBR-35	SBR-36	SBR-42	SBR-43
INGREDIENTS							
Firestone FRS 1500 SBR Rubber	100.00	---	---	---	---	---	---
Copolymer SBR 1500	---	100.00	---	---	---	---	---
Goodyear Plioflex SBR 1500C	---	---	100.00	---	---	---	---
Goodrich Ameripol SBR 1500	---	---	---	100.00	---	---	---
Texas US Synpol SBR 1500	---	---	---	---	100.00	---	---
Krylene SBR 1500	---	---	---	---	---	100.00	---
Gentro SBR 1500	---	---	---	---	---	---	100.00
Zinc Oxide	4.00	4.00	4.00	4.00	4.00	4.00	4.00
Stearic Acid	2.00	2.00	2.00	2.00	2.00	2.00	2.00
N-121, SAF-HS Black	45.00	45.00	45.00	45.00	45.00	45.00	45.00
Antiox. DQ, Agerite Resin D	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Agerite White	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Antozite 2	3.00	3.00	3.00	3.00	3.00	3.00	3.00
Sulfur, Rubber Makers	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Santocure	1.50	1.50	1.50	1.50	1.50	1.50	1.50
Formula Weight	158.50	158.50	158.50	158.50	158.50	158.50	158.50

Table 6b SBR properties: SBR 1500 from various suppliers

Compound ID	SBR-1	SBR-26	SBR-34	SBR-35	SBR-36	SBR-42	SBR-43
Properties							
Mooney Viscometer							
ML +4 at 212 Deg F	63.4	63.8	57.6	60.3	59.6	61.0	61.0
T5 @ 250 Deg F, Minutes	10.0	11.5	23.6	28.8	30.0	20.0	15.0
Cure Conditions, Minutes/Deg F	30/310	30/310	30/310	30/310	30/310	35/300	40/300
Original Properties							
Tensile Strength, psi	3911	3779	3297	3537	3357	4250	4210
200% Modulus, psi	667	734	937	970	920	603	830
Ultimate Elongation, %	493	525	437	443	453	595	547
Hardness, Shore A	67	65	68	68	67	65	66
Bashore Rebound, %	39	40	39	39	39	40	35
Specific Gravity	1.1319	1.1210	1.1217	1.1250	1.1250	1.1120	1.1274
Abrasion Tests							
Taber, Grams/1000 Cycles	0.1844	0.0575	0.1204	0.1160	0.0782	0.0801	0.0546
Tear Strength Using ASTM Die C							
Unaged, Lb/In	304	312	315	340	328	300	313
10 Minutes @ 250 Deg F, Lb/In	165	141	131	132	140	139	151
De Mattia Flex Properties							
Unaged Growth Rate, Mils/Minute	26.1	25.0	79.0	38.2	44.2	30.0	36.0
After 70 Hours @ 212 Deg F, Mils/Minute	240.0	18.0	494.0	359.0	406.0	408.0	408.0
Goodrich Flex Properties at 50 Deg C							
External Temperature Rise Rate, Deg C/Min	6.4	7.2	4.9	4.6	4.7	---	---
Blow Out Time at 141.6 psi, Minutes	25	>120	>120	51	36	>120	>120
Heat Resistance							
Stress Relaxation, F/F0 @ 250 Deg F = 70%	500	190	503	460	460	430	---
After Heat Aging for 70 Hrs at 250 Deg F							
Elongation Retention, %	33	85	21	22	20	39	38
Tensile Retention, %	59	76	54	42	44	66	75

Table 7a SBR formulations: SBR 1502 and 1503 from various suppliers

Compound ID	SBR-1	SBR-44	SBR-45	SBR-46	SBR-47	SBR-49	SBR-50	SBR-51	SBR-52	SBR-53
INGREDIENTS										
Firestone FRS 1500 SBR Rubber	100.00	---	---	---	---	---	---	---	---	---
Gentro SBR 1502	---	100.00	---	---	---	---	---	---	---	---
Krylene SBR 1502	---	---	100.00	---	---	---	---	---	---	---
Goodrich Plioflex SBR 1502	---	---	---	100.00	---	---	---	---	---	---
Ameripol SBR 1502	---	---	---	---	100.00	---	---	---	---	---
Copo SBR 1502	---	---	---	---	---	100.00	---	---	---	---
Gentro SBR 1503	---	---	---	---	---	---	100.00	---	---	---
Goodrich Plioflex SBR 1503	---	---	---	---	---	---	---	100.00	---	---
Ameripol SBR 1503	---	---	---	---	---	---	---	---	100.00	---
Copo SBR 1503	---	---	---	---	---	---	---	---	---	100.00
Zinc Oxide	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00
Stearic Acid	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
N-121, SAF-HS Black	45.00	45.00	45.00	45.00	45.00	45.00	45.00	45.00	45.00	45.00
Antiox. DQ, Agerite Resin D	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Agerite White	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Antozite 2	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00
Sulfur, Rubber Makers	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Santocure	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
Formula Weight	58.50	158.50	158.50	158.50	158.50	158.50	158.50	158.50	158.50	158.50

Table 7b SBR properties: SBR 1502 and 1503 from various suppliers

Compound ID	SBR-1	SBR-44	SBR-45	SBR-46	SBR-47	SBR-49	SBR-50	SBR-51	SBR-52	SBR-53
Properties										
Mooney Viscometer										
ML +4 at 212 Deg F	63.4	59.00	---	---	---	---	---	---	---	---
T5 @ 250 Deg F, Minutes	10	13.00	---	---	---	---	---	---	---	---
Cure Conditions, Minutes/Deg F	30/310	40/310	35/310	30/310	40/300	30/310	30/310	30/310	30/310	30/310
Original Properties										
Tensile Strength, psi	3911	4200	4240	3150	4060	1920	3187	4200	4127	3975
200% Modulus, psi	667	820	880	950	940	900	877	1130	940	990
Ultimate Elongation, %	493	528	528	423	478	325	447	440	473	450
Hardness, Shore A	67	71	73	72	70	71	70	75	73	72
Bashore Rebound, %	39	38	37	37	39	39	41	39	39	38
Specific Gravity	1.1319	---	---	---	---	---	---	---	---	---
Abrasion Tests										
Taber, Grams/1000 Cycles	0.1844	0.0686	0.0861	---	0.0540	---	---	---	---	---
Pico, Rating	143	238	---	---	242	---	---	---	---	---
Tear Strength Using ASTM Die C										
Unaged, Lb/In	304	295	306	312	284	303	299	305	316	299
10 Minutes @ 250 Deg F, Lb/In	165	150	143	137	137	134	147	146	147	144
De Mattia Flex Properties										
Unaged Growth Rate, Mils/Minute	26.1	35.00	---	---	21.00	---	---	---	---	---
After 70 Hours @ 212 Deg F, Mils/Minute	240	393.00	---	---	522.00	---	---	---	---	---
Goodrich Flex Properties at 50 Deg C										
External Temperature Rise Rate, Deg C/Min	6.4	---	---	---	---	---	---	---	---	---
Blow Out Time at 141.6 psi, Minutes	25	---	---	---	>120	---	---	---	---	---
Heat Resistance										
Stress Relaxation, F/F0 @ 250 Deg F = 70%	500	---	---	---	---	---	---	---	---	---
After Heat Aging for 70 Hrs at 250 Deg F										
Elongation Retention, %	33	35	38	---	38	---	34	45	42	48
Tensile Retention, %	59	60	69	---	67	---	68	67	74	75

Table 8a Natural rubber formulations from various grades of NR polymers

Compound ID	NR-1	NR-19	NR-20	NR-21	NR-27	NR-65	NR-68	NR-69	NR-70	NR-87
INGREDIENTS										
Natural Rubber RSS-1	100.00	---	---	---	---	---	---	---	---	---
Natural Rubber SMR-CV	---	100.00	---	---	---	---	---	---	---	---
Natural Rubber SMR-GP	---	---	100.00	---	---	---	---	---	---	---
Natural Rubber Pale Crepe #1	---	---	---	100.00	---	---	---	---	---	---
Synthetic Natural Rubber, Ameripol SN60	---	---	---	---	100.00	---	---	---	---	---
Natural Rubber, Guayule from Texus A&M	---	---	---	---	---	100.00	---	---	---	---
Natural Rubber SMR-5	---	---	---	---	---	---	100.00	---	---	---
Natural Rubber SMR-WF	---	---	---	---	---	---	---	100.00	---	---
Natural Rubber SMR-CV	---	---	---	---	---	---	---	---	100.00	---
Natural Rubber SIR-20	---	---	---	---	---	---	---	---	---	100.00
Zinc Oxide	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00
Stearic Acid	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
N-110, SAF Black	45.00	45.00	45.00	45.00	45.00	45.00	45.00	45.00	45.00	45.00
Antiox. DQ, Agerite Resin D	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Agerite White	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Antozite 2	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00
Sulfur, Rubber Makers	2.50	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Santocure	0.80	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
Formula Weight	158.30	158.50	158.50	158.50	158.50	158.50	158.50	158.50	158.50	158.50

Table 8b Natural rubber properties from various grades of NR polymer

Compound ID	NR-1	NR-19	NR-20	NR-21	NR-27	NR-65	NR-68	NR-69	NR-70	NR-87
Properties										
Mooney Viscometer										
ML +4 at 212 Deg F	49.2	51.0	50.5	64.6	51.3	32.4	30.8	33.9	31.6	77.0
T5 @ 250 Deg F, Minutes	11.8	11.1	11.1	11.1	17.8	7.4	18.9	20.8	21.5	18.8
Cure Conditions, Minutes/Deg F	20/300	20/300	20/300	20/300	20/300	15/280	25/290	30/290	35/290	22/300
Original Properties										
Tensile Strength, psi	3870	3353	3480	3209	3550	3343	3897	4083	4063	4033
200% Modulus, psi	712	721	742	737	571	1150	887	1000	1020	950
Ultimate Elongation, %	503	493	503	463	560	443	527	533	517	533
Hardnes, Shore A	71	71	70	68	65	75	68	68	67	65
Bashore Rebound, %	44	44	45	48	46	41	44	42	41	40
Specific Gravity	1.1090	1.0941	1.0934	1.0910	1.0882	1.1170	1.1090	1.1060	1.1070	1.1070
Abrasion Tests										
Taber, Grams/1000 Cycles	0.3517	0.4364	0.4396	0.3989	0.4198	0.3566	0.0340	0.0402	0.0283	0.2954
Pico, Rating	134	115	117	135	144	122	149	163	173	170
Tear Strength using ASTM Die C										
Unaged, Lb/In	595	570	591	632	457	492	563	621	484	638
10 Minutes @ 250 Deg F, Lb/In	296	293	323	328	263	189	353	290	288	272
De Mattia Flex Properties										
Unaged Growth rate, Mils/Minute	18.5	14.3	16.9	14.1	17.2	16.6	13.7	15.1	13.9	13.5
Unaged Crack Initiatlization, Kilocycles	71.5	162.0	13.5	68.0	94.5	38.0	102.3	79.0	82.0	---
After 70 Hours @ 212 Deg F, Mils/Minute	24.2	22.1	27.1	30.8	26.6	49.6	17.7	19.3	20.6	15.9
Goodrich Flex Properties at 50 Deg C										
External Temperature Rise Rate, Deg C/Min	3.9	4.3	3.7	3.5	4.3	3.3	3.1	3.0	3.2	3.1
Blow Out Time at 141.6 psi, Minutes	29	21	31	44	36	>120	58	52	63	41
Heat Resistance										
Stress Relaxation, F/F0 @ 250 Deg F = 70%	110	60	70	72	125	153	100	120	90	255
After Heat Aging for 70 Hrs at 250 Deg F										
Elongation Retention, %	13	9	12	17	12	5	14	16	17	14
Tensile Retention, %	14	14	17	20	14	20	19	17	19	20

Table 8c Rankings of properties for natural rubber compounds from various types of NR polymers

Compound ID	NR-1	NR-19	NR-20	NR-21	NR-27	NR-65	NR-68	NR-69	NR-70	NR-87
Natural Rubber Polymers	RSS-1	SMR-CV	SMR-GP	Pale Crepe #	Synthetic	Guayule	SMR-5	SMR-WI	SMR-CV	SIR-20
Properties										
Original Properties										
Tensile Strength	5	8	7	10	6	9	4	1	2	3
200% Modulus	9	8	6	7	10	1	5	3	2	4
Ultimate Elongation	6	8	7	9	1	10	4	3	5	2
Hardness, Shore A	2	3	4	5	9	1	6	7	8	10
Bashore Rebound	5	4	3	1	2	8	6	7	9	10
Pico Abrasion	7	10	9	6	5	8	4	3	1	2
Tear Strength Using ASTM Die C										
Unaged	4	6	5	2	10	8	6	3	9	1
10 Minutes @ 250 Deg F	4	5	3	2	9	10	1	6	7	8
De Mattia Flex Properties										
Unaged Growth Rate	10	5	8	4	9	7	2	6	3	1
After 70 Hours @ 212 Deg F	6	5	8	9	7	10	2	3	4	1
Goodrich Flex Properties at 50 Deg C										
External Temperature Rise Rat	6	1	2	3	8	9	5	7	4	10
Blow Out Time at 141.6 psi	9	10	8	5	7	1	3	4	2	6
Totals	73	73	70	63	83	82	48	53	56	58
Rankings	7	8	6	5	10	9	1	2	3	4

Table 9a shows 36 NR formulations consisting of 15 high-sulfur curing systems (NR-1, NR-9 through NR-15, NR-45, NR-48, NR-51, NR-58, NR-78, NR-83, NR-84, and NR-112), 9 polyurethane curing systems using Novor 924 or Novor 950 (NR-22, NR-22A, NR-46, NR-89, NR-47, NR-54, NR-55, NR-66, and NR-67), and 12 low-sulfur curing systems (NR-23, NR-24, NR-90, NR-25, NR-25A, NR-58, NR-59, NR-79, NR-80, NR-81, and NR-85). The properties for these materials are compared in Table 9b. With the exception of NR-83, all the formulations using the high-sulfur curing systems provided the poorest heat resistance. With the exception of formulations NR-15 and NR-78, all the compounds containing the high-sulfur curing system provided room temperature tear strength values of over 500 lb/inch. Compound NR-15 had a sulfur level of 5 pphr (parts-per-hundred-parts rubber), compared to 2.5 pphr for the other 7 compounds. This material provided lower tear strength along with higher 200% modulus, hardness, and crack growth rates after heat aging as well as lower abrasion resistance values. The NR-78, which used the Butyl Tuads accelerator, provided extremely low tensile, hardness, and tear strength values, indicating that this material was not properly cured. The 2 high-sulfur compounds (NR-9 and NR-10), which contained treated zinc oxide and polydispersed zinc oxide, provided excellent tear strength values of over 500 lb/inch at 250 °F. All high-sulfur formulations, except for NR-15, provided similar crack growth and crack initiation values. Only NR-12 and NR-15 provided blowout values over 120 min.

Formulation NR-12 used polydispersed sulfur and Santocure ingredients. NR-22, which used the Novor 924 curing system with Antioxidant DQ, Agerite White, and Antozite 2, provided the highest room temperature tear value of 704 lb/inch, high hardness, low 200% modulus, low Pico abrasion, and a low blowout time value of over 120 min. However, when additional antioxidants were introduced, as in NR-22A, the tear strength, abrasion, and blowout resistance values were drastically reduced. The addition of Santoguard PVI in formulation NR-89 also adversely affected the blowout resistance of the Novor curing system but improved crack growth resistance. The addition of Sulfasan R to formulation NR-67 caused a marked reduction in the abrasion resistance of that Novor cured material. All of the materials using the Novor curing systems, except for NR- 66, exhibited low abrasion values below 100.

Table 9a Natural rubber formulations: cure systems

Compound ID	NR-1	NR-9	NR-10	NR-11	NR-12	NR-13	NR-14	NR-15	NR-22	NR-22A	NR-23	NR-90	NR-24
Curing System Type	HS	HS	HS	HS	HS	HS	HS	HS	Novor	Novor	LS	LS	LS
INGREDIENTS													
Natural Rubber RSS-1	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Zinc Oxide	4.00	---	---	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	0.75	4.00
Stearic Acid	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	---	2.00
Treated Zinc Oxide	---	4.00	---	---	---	---	---	---	---	---	---	---	---
Poly Dispersion (SZD-85)	---	---	4.70	---	---	---	---	---	---	---	---	---	---
N-110, SAF Black	45.00	45.00	45.00	45.00	45.00	45.00	45.00	45.00	45.00	45.00	45.00	45.00	45.00
Antiox. DQ, Agerite Resin D	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Agerite White	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Antozite 2	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	5.00	3.00	3.00	3.00
Vanox MTI	---	---	---	---	---	---	---	---	---	0.50	---	---	---
Santoflex 13	---	---	---	---	---	---	---	---	---	1.50	---	---	---
Sulfur, Rubber Makers	2.50	2.50	2.50	---	---	2.50	1.50	5.00	0.40	0.40	0.60	1.00	1.00
Sulfur, Spider Brand	---	---	---	2.50	---	---	---	---	---	---	---	---	---
Santocure	0.80	0.80	0.80	0.80	---	0.40	0.80	0.80	---	---	---	---	---
Polydox S (SS-75)	---	---	---	---	3.30	---	---	---	---	---	---	---	---
Polydox S (SA-75))	---	---	---	---	1.10	---	---	---	---	---	---	---	---
Santoguard PVI	---	---	---	---	---	---	---	---	---	---	---	2.00	---
Novor 924	---	---	---	---	---	---	---	---	4.20	4.20	---	---	---
TMTM, Monex	---	---	---	---	---	---	---	---	1.50	1.50	---	---	---
Santocure NS	---	---	---	---	---	---	---	---	0.08	0.08	---	---	---
Morfax	---	---	---	---	---	---	---	---	---	---	1.90	---	---
Methyl Tuads	---	---	---	---	---	---	---	---	---	---	---	0.63	---
Butyl Tuads	---	---	---	---	---	---	---	---	---	---	0.50	---	0.50
Octoate Z	---	---	---	---	---	---	---	---	---	---	1.50	2.00	1.50
Amyl Ledate	---	---	---	---	---	---	---	---	---	---	0.80	1.00	0.80
Amax	---	---	---	---	---	---	---	---	---	---	---	1.90	1.80
Formula Weight	158.30	158.30	159.00	158.30	159.40	157.90	157.30	160.80	161.18	165.18	160.30	158.28	160.60
Notes for Curing System Types:													
HS - High Sulfur Curing System													
LS - Low Sulfur Curing System													
Novor - Polyurethane Curing System Using Novor 950 or 924													

Table 9a Natural rubber formulations: cure systems (continued)

Compound ID	NR-1	NR-25	NR-25A	NR-45	NR-46	NR-89	NR-47	NR- 48	NR-51	NR-54	NR-55	NR-58
Curing System Type	HS	LS	LS	HS	Novor	Novor	Novor	HS	HS	Novor	Novor	LS
INGREDIENTS												
Natural Rubber RSS-1	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Zinc Oxide	4.00	4.00	4.00	4.00	4.00	4.00	4.00	5.00	4.00	4.00	4.00	4.00
Stearic Acid	2.00	2.00	2.00	2.00	2.00	2.00	2.00	---	2.00	2.00	2.00	2.00
Poly Dispersion (SZD-85)	---	---	---	---	---	---	---	---	---	---	---	---
N-110, SAF Black	45.00	45.00	45.00	45.00	45.00	45.00	45.00	45.00	45.00	45.00	45.00	45.00
Antiox. DQ, Agerite Resin D	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Agerite White	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Antozite 2	3.00	3.00	5.00	5.00	5.00	---	5.00	5.00	5.00	5.00	5.00	3.00
Vanox MTI	---	---	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	---
Santoflex 13	---	---	1.50	1.50	1.50	3.00	1.50	1.50	1.50	1.50	1.50	---
Desical	---	---	---	---	3.00	---	3.00	---	---	---	---	---
Sulfur, Rubber Makers	2.50	0.80	0.75	1.20	0.40	0.50	0.95	4.00	---	0.40	0.95	2.00
Santocure	0.80	---	---	0.80	---	---	0.18	---	---	---	---	---
Polydox S (SS-75)	---	---	---	---	---	---	---	---	1.10	---	---	---
Polydox S (SA-75))	---	---	---	---	---	---	---	---	3.30	---	---	---
Polydox SZ-85F	---	---	---	---	---	---	---	---	4.70	---	---	---
Vulkacit J	---	---	---	---	---	---	---	---	---	---	---	2.70
Novor 950	---	---	---	---	---	---	---	---	---	4.20	7.32	---
Novor 924	---	---	---	---	4.20	4.20	7.32	---	---	---	---	---
TMTM, Monex	---	---	---	---	1.50	1.50	1.92	---	---	1.50	1.92	---
Santocure NS	---	---	---	---	0.08	0.50	---	---	---	0.08	0.18	---
Santoguard PVI	---	---	---	---	---	2.00	---	---	---	---	---	---
Methazate	---	---	---	---	---	---	---	1.00	---	---	---	---
Morfax	---	---	---	---	---	---	---	---	---	---	---	---
Ethyl Cadmate	---	---	---	---	---	---	---	---	---	---	---	---
Methyl Tuads	---	---	---	0.40	---	---	---	---	---	---	---	---
Butyl Tuads	---	0.6	0.6	---	---	---	---	---	---	---	---	---
Octoate Z	---	1.5	1.5	---	---	---	---	---	---	---	---	---
Amyl Ledate	---	1.0	1.0	---	---	---	---	---	---	---	---	---
Amax	---	1.9	1.9	---	---	---	---	---	---	---	---	---
Formula Weight	158.30	160.80	164.75	161.40	168.18	164.20	172.37	163.00	168.10	165.18	169.37	159.70
Notes for Curing System Types:												
HS - High Sulfur Curing System												
LS - Low Sulfur Curing System												
Novor - Polyurethane Curing System Using Novor 950 or 924												

Table 9a Natural rubber formulations: cure systems (continued)

Compound ID	NR-1	NR-59	NR-66	NR-67	NR-78	NR-79	NR-80	NR- 81	NR-83	NR-84	NR-85	NR-88	NR-112
Curing System Type	HS	LS	Novor	Novor	HS	LS	LS	LS	HS	HS	LS	LS	HS
INGREDIENTS													
Natural Rubber RSS-1	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Zinc Oxide	4.00	4.00	5.00	---	4.00	4.00	4.00	5.00	4.00	4.00	4.00	4.00	8.00
Stearic Acid	2.00	2.00	2.00	2.00	2.00	2.00	2.00	---	2.00	2.00	2.00	2.00	4.00
Poly Dispersion (SZD-85)	---	---	---	4.70	---	---	---	---	---	---	---	---	---
N-110, SAF Black	45.00	45.00	45.00	45.00	45.00	45.00	45.00	45.00	45.00	45.00	45.00	45.00	45.00
Antiox. DQ, Agerite Resin D	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Agerite White	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Antozite 2	3.00	3.00	5.00	5.00	3.00	5.00	5.00	5.00	3.00	3.00	---	---	3.00
Vanox MTI	---	---	0.50	0.50	---	0.50	0.50	0.50	---	---	0.50	---	---
Santoflex 13	---	---	1.50	1.50	---	1.50	1.50	1.50	---	---	3.00	0.50	---
Akrochem PANA	---	---	---	---	---	---	---	---	---	---	---	3.00	---
Sulfur, Rubber Makers	2.50	1.30	1.00	---	2.50	0.50	0.50	0.50	0.50	2.50	1.00	0.50	2.50
Sulfur, Spider Brand	---	---	---	---	---	---	---	---	2.00	0.80	---	---	---
Santocure	0.80	---	---	---	---	---	---	---	---	---	---	---	0.8
Santocure IPS	---	3.20	---	---	---	---	---	---	---	---	---	---	---
Santoguard PVI	---	0.20	1.00	1.00	---	---	---	---	---	---	2.00	---	---
Sulfasan R	---	---	---	1.50	---	---	---	---	1.00	---	---	---	---
Structol A-60	---	---	---	---	---	---	---	---	---	6.00	---	---	---
Novor 924	---	---	2.70	2.70	---	---	---	---	---	---	---	---	---
Curerite 18	---	---	6.00	6.00	---	6.00	6.00	---	---	---	---	---	---
MBTS	---	---	---	---	---	3.00	3.00	3.00	---	---	---	---	---
Butazate	---	---	---	---	---	1.00	---	---	---	---	---	---	---
Butyl Tuads	---	---	---	---	0.80	---	1.00	1.00	---	---	0.63	---	---
Akrochem OBTS	---	---	---	---	---	---	---	6.00	---	---	---	---	---
Octoate Z	---	---	---	---	---	---	---	---	---	---	1.5	---	---
Amyl Ledate	---	---	---	---	---	---	---	---	---	---	1.00	---	---
Amax	---	---	---	---	---	---	---	---	---	---	1.90	---	---
Morfax	---	---	---	---	---	---	---	---	---	---	---	2.0	---
Vanax A	---	---	---	---	---	---	---	---	---	---	---	1.0	---
Formula Weight	158.30	159.70	170.70	170.90	158.30	169.50	169.50	168.50	158.50	164.30	162.03	159.00	164.30
Notes for Curing System Types:													
HS - High Sulfur Curing System													
LS - Low Sulfur Curing System													
NOVOR - Polyurethane Curing System Using Novor 950 or 924													

Table 9a Natural rubber formulations: cure systems (continued)

Compound ID	NR-1	NR-112	NR-88	NR-89	NR-90
INGREDIENTS					
Natural Rubber RSS-1	100.00	100.00	100.00	100.00	100.00
Zinc Oxide	4.00	8.00	4.00	4.00	0.75
Stearic Acid	2.00	4.00	2.00	2.00	---
N-110, SAF Black	45.00	45.00	45.00	45.00	45.00
Antiox. DQ, Agerite Resin D	0.50	0.50	0.50	0.50	0.50
Agerite White	0.50	0.50	0.50	0.50	0.50
Antozite 2	3.00	3.00	---	---	3.00
Vanox MTI	---	---	0.50	0.50	---
Santoflex 13	---	---	3.00	3.00	---
Sulfur, Rubber Makers	2.50	2.50	0.50	0.50	1.00
Santocure	0.80	0.80	---	---	---
Santoguard PVI	---	---	---	2.00	2.00
Novor 924	---	---	---	4.20	---
TMTM, Monex	---	---	---	1.50	---
Santocure NS	---	---	---	0.50	---
Morfax	---	---	2.00	---	---
Vanax A	---	---	1.00	---	---
Methyl Tuads	---	---	---	---	0.63
Octoate Z	---	---	---	---	2.00
Amyl Ledate	---	---	---	---	1.00
Amax	---	---	---	---	1.90
Formula Weight	158.30	164.30	159.00	164.20	158.28

Table 9b Natural rubber properties: cure systems

Compound ID	NR-1	NR-9	NR-10	NR-11	NR-12	NR-13	NR-14	NR-15	NR-22	NR-22A	NR-23	NR-90	NR-24
Curing System Type	HS	HS	HS	HS	HS	HS	HS	HS	Novor	Novor	LS	LS	LS
Properties													
Mooney Viscometer													
ML +4 at 212 Deg F	49.2	67.0	66.1	65.8	64.4	65.9	68.1	57.9	63.9	39.1	46.1	41.0	41.0
T5 @ 250 Deg F, Minutes	11.8	14.0	15.1	11.0	15.7	19.2	19.2	14.4	10.1	9.1	9.6	37.8	10.7
Cure Conditions, Minutes/Deg F	20/300	20/300	20/300	20/300	20/300	20/300	20/300	20/300	20/300	20/310	15/300	35/300	15/300
Original Properties													
Tensile Strength, psi	3870	3384	3599	3559	3724	3791	3334	3482	3289	3412	3830	3760	3770
200% Modulus, psi	712	823	900	846	792	711	606	1049	543	592	762	520	779
Ultimate Elongation, %	503	477	500	490	490	530	510	453	533	596	530	643	507
Hardness, Shore A	71	71	71	72	71	69	67	73	77	76	65	67	68
Bashore Rebound, %	44	45	45	45	46	46	47	49	44	44	47	37	47
Specific Gravity	1.1090	1.0962	1.0969	1.1103	1.0692	1.0968	1.1064	1.0969	1.1100	1.0380	1.1094	1.0954	1.0930
Abrasion Tests													
Taber, Grams/1000 Cycles	0.3517	0.2563	0.2565	0.2701	0.2880	0.2121	0.2351	0.4910	0.2529	0.1073	0.1805	0.1138	0.2297
Pico, Rating	134	160	156	139	151	147	156	138	113	92	122	98	137
Tear Strength Using ASTM Die C													
Unaged, Lb/In	595	623	544	558	513	626	679	420	704	459	453	513	507
10 Minutes @ 250 Deg F, Lb/In	296	516	512	289	289	319	306	247	288	157	246	268	244
De Mattia Flex Properties													
Unaged Growth Rate, Mils/Minute	18.5	15.4	17.5	18.7	17.2	14.3	14.0	16.4	8.6	7.5	10.2	5.5	16.4
Unaged Crack Initiation, Kilocycles	71.5	---	---	---	---	---	---	---	41.5	52.5	33.5	---	33.5
After 70 Hours @ 212 Deg F, Mils/Minute	24.2	21.9	25.5	26.8	24.7	12.2	16.4	293.0	8.6	6.0	43.7	5.2	35.2
Goodrich Flex Properties at 50 Deg C													
External Temperature Rise Rate, Deg C/Min	3.9	3.7	4.2	4.0	3.5	3.9	4.4	3.2	4.9	4.0	4.0	4.4	4.0
Blow Out Time at 141.6 psi, Minutes	29	45	69	45	>120	25	41	>120	>120	77	>120	12	>120
Heat Resistance													
Stress Relaxation, F/F0 @ 250 Deg F = 70%	110	---	---	103	90	70	110	83	282	345	623	415	640
After Heat Aging for 70 Hrs at 250 Deg F													
Elongation Retention, %	13	---	---	12	11	13	28	8	60	69	52	15	47
Tensile Retention, %	14	---	---	17	14	15	21	18	31	50	52	19	45
Notes for Curing System Types:													
HS - High Sulfur Curing System													
LS - Low Sulfur Curing System													
Novor - Polyurethane Curing System Using Novor 950 or 924													

Table 9b Natural rubber properties: cure systems (continued)

Compound ID	NR-1	NR-25	NR-25A	NR-45	NR-46	NR-89	NR-47	NR- 48	NR-51	NR-54	NR-55	NR-58
Curing System Type	HS	LS	LS	HS	Novor	Novor	Novor	HS	HS	Novor	Novor	LS
Properties												
Mooney Viscometer												
ML +4 at 212 Deg F	49.2	47.3	16.1	20.3	24.6	38.0	---	37.5	25.7	28.8	29.1	34.0
T5 @ 250 Deg F, Minutes	11.8	10.0	5.0	4.0	8.9	19.2	---	3.0	10.2	6.4	4.9	44.6
Cure Conditions, Minutes/Deg F	20/300	20/300	20/300	15/280	35/310	35/310	40/280	15/280	30/280	40/300	35/300	35/300
Original Properties												
Tensile Strength, psi	3870	3837	3643	3777	3337	3350	3123	3443	3913	3390	3057	3837
200% Modulus, psi	712	749	573	700	597	557	947	1270	907	597	889	563
Ultimate Elongation, %	503	537	597	580	577	613	483	440	547	583	470	587
Hardness, Shore A	71	65	64	68	76	71	84	71	73	75	84	58
Bashore Rebound, %	44	46	40	41	42	41	45	48	43	43	44	44
Specific Gravity	1.1090	1.0940	1.1050	1.1151	1.1066	1.1049	1.1164	1.1269	1.0920	1.0710	1.0745	1.0979
Abrasion Tests												
Taber, Grams/1000 Cycles	0.3517	0.1655	0.0852	0.1569	0.0654	0.1125	0.6055	0.3533	0.3157	0.0718	0.1918	0.1216
Pico, Rating	134	115	85	114	76	---	96	105	135	79	99	101
Tear Strength Using ASTM Die C												
Unaged, Lb/In	595	479	582	530	484	563	341	361	557	540	456	663
10 Minutes @ 250 Deg F, Lb/In	296	270	204	246	192	202	182	226	277	224	224	330
De Mattia Flex Properties												
Unaged Growth Rate, Mils/Minute	18.5	10.2	8.6	12.8	11.0	5.2	23.4	23.4	15.7	20.6	21.0	6.3
Unaged Crack Initiation, Kilocycles	71.5	33.5	18.0	60.5	17.0	---	11.5	225.0	41.0	32.0	19.5	50.0
After 70 Hours @ 212 Deg F, Mils/Minute	24.2	25.5	10.4	8.6	6.3	5.0	42.4	27.1	27.9	41.0	26.3	5.7
Goodrich Flex Properties at 50 Deg C												
External Temperature Rise Rate, Deg C/Min	3.9	4.0	3.8	3.8	4.9	---	5.5	2.5	3.1	2.3	4.3	3.4
Blow Out Time at 141.6 psi, Minutes	29	>120	>120	67	>120	22	>120	>120	54	>120	>120	>120
Heat Resistance												
Stress Relaxation, F/F0 @ 250 Deg F = 70%	110	678	910	250	310	490	450	150	157	202	543	363
After Heat Aging for 70 Hrs at 250 Deg F												
Elongation Retention, %	13	55	63	51	64	38	45	9	19	17	36	60
Tensile Retention, %	14	62	69	41	52	25	51	22	28	21	39	14
Notes for Curing System Types:												
HS - High Sulfur Curing System												
LS - Low Sulfur Curing System												
Novor - Polyurethane Curing System Using Novor 950 or 924												

Table 9b Natural rubber properties: cure systems (continued)

Compound ID	NR-1	NR-59	NR-66	NR-67	NR-78	NR-79	NR-80	NR- 81	NR-83	NR-84	NR-85	NR-88	NR-112
Curing System Type	HS	LS	Novor	Novor	HS	LS	LS	LS	HS	HS	LS	LS	HS
Properties													
Mooney Viscometer													
ML +4 at 212 Deg F	49.2	36.4	24.3	24.3	23.4	18.9	14.0	16.0	32.3	20.0	33.0	44.0	41.0
T5 @ 250 Deg F, Minutes	11.8	38.6	20.4	21.2	14.9	5.8	5.1	7.0	21.6	22.2	34.4	25.4	37.8
Cure Conditions, Minutes/Deg F	20/300	30/300	20/310	40/310	12/290	35/310	30/300	30/300	30/300	35/300	25/300	25/300	35/300
Original Properties													
Tensile Strength, psi	3870	4257	3500	3897	1360	2977	2750	3260	3917	3863	3650	4023	3760
200% Modulus, psi	712	940	900	887	218	807	807	587	690	900	523	1017	520
Ultimate Elongation, %	503	533	483	527	533	450	437	560	590	530	640	517	643
Hardness, Shore A	71	68	78	75	42	73	74	79	65	70	67	72	67
Bashore Rebound, %	44	47	45	42	40	41	42	41	43	43	39	44	37
Specific Gravity	1.1090	1.1040	1.1090	1.1080	1.0776	1.1095	1.1110	1.1121	1.0952	1.0988	1.1124	1.1051	1
Abrasion Tests													
Taber, Grams/1000 Cycles	0.3517	0.1426	0.5002	0.1147	---	0.2606	0.3046	0.1332	0.0597	0.2696	0.0579	0.2337	0.1138
Pico, Rating	134	121	129	95	---	---	---	---	165	213	93	193	105
Tear Strength Using ASTM Die C													
Unaged, Lb/In	595	614	325	468	146	233	296	443	527	625	556	510	513
10 Minutes @ 250 Deg F, Lb/In	296	333	186	211	82	147	175	233	316	282	306	264	268
De Mattia Flex Properties													
Unaged Growth Rate, Mils/Minute	18.5	14.6	19.8	5.8	4.4	17.7	19.5	8.4	6.5	15.4	5.2	19.3	5.5
Unaged Crack Initiation, Kilocycles	71.5	52.4	23.0	9.9	208.0	36.3	45.0	83.5	136.5	110.5	---	15.1	---
After 70 Hours @ 212 Deg F, Mils/Minute	24.2	48.1	19.3	6.0	3.4	19.0	21.6	7.6	22.2	8.9	6.3	20.1	118.0
Goodrich Flex Properties at 50 Deg C													
External Temperature Rise Rate, Deg C/Min	3.9	3.2	3.6	3.9	4.5	3.3	3.2	4.2	3.2	3.0	3.6	3.1	4.4
Blow Out Time at 141.6 psi, Minutes	29	>120	>120	>120	116	>120	>120	>120	>120	57	32	>120	12
Heat Resistance													
Stress Relaxation, F/F0 @ 250 Deg F = 70	110	337	230	395	---	1300	1210	920	515	145	345	255	---
After Heat Aging for 70 Hrs at 250 Deg F													
Elongation Retention, %	13	37	19	47	6	30	36	38	50	12	29	14	15
Tensile Retention, %	14	38	19	23	27	27	37	34	27	15	30	20	19
Notes for Curing System Types:													
HS - High Sulfur Curing System													
LS - Low Sulfur Curing System													
Novor - Polyurethane Curing System Using Novor 950 or 924													

Table 9b Natural rubber properties: cure systems (continued)

Compound ID	NR-1	NR-112	NR-88	NR-89	NR-90
Properties					
Mooney Viscometer					
ML +4 at 212 Deg F	49.2	---	44.0	38.0	41.0
T5 @ 250 Deg F, Minutes	11.8	---	25.4	19.2	37.8
Cure Conditions, Minutes/Deg F	20/300	40/290	25/300	35/310	35/300
Original Properties					
Tensile Strength, psi	3870	4280	4023	3350	3760
200% Modulus, psi	712	1020	1017	557	520
Ultimate Elongation, %	503	526	517	613	643
Hardness, Shore A	71	---	72	71	67
Bashore Rebound, %	44	---	44	41	37
Specific Gravity	1.1090	1.1245	1.1051	1.1049	1.0954
Abrasion Tests					
Taber, Grams/1000 Cycles	0.3517	0.0349	0.2337	0.1125	0.1138
Pico, Rating	134	193	193	---	105
Tear Strength Using ASTM Die C					
Unaged, Lb/In	595	622	510	563	513
10 Minutes @ 250 Deg F, Lb/In	296	328	264	202	268
De Mattia Flex Properties					
Unaged Growth Rate, Mils/Minute	18.5	18.8	19.3	5.2	5.5
Unaged Crack Initiation, Kilocycles	71.5	---	15.1	---	---
After 70 Hours @ 212 Deg F, Mils/Minute	24.2	23.4	20.1	5.0	118.0
Goodrich Flex Properties at 50 Deg C					
External Temperature Rise Rate, Deg C/Min	3.9	---	3.1	---	4.4
Blow Out Time at 141.6 psi, Minutes	29	---	>120	22	12
Heat Resistance					
Stress Relaxation, F/F0 @ 250 Deg F = 70%	110	---	255	---	---
After Heat Aging for 70 Hrs at 250 Deg F					
Elongation Retention, %	13	13	14	38	15
Tensile Retention, %	14	16	20	25	19

The low-sulfur curing systems (especially formulations NR-79 through NR-81) provided the best resistance to heat aging. Except for NR-85 and NR-90 (which contained Santoguard PVI), all the other low-sulfur cured materials provided excellent blowout resistance and abrasion values over 100. NR-90 and NR-58 materials provided lower Pico abrasion resistance and better crack growth resistance, and only NR-90 exhibited poor blowout resistance. The low-sulfur compounds containing Curerite 18 (NR-79 and NR-80) provided low tear strength values (under 300 lb/inch) at room temperature and dropped to below 200 lb/inch at 250 °F.

NR formulations using 10 types of carbon black fillers are presented in Table 10a, and their properties are compared in Table 10b. In Table 10c, all the properties for track pad potential are ranked individually from 1 (most desirable) to 10 (least desirable) and totaled for each material. The average ranking for each material is provided in the bottom row. The NR compound formulations containing N-326 and N-234 blacks ranked 1 and 2 for their potential to be used in track pad applications. The Austin Black 325 was the worst performer, followed by N-220 black. The N-110 black provided the best tear resistance with only average abrasion and crack growth resistance. The N-299 and N-330 blacks provided the best abrasion resistance, above average cut growth, and only average tear resistance values.

Table 10a Natural rubber formulations: black types

Compound ID	NR-1	NR-16	NR-18	NR-38	NR-41	NR-42	NR- 43	NR-44	NR-52	NR-53
INGREDIENTS										
Natural Rubber RSS-1	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Zinc Oxide	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00
Stearic Acid	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
N-110, SAF Black	45.00	---	---	---	---	---	---	---	---	---
N-220, ISAF Black	---	45.00	---	---	---	---	---	---	---	---
N-234, ISAF-HS Black	---	---	45.00	---	---	---	---	---	---	---
N-472, Conductive Black	---	---	---	45.00	---	---	---	---	---	---
N-299, GTP-HS Black	---	---	---	---	45.00	---	---	---	---	---
N-326, HAF-LS Black	---	---	---	---	---	45.00	---	---	---	---
N-351, HAF-HM Black	---	---	---	---	---	---	45.00	---	---	---
N-330, HAF Black	---	---	---	---	---	---	---	45.00	---	---
Austin Black 325	---	---	---	---	---	---	---	---	45.00	---
Shawinigan Acetylene Black	---	---	---	---	---	---	---	---	---	45.00
Antiox. DQ, Agerite Resin D	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Agerite White	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Antozite 2	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00
Sulfur, Rubber Makers	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50
Santocure	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
Formula Weight	158.30	158.30	158.30	158.30	158.30	158.30	158.30	158.30	158.30	158.30

Table 10b Natural rubber properties: black type

Compound ID	NR-1	NR-16	NR-18	NR-38	NR-41	NR-42	NR-43	NR-44	NR-52	NR-53
Carbon Black Type	N-110	N-220	N-234	N-472	N-299	N-326	N-351	N-330	Austin 32	Acetylene
Properties										
Mooney Viscometer										
ML +4 at 212 Deg F	49.2	65.0	59.0	43.0	33.0	19.0	32.0	24.0	13.0	23.0
T5 @ 250 Deg F, Minutes	11.8	15.3	13.3	15.7	15.4	16.9	16.4	16.2	28.3	18.6
Cure Conditions, Minutes/Deg F	20/300	20/300	20/300	25/300	30/290	30/290	30/290	30/290	30/290	35/280
Original Properties										
Tensile Strength, psi	3870	3482	3811	3253	3717	3800	3713	3513	2343	3200
200% Modulus, psi	712	1049	865	880	1197	897	1207	1093	510	1130
Ultimate Elongation, %	503	440	493	490	453	507	447	460	530	460
Hardness, Shore A	71	70	71	67	70	66	66	65	58	71
Bashore Rebound, %	44	47	47	48	48	51	52	55	71	51
Specific Gravity	1.1090	1.0969	1.0947	1.1140	1.1074	1.1058	1.1082	1.1140	1.0368	1.1026
Abrasion Tests										
Taber, Grams/1000 Cycles	0.3517	0.4722	0.5540	0.3261	0.2707	0.4096	0.2974	0.3525	1.1489	0.3249
Pico, Rating	134	134	140	147	174	110	144	151	30	130
Tear Strength Using ASTM Die C										
Unaged, Lb/In	595	447	512	504	478	454	555	477	211	480
10 Minutes @ 250 Deg F, Lb/In	296	190	192	217	216	216	189	211	151	204
De Mattia Flex Properties										
Unaged Growth Rate, Mils/Minute	18.5	17.0	18.0	15.0	18.0	15.0	19.0	19.0	30.0	21.0
Unaged Crack Initiation, Kilocycles	71.5	35.0	28.0	295.0	40.0	40.0	93.0	57.0	12	32
After 70 Hours @ 212 Deg F, Mils/Minute	24.2	24.0	21.0	25.0	28.0	28.0	28.0	28.0	75.0	41.0
Goodrich Flex Properties at 50 Deg C										
External Temperature Rise Rate, Deg C/Min	3.9	3.6	3.8	3.3	3.2	2.6	2.8	2.3	5	3.0
Blow Out Time at 141.6 psi, Minutes	29	>120	>120	66	65	>120	>120	>120	>120	>120
Heat Resistance										
Stress Relaxation, F/F0 @ 250 Deg F = 70%	110	135	133	140	168	177	228	218	170	202
After Heat Aging for 70 Hrs at 250 Deg F										
Elongation Retention, %	13	13	16	19	13	14	12	12	18	17
Tensile Retention, %	14	18	17	19	17	16	17	16	17	21

Table 10c Rankings of properties for natural rubber compounds with various carbon blacks

Compound ID	NR-1	NR-16	NR-18	NR-38	NR-41	NR-42	NR-43	NR-44	NR-52	NR-53
Carbon Black Type	N-110	N-220	N-234	N-472	N-299	N-326	N-351	N-330	Austin 32	Acetylene
Properties										
Original Properties										
Tensile Strength	1	7	2	8	4	3	5	6	10	9
200% Modulus	9	5	8	7	2	6	1	4	10	3
Ultimate Elongation	3	10	4	5	8	2	9	6	1	7
Hardness, Shore A	3	4	1	6	5	7	8	9	10	2
Bashore Rebound	10	8	9	6	7	4	3	2	1	5
Pico Abrasion	7	6	5	3	1	9	4	2	10	8
Tear Strength Using ASTM Die C										
Unaged	1	9	3	4	6	8	2	7	10	5
10 Minutes @ 250 Deg F	1	8	7	2	4	3	9	5	10	6
De Mattia Flex Properties										
Unaged Growth Rate	6	3	4	1	5	2	7	8	10	9
After 70 Hours @ 212 Deg F	8	4	2	10	5	6	9	7	1	3
Goodrich Flex Properties at 50 Deg C										
External Temperature Rise Rate	9	7	8	6	5	2	3	1	10	4
Blow Out Time at 141.6 psi	2	1	1	5	5	1	1	1	1	1
Totals	60	72	54	63	57	53	61	58	84	62
Rankings	5	9	2	8	3	1	6	4	10	7

In Table 11a, 3 NR formulations, with various combinations of blacks and some containing molybdenum disulfide, are provided with 2 NR formulations containing N-110 or N-550 black. Their properties are compared in Table 11b. Compound NR-62, which contained 65 pphr of the N-110 black and 10 pphr of Phillips XE-2 black, provided the highest Pico abrasion rating of 192 compared to 134 obtained with NR-1, which contained 45 pphr of N-110 black. All other properties between these 2 materials were comparable. The addition of 10 pphr of molybdenum disulfide in compound NR-26, when compared to NR-1, drastically increased blowout resistance, with some sacrifice in tear and abrasion resistance. Replacing some of the N-110 black with the Phillips XE-2 black (NR-67) improved the time to blowout from 29 to 61 min while keeping all the other properties about equal.

Table 11a Natural rubber formulations: filler combinations

Compound ID	NR-1	NR-26	NR-57	NR-62	NR-63
INGREDIENTS					
Natural Rubber RSS-1	100.00	100.00	100.00	100.00	100.00
Zinc Oxide	4.00	4.00	4.00	5.00	5.00
Stearic Acid	2.00	2.00	2.00	2.00	2.00
N-110, SAF Black	45.00	45.00	30.00	65.00	---
N-550, FEF Black	---	---	---	---	40.00
Molybdenum Disulfide	---	20.00	---	---	---
Phillips XE-2 Black	---	---	10.00	10.00	---
Antiox. DQ, Agerite Resin D	0.50	0.50	0.50	2.00	2.00
Agerite White	0.50	0.50	0.50	---	---
Antozite 2	3.00	3.00	3.00	---	---
Sulfur, Rubber Makers	2.50	2.50	2.50	2.50	2.50
Santocure	0.80	0.80	0.80	---	---
Santocure MOR	---	---	---	0.70	0.70
Formula Weight	158.30	178.30	153.30	187.20	152.20

Table 11b Natural rubber properties: filler combinations

Compound ID	NR-1	NR-26	NR-57	NR-62	NR-63
Properties					
Mooney Viscometer					
ML +4 at 212 Deg F	49.2	40.0	55.0	79.0	57.0
T5 @ 250 Deg F, Minutes	11.8	17.7	15.4	14.6	22.4
Cure Conditions, Minutes/Deg F	20/300	20/300	25/300	35/300	20/300
Original Properties					
Tensile Strength, psi	3870	3708	4017	3400	3100
200% Modulus, psi	712	928	870	1483	1387
Ultimate Elongation, %	503	500	510	387	383
Hardness, Shore A	71	66	69	77	72
Bashore Rebound, %	44	49	42	34	44
Specific Gravity	1.1090	1.0191	1.0751	1.1624	1.1308
Abrasion Tests					
Taber, Grams/1000 Cycles	0.3517	0.5297	0.0410	0.0459	---
Pico, Rating	134	106	139	192	134
Tear Strength Using ASTM Die C					
Unaged, Lb/In	595	365	609	519	524
10 Minutes @ 250 Deg F, Lb/In	296	219	269	233	162
De Mattia Flex Properties					
Unaged Growth Rate, Mils/Minute	18.5	26.0	14.0	15.0	14.0
Unaged Crack Initiation, Kilocycles	71.5	17.0	131.0	76.0	39.0
After 70 Hours @ 212 Deg F, Mils/Minute	24.2	29.0	46.0	200.0	52.0
Goodrich Flex Properties at 50 Deg C					
External Temperature Rise Rate, Deg C/Min	3.9	3.4	3.1	5.0	3.4
Blow Out Time at 141.6 psi, Minutes	29	>120	61	17	7
Heat Resistance					
Stress Relaxation, F/F0 @ 250 Deg F = 70%	110	90	173	55	53
After Heat Aging for 70 Hrs at 250 Deg F					
Elongation Retention, %	13	11	14	12	16
Tensile Retention, %	14	14	14	22	21

Eleven NR formulations containing various types of silica fillers or combinations of silica with carbon blacks are provided in Table 12a, and their properties are compared in Table 12b. All the materials exhibited similar good crack growth resistance. The best room temperature tear strength values were provided by NR-40, NR-73, and NR-95 (all over 500 lb/inch). The best tear values (over 250 lb/inch) were obtained on NR-40, NR-49, and NR-73. Only NR-72, NR-71, and NR-28 provided poor blowout resistance values. NR-120, with a combination filler system containing 2 types of carbon blacks and the Cabosil MS-7SD silica, provided a good Pico abrasion value of 168 but relatively low tear resistance values of 297 lb/inch at room temperature and 180 lb/inch at 250 °F. The 2 compounds containing only the Cabosil MS-7SD silica filler exhibited low tensile, modulus, hardness, Pico abrasion resistance, tear strength, and blowout resistance values. Adding the SI-69 coupling agent to the formulation containing the Cabosil MS-7SD silica did not enhance the Pico abrasion resistance of NR-98.

Table 12a Natural rubber formulations: fillers with silica

Compound ID	NR-28	NR-29	NR-40	NR-73	NR-49	NR-50	NR-71	NR-72	NR-120	NR-95	NR-98
INGREDIENTS											
Natural Rubber RSS-1	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Zinc Oxide	4.00	4.00	4.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
Stearic Acid	2.00	2.00	2.00	1.50	2.00	2.00	1.50	1.50	2.00	1.50	1.50
Struktol A-60	---	---	---	---	---	---	---	---	---	3.00	3.00
N-110, SAF Black	15.00	15.00	---	---	---	---	---	---	---	---	---
N-472, Conductive Black	---	---	45.00	---	---	---	---	---	15.00	---	---
N-121, HAF-HS Black	---	---	---	---	---	---	---	---	15.00	---	---
N-550, FEF Black	---	---	---	---	---	---	---	---	---	---	---
Phillips XE-2 Black	---	---	---	10.00	---	---	---	---	---	---	---
Cabosil HS-5	20.00	20.00	20.00	---	---	---	---	---	---	---	---
Cabosil MS-7SD	---	---	---	30.00	---	---	40.00	35.00	15.00	45.00	45.00
Hi Sil 233	---	---	---	---	66.00	---	---	---	---	---	---
Durasil	---	---	---	---	---	66.00	---	---	---	---	---
Antiox. DQ, Agerite Resin D	0.50	0.50	0.50	0.50	0.20	0.20	0.50	0.50	1.50	0.50	0.50
Agerite White	0.50	0.50	0.50	0.50	---	---	0.50	0.50	1.50	0.50	0.50
Antozite 2	3.00	3.00	3.75	3.00	---	---	3.00	3.00	2.00	---	---
Wingstay 100	---	---	0.60	5.00	---	---	5.00	5.00	---	---	---
Vanox MTI	---	---	---	0.50	---	---	0.50	0.50	---	1.50	0.50
Santoflex 13	---	---	---	1.50	3.00	3.00	1.50	1.50	1.00	3.00	3.00
Methy Ethyl Tuads	---	---	---	---	---	---	---	---	---	3.00	3.00
Sulfur, Rubber Makers	2.50	0.80	0.80	0.80	---	---	0.80	0.40	---	---	---
Santocure	1.50	---	---	---	---	---	---	---	---	---	---
Butyl Tuads	---	0.70	0.70	0.70	---	---	0.70	---	---	---	---
Octoate Z	---	1.50	1.50	1.50	---	---	1.50	---	---	---	---
Amy Ledate	---	1.00	1.00	1.00	---	---	1.00	---	---	---	---
Amax	---	1.90	1.90	1.90	---	---	1.90	---	---	---	---
Santocure MOR	---	---	---	---	---	---	---	---	---	4.00	4.00
Warecure A189	---	---	---	2.00	---	---	2.00	2.00	---	---	---
Novor 924	---	---	---	---	---	---	---	4.20	---	---	---
TMTM, Monex	---	---	---	---	---	---	---	1.50	2.00	---	---
Santocure NS	---	---	---	---	---	---	---	0.80	2.00	---	---
Morfax	---	---	---	---	---	---	---	---	1.00	---	---
Vulkacit J	---	---	---	---	2.70	2.70	---	---	---	---	---
SI-69	---	---	---	---	---	---	---	---	---	---	1.00
X-50-S	---	---	---	---	8.00	8.00	---	---	---	---	---
Formula Weight	149.00	150.90	182.25	165.40	186.90	186.90	165.40	161.40	163.00	167.00	167.00

Table 12b Natural rubber properties: fillers with silica

Compound ID	NR-28	NR-29	NR-40	NR-73	NR-49	NR-50	NR-71	NR-72	NR-120	NR-95	NR-98
Properties											
Mooney Viscometer											
ML +4 at 212 Deg F	43	41	---	23	41	20	35	51	---	31	29
T5 @ 250 Deg F, Minutes	28.9	21.6	---	9.2	22.8	24.6	23.7	20.9	---	25.8	23.2
Cure Conditions, Minutes/Deg F	30/300	15/300	15/300	10/290	40/300	50/310	15/300	17/300	30/300	40/300	40/300
Original Properties											
Tensile Strength, psi	3550	4047	2863	4083	3557	2820	3103	2033	3770	2850	4217
200% Modulus, psi	272	220	1113	380	1200	1210	193	185	770	290	583
Ultimate Elongation, %	653	670	420	737	420	403	777	680	510	707	610
Hardness, Shore A	56	49	73	59	83	63	53	51	---	70	70
Bashore Rebound, %	54	56	36	46	41	53	50	45	---	49	51
Specific Gravity	1.0890	1.0750	1.1790	1.1020	1.2016	1.1947	1.1070	1.0940	1.1245	1.1435	1.1285
Abrasion Tests											
Taber, Grams/1000 Cycles	0.7026	0.4959	1.0502	0.0522	0.0930	0.0853	0.0626	0.0527	0.0233	0.1351	0.3169
Pico, Rating	95	81	106	82	100	77	60	47	168	95	79
Tear Strength Using ASTM Die C											
Unaged, Lb/In	479	441	699	528	478	302	427	445	297	508	404
10 Minutes @ 250 Deg F, Lb/In	199	194	299	261	274	163	169	114	180	185	242
De Mattia Flex Properties											
Unaged Growth Rate, Mils/Minute	13.3	6.0	10.2	7.0	12.5	12.2	3.9	4.2	27.0	8.3	11.0
Unaged Crack Initiation, Kilocycles	22	33	---	81	62	22	72	145	154	---	---
After 70 Hours @ 212 Deg F, Mils/Minute	17	12	27	10	12	11	6	4	21	15	88
Goodrich Flex Properties at 50 Deg C											
External Temperature Rise Rate, Deg C/Min	4.0	1.9	5.3	2.7	4.0	2.1	2.7	3.2	2	4	4
Blow Out Time at 141.6 psi, Minutes	44	>120	>120	>120	>120	>120	38	11	>120	>120	>120
Heat Resistance											
Stress Relaxation, F/F0 @ 250 Deg F = 70	130	415	700	185	498	640	490	110	---	1600	1761
After Heat Aging for 70 Hrs at 250 Deg F											
Elongation Retention, %	23	33	57	46	74	80	55	53	63	88	85
Tensile Retention, %	16	14	40	35	47	46	47	31	66	66	65

In Table 13 the properties of 6 rubber compounds containing Guayule NR and one with Hevea NR are compared. Five Guayule NR polymers, provided by Texas A&M, were prepared as described in Table 13, and one was obtained from Mexico. The SMR-20 NR polymer was used in the compounding study for comparison of its properties with those of the Guayule polymers. All the other ingredients were the same for all compounds. All of the Guayule polymers prepared by Texas A&M contained Butyl Zimate to serve as an antioxidant during their production processes. Butyl Zimate can also serve as an accelerator; consequently, all the compounds made with these materials cured faster. Thus, in the future Butyl Zimate should not be used during polymer production because it also acts as an accelerator, severely limiting compounding variations and promoting scorch problems. All of the compounds that used the Texas A&M polymers, except Compound E, exhibited lower tensile values than that provided by the Mexican Guayule and SMR-20 materials. Compound A provided the highest rebound (resilience) value. Of the Guayule polymers prepared by Texas A&M, the polymer used in Compound E provided the best balance of properties and more closely simulated the properties provided by the SMR-20 and Mexican Guayule polymers.

Table 13 Guayule rubber properties

Compound Code	A	B	C	D	E	F	G	
Polymer Used	Natural Rubber SMR-20	Guayule Mexican	Guayule Texas A&M	Guayule Texas A&M	Guayule Texas A&M	Guayule Texas A&M	Guayule Texas A&M	Requirement ASTM D 2227 Max
Guayule Rubber Supplier	---	Mexico	Texas A&M	Texas A&M	Texas A&M	Texas A&M	Texas A&M	---
Guayule Shrub Source	---	---	Brawley, CA	Pecos, TX	Pecos, TX	Pecos, TX	Pecos, TX	---
Guayule Shrub Variety	---	---	Mixed	Mixed	11605	11605	11605	---
Schrub Harvest	---	---	Clipping Bale	Whole Bale	Whole Bale	Whole Bale	Whole Bale	---
Amount of Butyl Zimate Used	---	---	0.9 PHR	1.1 PPHR	2.0 PPHR	2.3 PPHR	7 PPHR	---
Dirt Content, %	---	.02	.04	.033	.05	.034	.04	.2
Ash Content, %	---	.78	.5	2.	.57	.53	.51	1
Nitrogen, %	---	---	.09	.003	.003	.0000	.09	.256
Volatile, %	---	---	1	---	---	---	1	.8
Copper, %	---	5.5	.00022	.004	.00024	.00018	.00039	.0008
Manganese, %	---	.00047	.0002	.0017	.00071	.00032	.00075	.0015
Acetone Extract, %	---	3.54	2.15	1.88	.91	2.24	5.87	---
Wallace Plastometer								
P(0)	---	41	14	22	72	24	7	35
P(RI)	---	89	25	90	78	80	29	40
Molecular Weight Using THF								
M(W)	---	1,063,620	336,799	762,785	813,030	715,656	529,913	---
Month/Year Supplied	---	---	7/27/84	8/7/84	8/17/84	8/20/84	9/5/84	---
Properties								
Cure Conditions, Minutes at 284 Deg F	45	50	20	15	20	20	30	
Mooney Viscosity Measurements								
Scorch @ 250°F, Minutes	28	44	10	9	16	7	33	
ML 1 + 4 (212°F)	20	20	9	16	20	18	7	
Original Properties								
Tensile Strength, psi	4107	4027	3300	2797	3997	3060	3150	
300% Modulus, psi	2040	1333	1950	2197	1630	2037	1013	
Ultimate Elongation, %	467	570	423	353	530	387	603	
Hardnes, Shore A	62	56	64	65	60	64	51	
Bashore Rebound, %	55	46	44	47	49	51	39	
Specific Gravity	1.0930	1.0920	1.097	1.1150	1.0910	1.0950	1.0930	
Tear Strength Using ASTM Die C								
Unaged, Lb/In	416	394	319	269	405	289	454	
Goodrich Flex Properties at 50 Deg C								
Blowout Time at 141.6 psi, Minutes	>120	88.0	>120	>120	>120	>120	45.0	

Formulation PBD-1 of Table 14a used Cis 1,4-1203, a solution polymerized BR supplied by Phillips Petroleum, and the resulting properties are presented in Table 14b. This compound provided low tensile strength and tear strength slightly above 300 lb/inch. PBD-1 also performed poorly in crack growth resistance, especially after heat aging. Another solution polymerized polybutadiene, Taktene 220, a polymer with more branching than the Cis 1,4-1203 for easier processing, was used in formulation PBD-4 of Table 14a, and the resulting properties are presented in Table 14b. This material provided better tensile strength, Pico abrasion, and cut growth resistance than PBD-1 but provided much lower tear resistance values. Diene 35 NF, a stereo-specific solution polymerized BR, was used in formulation PBD-2. Synpol E-BR 8418 (containing 20 parts of high aromatic oil) and Nipol BR-1245 BRs were used in formulations PBD-5 and PBD-8, respectively. These materials provide better tensile and Pico abrasion than PBD-1 but lower tear strength values. UBE POL-VCR 412 polybutadiene is produced by combining high cis BR with high crystalline/ high melting point syndiotact-1,2 polybutadiene.

Compounds from this polymer provided excellent mixing and curing properties along with better resistance to crack growth, and high tear and abrasion resistance when compared to other polybutadiene materials. Compound PBD-7, which also used a low-sulfur curing system, provided the highest Pico abrasion rating (791) of any material evaluated to date.

Table 14a Polybutadiene rubber formulations

Compound ID	PBD-1	PBD-2	PBD-3	PBD-4	PBD-5	PBD-6	PBD-7	PBD-8
INGREDIENTS								
Cis 1, 4- 1203, Polybutadiene Rubber	100.00	---	---	---	---	---	---	---
Diene 35 NF, Polybutadiene Rubber	---	100.00	---	---	---	---	---	---
UBE POL-VCR 412, Polybutadiene Rubber	---	---	100.00	---	---	100.00	100.00	---
Taktene 220, Polybutadiene Rubber	---	---	---	100.00	---	---	---	---
Synpol E-BR8418, Polybutadiene Rubber	---	---	---	---	120.00	---	---	---
Nipol BR-1245, Polybutadiene Rubber	---	---	---	---	---	---	---	100.00
Zinc Oxide	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00
Stearic Acid	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
N-110, SAF Black	45.00	45.00	45.00	45.00	65.00	35.00	45.00	45.00
Agerite Resin D	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Agerite White	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Antozite 2	3.00	3.00	3.00	3.00	3.00	5.00	5.00	3.00
Vanox MTI	---	---	---	---	---	0.50	0.50	---
Santoflex 13	---	---	---	---	---	1.50	1.50	---
Sulfur	2.00	2.00	2.00	2.00	2.00	0.40	0.75	2.00
Butyl Tuads	---	---	---	---	---	---	0.63	---
Octoate Z	---	---	---	---	---	---	1.50	---
Amyl Ledate	---	---	---	---	---	---	1.00	---
Amax	---	---	---	---	---	---	1.90	---
Novor 924	---	---	---	---	---	4.20	---	---
TMTM, Monex	---	---	---	---	---	1.50	---	---
Santocure NS	---	---	---	---	---	0.10	---	---
Santocure	2.50	1.50	1.50	1.50	1.50	---	---	1.50
Formula Weight	159.50	158.50	158.50	158.50	198.50	155.20	164.78	158.50

Table 14b Polybutadiene rubber properties

Compound ID	PBD-1	PBD-2	PBD-3	PBD-4	PBD-5	PBD-6	PBD-7	PBD-8
Curing System Type	HS	HS	HS	HS	HS	Novor	LS	HS
Properties								
Mooney Viscometer								
ML +4 at 212 Deg F	100	75	86	61	64	116	149	80
T5 @ 250 Deg F, Minutes	7	9	7	11	23	12	5	23
Cure Conditions, Minutes/Deg F	20/300	15/300	15/300	15/300	35/300	30/300	25/300	45/300
Original Properties								
Tensile Strength, psi	831	1956	2385	2150	2475	1258	2417	2330
200% Modulus, psi	545	475	1436	835	858	747	820	805
Ultimate Elongation, %	260	443	320	360	395	317	480	368
Hardness, Shore A	75	74	84	72	71	74	68	---
Bashore Rebound, %	59	54	48	52	32	49	45	---
Specific Gravity	1.1030	1.0922	1.1036	1.0775	1.1336	1.0585	1.0824	1.0815
Abrasion Tests								
Taber, Grams/1000 Cycles	0.0498	0.0909	0.0404	0.0129	0.0087	0.0662	0.0406	0.2420
Pico, Rating	167	146	225	409	229	369	791	183
Tear Strength Using ASTM Die C								
Unaged, Lb/In	317	261	344	173	205	269	253	217
10 Minutes @ 250 Deg F, Lb/In	196	202	219	141	118	138	168	---
De Mattia Flex Properties								
Unaged Growth Rate, Mils/Minute	169	256	36	60	178	74	75	144
Unaged Crack Initiation, Kilocycles	10	4	21	8	---	---	---	---
After 70 Hours @ 212 Deg F, Mils/Minute	1213	1540	740	295	4677	41	54	571
Goodrich Flex Properties at 50 Deg C								
External Temperature Rise Rate, Deg C/Min	5.3	5.9	7.7	3.3	3.2	3.0	3.0	---
Blow Out Time at 141.6 psi, Minutes	---	---	---	---	---	---	---	---
Heat Resistance								
Stress Relaxation, F/F0 @ 250 Deg F = 70%	---	---	---	---	---	---	---	---
After Heat Aging for 70 Hrs at 250 Deg F								
Elongation Retention, %	---	---	---	---	---	---	---	---
Tensile Retention, %	---	---	---	---	---	---	---	---
Notes for Curing System Types:								
HS - High Sulfur Curing System								
LS - Low Sulfur Curing System								
Novor - Polyurethane Curing System Using Novor 924								

Thirty-five tri-blend compounds containing NR, SBR, and BR polymers, along with various curing and antioxidant systems, are shown in Table 15a, and their properties are compared in Table 15b. Compounds NSP-4, NSP-35, and NSP-34 provided the best Pico abrasion values (all over 240) with low tear strength values. Compounds NSP-13, NSP-15, NSP-17, NSP-32, NSP-11, NSP-12, and NSP-3 all provided low Pico abrasion values (below 100). The best room temperature tear strength values (over 550 lb/inch) were provided by compounds NSP-36, NSP-29, NSP-30, NSP-36, and NSP-23 through NSP-25. The best tear strength values (over 240 lb/inch) were provided by NSP-35, NSP-9, NSP-8, NSP-34, and NSP-24. In comparing NSP-28 with NSP-29, the only difference in the formulation was that Stereon 750 SBR was used in NSP-29 instead of the Copo 1500 SBR, and that resulted in improved abrasion and tear values for the NSP-29 material. In comparing the NSP-35 and NSP-36 formulations, the only difference was that the stearic acid content in NSP-36 was increased from 2 to 6 pphr; this increased the tear strength but decreased the abrasion resistance. Compounds NSP-24, NSP-25, and NSP-29 merit further investigations for use in track pad compounds.

Table 15a Natural-SBR-PBD rubber blends: formulations

Compound ID	NSP-1	NSP-2	NSP-3	NSP-4	NSP-5	NSP-6	NSP-7	NSP-8	NSP-9	NSP-10	NSP-11	NSP-12
INGREDIENTS												
Natural Rubber RSS-1	---	60.00	60.00	60.00	55.00	60.00	60.00	60.00	60.00	60.00	60.00	60.00
Natural Rubber, SMR-CV	60.00	---	---	---	---	---	---	---	---	---	---	---
Strene Butadiene (SBR) Rubbers												
Stereon 750	38.50	---	---	---	---	---	---	---	---	---	38.50	38.50
Gentro-Jet 9106	---	---	---	---	25.00	28.00	---	---	---	---	---	---
Philprene 1609	---	40.60	40.60	40.60	---	---	40.60	40.60	40.60	40.60	---	---
Polybutadiene (PBD) Rubber												
UBE POL-VCR 412	12.00	---	---	---	10.00	12.00	---	---	---	---	---	12.00
Cis 1, 4 1203	---	---	---	---	---	---	---	---	---	---	12.00	---
Taktene 1354	---	30.30	30.30	30.30	---	---	30.30	30.30	30.30	30.30	---	---
Vestenamer 8012 (Transoctenamer)	---	---	---	---	10.00	---	---	---	---	---	---	---
Zinc Oxide	4.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	4.00	4.00	4.00	4.00
Stearic Acid	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Piccopale 100		3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50
N-110, SAF Black	45.00	42.00	7.00	65.00	45.00	45.00	15.00	45.00	55.00	45.00	45.00	55.00
Antiox. DQ, Agerite Resin D	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Agerite White	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Antozite 2	3.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
Santoflex 13	---	---	---	---	---	---	---	1.50	1.50	1.50	1.50	1.50
Vanox MTI	---	---	---	---	---	---	---	0.50	0.50	0.50	0.50	0.50
Sulfur, Rubber Makers	0.40	2.00	2.00	2.00	0.75	0.75	2.00	0.75	0.75	0.40	0.40	0.75
Santocure	---	1.50	1.50	1.50	---	---	---	1.50	1.50	---	---	1.50
Butyl Tuads	---	---	---	---	0.63	0.63	---	0.63	0.63	---	---	0.63
Octoate Z	---	---	---	---	1.50	1.50	---	1.50	1.50	---	---	1.50
Amy Ledate	---	---	---	---	1.00	1.00	---	1.00	1.00	---	---	1.00
Amax	---	---	---	---	1.88	1.88	---	1.88	1.88	---	---	1.88
Novor 924	4.20	---	---	---	---	---	---	---	---	4.20	4.20	---
TMTM, Monex	1.50	---	---	---	---	---	---	---	---	1.50	1.50	---
Santocure NS	0.08	---	---	---	---	---	---	---	---	0.08	0.08	---
Formula Weight	171.68	190.90	155.90	213.90	165.26	165.26	162.40	199.66	210.66	199.58	179.18	190.26

Table 15a Natural-SBR-PBD rubber blends: formulations (continued)

Compound ID	NSP-13	NSP-14	NSP-15	NSP-16	NSP-17	NSP-18	NSP-19	NSP-20	NSP-21	NSP-22	NSP-23	NSP-24
INGREDIENTS												
Natural Rubber RSS-1	60.00	60.00	60.00	60.00	60.00	60.00	50.00	60.00	70.00	35.00	65.00	60.00
Strene Butadiene (SBR) Rubbers												
Stereon 750	38.50	38.50	---	38.50	38.50	38.50	---	---	---	---	---	38.50
Gentro-Jet 9106	---	---	28.00	---	---	---	---	---	---	---	---	---
Copo 1500	---	---	---	---	---	---	35.00	30.00	25.00	35.00	10.00	---
Polybutadiene (PBD) Rubber												
UBE POL-VCR 412		12.00	12.00	12.00	12.00	12.00	---	---	---	---	---	12.00
Cis 1, 4 1203	12.00	---	---	---	---	---	---	---	---	---	---	---
Taktene 220	---	---	---	---	---	---	15.00	10.00	5.00	30.00	25.00	---
Zinc Oxide	4.00	4.00	4.00	---	---	4.00	3.00	3.00	3.00	3.00	3.00	---
Stearic Acid	2.00	2.00	2.00	2.00	2.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50
Piccopale 100	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50
N-110, SAF Black	45.00	45.00	45.00	55.00	55.00	60.00	45.00	45.00	45.00	45.00	45.00	70.00
Molybdenium Disulfide	---	---	---	---	20.00	---	---	---	---	---	---	---
Antiox. DQ, Agerite Resin D	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Agerite White	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Antozite 2	5.00	5.00	5.00	5.00	5.00	5.00	3.00	3.00	3.00	3.00	3.00	3.00
Vanox MTI	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Santoflex 13	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
Sulfur, Rubber Makers	0.75	2.00	0.40	---	---	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Santocure	---	1.50	---	---	---	---	1.50	1.50	1.50	1.50	1.50	---
Novor 924	---	---	4.20	---	---	---	---	---	---	---	---	---
TMTM, Monex	---	---	1.50	---	---	---	---	---	---	---	---	---
Santocure NS	---	---	0.80	---	---	---	---	---	---	---	---	---
Polydox SZD-85	---	---	---	4.70	4.70	---	---	---	---	---	---	---
Polydox S (SA-75)	---	---	---	2.00	2.00	---	---	---	---	---	---	---
Polydox S (SS-75)	---	---	---	2.70	2.70	---	---	---	---	---	---	1.00
Polydox SZ-85F	---	---	---	---	---	---	---	---	---	---	---	3.50
Butyl Tuads	0.63	---	---	---	---	0.63	---	---	---	---	---	---
Octoate Z	1.50	---	---	---	---	1.50	---	---	---	---	---	1.50
Amy Ledate	1.00	---	---	---	---	1.00	---	---	---	---	---	1.00
Amax	1.88	---	---	---	---	1.88	---	---	---	---	---	---
Drimix OBTS (70/30)	---	---	---	---	---	---	---	---	---	---	---	2.70
Formula Weight	178.76	176.50	169.40	188.40	208.40	194.51	162.50	162.50	162.50	162.50	162.50	203.20

Table 15a Natural-SBR-PBD rubber blends: formulations (continued)

Compound ID	NSP-25	NSP-26	NSP-28	NSP-29	NSP-30	NSP-31	NSP-32	NSP-33	NSP-34	NSP-35	NSP-36
INGREDIENTS											
Natural Rubber RSS-1	85.00	85.00	85.00	85.00	85.00	---	85.00	35.00	35.00	60.00	60.00
Natural SMR-5	---	---	---	---	---	35.00	---	---	---	---	---
Strene Butadiene (SBR) Rubbers											
Stereon 750	---	6.90	---	6.90	6.90	---	6.90	---	---	---	---
Philprene 1609	---	---	---	---	---	---	---	---	---	40.60	40.60
Copo 1500	5.00	---	5.00	---	---	35.00	---	---	---	---	---
Krylene 1502	---	---	---	---	---	---	---	---	35.00	---	---
XC-940	---	---	---	---	---	---	---	39.00	---	---	---
Polybutadiene (PBD) Rubber											
UBE POL-VCR 412	---	10.00	10.00	10.00	10.00	---	10.00	---	---	---	---
Taktene 1354	---	---	---	---	---	---	---	---	---	30.30	30.30
Taktene 220	10.00	---	---	---	---	30.00	---	30.00	30.00	---	---
Zinc Oxide	3.00	3.00	3.00	3.00	3.00	3.00	5.00	3.00	3.00	3.00	3.00
Stearic Acid	1.50	1.50	1.50	1.50	1.50	1.50	2.00	1.50	1.50	2.00	6.00
Piccopale 100	---	---	---	---	---	1.50	---	1.50	1.50	---	---
Sundex 790	---	---	---	---	---	4.00	---	4.00	4.00	---	---
N-110, SAF Black	45.00	50.00	55.00	55.00	45.00	---	45.00	---	---	45.00	45.00
N-220, ISAF Black	---	---	---	---	---	65.00	---	65.00	65.00	---	---
Antiox. DQ, Agerite Resin D	0.50	0.50	0.50	0.50	0.50	2.00	0.50	2.00	2.00	0.50	0.50
Agerite White	0.50	0.50	0.50	0.50	0.50	---	0.50	---	---	0.50	0.50
Antozite 2	3.00	3.00	5.00	5.00	5.00	---	5.00	---	---	---	---
Vanox MTI	---	---	---	0.50	0.50	---	0.50	---	---	0.50	0.50
Santoflex 13	1.50	1.50	1.50	1.50	1.50	3.00	1.50	3.00	3.00	3.00	3.00
Sunolite 100	---	---	---	---	---	1.50	---	1.50	1.50	---	---
Santogard PVI	---	---	---	---	---	0.20	1.00	0.20	0.20	0.50	0.50
Sulfur, Rubber Makers	2.00	2.00	0.80	0.80	0.40	1.30	1.00	1.30	1.30	2.00	2.00
Santocure	1.50	1.50	---	---	---	---	---	---	---	1.50	1.50
Butyl Tuads	---	---	0.70	0.70	---	---	---	---	---	---	---
Octoate Z	---	---	1.50	1.50	---	---	---	---	---	---	---
Amy Ledate	---	---	1.00	1.00	---	---	---	---	---	---	---
Amax	---	---	1.90	1.90	---	---	---	---	---	---	---
Curerite 18	---	---	---	---	---	---	6.00	---	---	---	---
Novor 924	---	---	---	---	4.20	---	2.70	---	---	---	---
TMTM, Monex	---	---	---	---	1.50	---	---	---	---	---	---
Santocure NS	---	---	---	---	0.10	---	---	---	---	---	---
Santocure IPS (DIBS)	---	---	---	---	---	3.20	---	3.20	3.20	---	---
Formula Weight	158.50	165.40	172.90	175.30	165.60	186.20	172.60	190.20	186.20	189.40	193.40

Table 15b Natural-SBR-PBD rubber blends: properties

Compound ID	NSP-1	NSP-2	NSP-3	NSP-4	NSP-5	NSP-6	NSP-7	NSP-8	NSP-9	NSP-10	NSP-11	NSP-12
Curing System Type	Novor	HS	HS	HS	LS	LS	HS	LS	LS	Novor	Novor	LS
Properties												
Mooney Viscometer												
ML +4 at 212 Deg F	41	36	20	80	31	37	25	38	44	45	26	26
T5 @ 250 Deg F, Minutes	23	17	24	15	15	16	24	12	7	14	13	7
Cure Conditions, Minutes/Deg F	25/320	25/290	25/290	25/290	35/290	35/290	25/290	30/300	20/290	30/310	20/310	25/280
Original Properties												
Tensile Strength, psi	3087	3100	2839	2900	3117	3325	3313	2743	2530	2460	2763	3167
200% Modulus, psi	503	867	140	1900	817	650	500	500	780	523	457	410
Ultimate Elongation, %	607	483	595	293	485	525	613	577	457	603	620	657
Hardness, Shore A	70	73	51	81	70	---	62	67	75	78	58	58
Bashore Rebound, %	36	34	51	27	39	36	45	27	26	30	41	37
Specific Gravity	1.0880	1.1346	1.0551	1.1874	1.0994	1.0987	1.1005	1.1421	1.1703	1.1437	1.0978	1.0576
Abrasion Tests												
Taber, Grams/1000 Cycles	0.0543	0.0387	0.4880	0.0373	0.0402	---	0.0502	0.0394	0.0632	0.0579	0.0752	0.0578
Pico, Rating	132	190	92	299	133	---	114	149	164	116	75	83
Tear Strength Using ASTM Die C												
Unaged, Lb/In	312	396	252	317	316	286	406	515	454	441	270	433
10 Minutes @ 250 Deg F, Lb/In	196	227	177	210	157	175	209	252	253	197	172	173
De Mattia Flex Properties												
Unaged Growth Rate, Mils/Minute	12.0	17.0	11.0	8.0	---	16.0	9.0	7.0	14.0	7.0	13.0	15.0
Unaged Crack Initiation, Kilocycles	235	19	31	48	---	---	51	240	204	271	67	60
After 70 Hours @ 212 Deg F, Mils/Minute	17	82	17	153	---	33	12	11	21	6	11	27
Goodrich Flex Properties at 50 Deg C												
External Temperature Rise Rate, Deg C/Min	6.1	5.8	2.7	5.7	---	4.6	4.2	6.3	8.4	8.2	5	3
Blow Out Time at 141.6 psi, Minutes	>120	21	>120	14	---	>120	38	29	15	38	28	55
Heat Resistance												
Stress Relaxation, F/F0 @ 250 Deg F = 70%	298	98	135	103	---	103	128	470	483	235	415	1070
After Heat Aging for 70 Hrs at 250 Deg F												
Elongation Retention, %	48	27	25	26	---	---	26	47	36	34	39	56
Tensile Retention, %	32	33	21	35	---	---	27	59	55	39	45	60
Notes for Curing System Types:												
HS - High Sulfur Curing System												
LS - Low Sulfur Curing System												
Novor - Polyurethane Curing System Using Novor 924												

Table 15b Natural-SBR-PBD rubber blends: properties (continued)

Compound ID	NSP-13	NSP-14	NSP-15	NSP-16	NSP-17	NSP-18	NSP-19	NSP-20	NSP-21	NSP-22	NSP-23	NSP-24
Curing System Type	LS	HS	Novor	Novor	Novor	HS	HS	HS	HS	HS	HS	LS
Properties												
Mooney Viscometer												
ML +4 at 212 Deg F	23	30	41	35	---	94	41	37	27	---	34	59
T5 @ 250 Deg F, Minutes	8	9	11	12	---	---	11	16	9	---	10	12
Cure Conditions, Minutes/Deg F	25/280	25/280	30/300	25/290	20/290	25/290	20/290	25/300	30/28/0	25/290	25/280	20/300
Original Properties												
Tensile Strength, psi	3113	3180	3107	3093	3027	2800	3560	3660	3737	3263	3633	2973
200% Modulus, psi	350	590	553	727	780	590	697	503	793	693	627	733
Ultimate Elongation, %	653	567	617	527	517	543	557	647	537	530	530	520
Hardness, Shore A	56	64	79	69	70	64	66	63	69	68	65	72
Bashore Rebound, %	37	41	40	37	36	31	42	41	42	46	45	30
Specific Gravity	1.0553	1.0643	1.0687	1.0817	1.1693	1.0912	1.0832	1.0795	1.0814	1.0825	1.0748	1.1260
Abrasion Tests												
Taber, Grams/1000 Cycles	0.0479	0.0250	0.1353	0.1288	0.0433	0.0449	0.1530	0.0300	0.0325	0.0296	0.0338	0.0603
Pico, Rating	84	119	96	126	93	118	143	130	137	144	137	152
Tear Strength Using ASTM Die C												
Unaged, Lb/In	251	317	301	300	296	258	284	544	545	263	551	551
10 Minutes @ 250 Deg F, Lb/In	167	192	191	218	221	195	188	220	213	154	234	242
De Mattia Flex Properties												
Unaged Growth Rate, Mils/Minute	14	17	12	22	27	21	19	12	16	25	18	15
Unaged Crack Initiation, Kilocycles	67	47	67	7	7	86	32	44	27	18	27	55
After 70 Hours @ 212 Deg F, Mils/Minute	34	26	13	36	37	37	57	22	36	25	24	22
Goodrich Flex Properties at 50 Deg C												
External Temperature Rise Rate, Deg C/Min	3.0	2.9	4.1	3.8	4.1	4.2	3.5	3.7	3.5	3.6	3.4	5.7
Blow Out Time at 141.6 psi, Minutes	59	30	15	4	5	3	3	7	38	29	22	44
Heat Resistance												
Stress Relaxation, F/F0 @ 250 Deg F = 70%	1130	213	580	245	193	1217	150	138	217	125	158	2010
After Heat Aging for 70 Hrs at 250 Deg F												
Elongation Retention, %	61	27	61	23	18	36	25	19	27	29	18	54
Tensile Retention, %	68	32	62	39	37	51	38	27	33	48	22	80
Notes for Curing System Types:												
HS - High Sulfur Curing System												
LS - Low Sulfur Curing System												
Novor - Polyurethane Curing System Using Novor 924												

Table 15b Natural-SBR-PBD rubber blends: properties (continued)

Compound ID	NSP-25	NSP-26	NSP-28	NSP-29	NSP-30	NSP-31	NSP-32	NSP-33	NSP-34	NSP-35	NSP-36
Curing System Type	HS	HS	LS	LS	Novor	LS	Novor	LS	LS	HS	HS
Properties											
Mooney Viscometer											
ML +4 at 212 Deg F	30	30	46	25	30	70	15	62	---	55	43
T5 @ 250 Deg F, Minutes	10	10	4	6	13	73	22	65	---	22	22
Cure Conditions, Minutes/Deg F	30/280	25/280	15/300	20/300	30/300	30/310	25/300	45/300	45/300	30/290	25/290
Original Properties											
Tensile Strength, psi	3993	3754	2120	3430	3153	3250	2967	3063	3027	3660	3300
200% Modulus, psi	835	925	607	800	580	1267	1200	1980	1577	1230	1160
Ultimate Elongation, %	528	520	427	520	567	427	413	303	297	463	420
Hardness, Shore A	67	70	72	72	71	74	78	80	76	78	81
Bashore Rebound, %	46	43	36	37	44	35	43	35	36	31	---
Specific Gravity	1.0930	1.1000	1.1121	1.1220	1.0750	1.1460	1.1150	1.1553	1.1504	1.1440	1.1391
Abrasion Tests											
Taber, Grams/1000 Cycles	0.1928	0.0315	---	0.0406	0.0488	0.0198	0.0221	0.0185	0.0098	0.2160	0.0335
Pico, Rating	151	155	112	155	100	160	97	204	244	267	175
Tear Strength Using ASTM Die C											
Unaged, Lb/in	566	534	334	554	638	159	302	197	263	316	581
10 Minutes @ 250 Deg F, Lb/in	255	255	230	287	268	157	156	151	167	239	246
De Mattia Flex Properties											
Unaged Growth Rate, Mils/Minute	16	17	18	14	8	24	23	55	32	21	23
Unaged Crack Initiation, Kilocycles	157	138	5	48	39	11	16	11	11	---	---
After 70 Hours @ 212 Deg F, Mils/Minute	21	20	23	16	6	51	30	600	120	50	100
Goodrich Flex Properties at 50 Deg C											
External Temperature Rise Rate, Deg C/Min	3.1	3.2	3.4	3.7	4.0	5.1	4.2	---	5	---	3
Blow Out Time at 141.6 psi, Minutes	>120	81	>120	>120	70	43	55	44	43	---	---
Heat Resistance											
Stress Relaxation, F/F0 @ 250 Deg F = 70%	---	---	400	536	125	270	335	205	505	240	270
After Heat Aging for 70 Hrs at 250 Deg F											
Elongation Retention, %	22	18	47	45	46	27	27	11	18	12	15
Tensile Retention, %	20	22	54	49	27	63	37	67	44	31	34
Notes for Curing System Types:											
HS - High Sulfur Curing System											
LS - Low Sulfur Curing System											
Novor - Polyurethane Curing System Using Novor 924											

Table 16a shows 3 SBR blends with BR (SP compounds) and 4 blends of SBR with NR (NS compounds), and their properties are compared in Table 16b. The SP blend compounds exhibited low tear strength values and poor resistance to blowout. The NS-1 blend provided the highest tear strength and average abrasion resistance. When the natural content was lowered to 40 pphr in NS-2, its tear strength was reduced by over 50%, with a slight increase in abrasion resistance. Compound NS-3, which used the low sulfur cure, provided the lowest abrasion and tear strength values.

Table 16a SBR blends with natural and polybutadiene rubber formulations

Compound ID	SP-1	SP-2	SP-3	NS-1	NS-2	NS-3	NS-4
INGREDIENTS							
Natural Rubber RSS-1	---	---	---	60.00	40.00	---	---
Natural Rubber SMR-CV	---	---	---	---	---	80.00	80.00
Copo 1500 SBR Rubber	60.00	20.00	40.00	40.00	60.00	---	---
Buna SL704 SBR Rubber	---	---	---	---	---	20.00	20.00
Taktene 220 Polybutadiene Rubber	40.00	---	---	---	---	---	---
UBE Poly-VCR 412 Polybutadiene Rubber	---	80.00	60.00	---	---	---	---
Zinc Oxide	3.00	4.00	4.00	3.00	3.00	5.00	5.00
Stearic Acid	1.50	2.00	2.00	1.50	1.50	2.50	2.50
Piccopale 100	3.50	---	---	3.50	3.50	---	---
Sundex 790	---	---	---	---	---	3.00	3.00
N-110, SAF Black	45.00	35.00	35.00	45.00	45.00	---	---
N-330, HAF Black	---	---	---	---	---	55.00	55.00
Antiox. DQ, Agerite Resin D	0.50	0.50	0.50	0.50	0.50	1.00	1.10
Agerite White	0.50	0.50	0.50	0.50	0.50	---	---
Antozite 2	3.00	5.00	5.00	3.00	3.00	---	---
Extra Sunproof Wax	---	---	---	---	---	1.00	1.00
Vanox MTI	0.50	0.50	0.50	0.50	0.50	0.50	---
Santoflex 13	1.50	1.50	1.50	1.50	1.50	---	---
Vulcanox 4010 NA	---	---	---	---	---	3.00	---
Permanex IPPD	---	---	---	---	---	1.60	1.60
Sulfur, Rubber Makers	2.00	0.40	0.40	2.00	2.00	0.25	---
Santocure	1.50	---	---	1.50	1.50	---	---
Methyl Tuads	---	---	---	---	---	1.10	2.50
Ethyl Tuads	---	---	---	---	---	1.30	---
Polydox S (SS-75), Sulfur	---	---	---	---	---	---	0.20
Novor 924	---	4.20	4.20	---	---	---	---
TMTM, Monex	---	1.50	1.50	---	---	---	---
Santocure NS	---	0.10	0.10	---	---	---	---
Formula Weight	162.50	155.20	155.20	162.50	162.50	175.25	171.90

Table 16b SBR blends with natural and polybutadiene rubber properties

Compound ID	SP-1	SP-2	SP-3	NS-1	NS-2	NS-3	NS-4
Curing System Type	HS	Novor	Novor	HS	LS	LS	SD
Properties							
Mooney Viscometer							
ML +4 at 212 Deg F	47	96	53	30	11	41	29
T5 @ 250 Deg F, Minutes	12	13	14	37	11	4	13
Cure Conditions, Minutes/Deg F	20/290	35/300	40/300	20/290	20/300	20/300	30/300
Original Properties							
Tensile Strength, psi	2737	2147	2350	3557	2990	2733	3160
200% Modulus, psi	500	670	485	613	590	1043	980
Ultimate Elongation, %	570	527	680	583	537	377	443
Hardness, Shore A	62	72	69	64	65	72	73
Bashore Rebound, %	45	47	46	38	38	41	39
Specific Gravity	1.0780	1.0635	1.0732	1.0722	1.0844	1.1084	1.1127
Abrasion Tests							
Taber, Grams/1000 Cycles	---	0.1123	0.0581	0.0126	0.0294	0.0932	0.0634
Pico, Rating	117	125	112	121	132	97	117
Tear Strength Using ASTM Die C							
Unaged, Lb/in	250	271	278	600	251	241	289
10 Minutes @ 250 Deg F, Lb/in	120	155	143	218	199	125	205
De Mattia Flex Properties							
Unaged Growth Rate, Mils/Minute	95	34	21	15	16	24	14
Unaged Crack Initiation, Kilocycles	2	---	---	28	36	45	33
After 70 Hours @ 212 Deg F, Mils/Minute	262	29	16	23	29	272	28
Goodrich Flex Properties at 50 Deg C							
External Temperature Rise Rate, Deg C/Min	3.9	3.5	3.9	---	---	---	---
Blow Out Time at 141.6 psi, Minutes	18	11	10	---	---	---	---
Heat Resistance							
Stress Relaxation, F/F0 @ 250 Deg F = 70%	365	380	800	---	---	---	---
After Heat Aging for 70 Hrs at 250 Deg F							
Elongation Retention, %	36	47	54	---	---	---	---
Tensile Retention, %	64	81	91	---	---	---	---
Notes for Curing System Types:							
HS - High Sulfur Curing System							
LS - Low Sulfur Curing System							
Novor - Polyurethane Curing System Using Novor 924							
SD - Sulfur Donor Cureing system							

Table 17a shows 3 nitrile and 9 HNBR rubber formulations, and their properties are compared in Table 17b. All of the HNBR compounds, except for NBR-01, provided excellent abrasion resistance. NBR-2 and NBR-12 provided the best retention of properties after heat aging at 250 °F. Only NBR-2 and NBR-3 provided good resistance to blowout. Compounds NBR-4 and NBR-12 merit further investigation for use in track pad compounds. NBR-12 was selected to fabricate track pads for a counter obstacle vehicle and T-142 track for an M-60 vehicle. Field testing indicated that the NBR-12 material provided a 2- to 3-fold improvement over commercial pads in the late 1980s.^{4,8,9} Two US patents based on NBR-12 were obtained in 1989 and 1993.^{1,2}

Table 17a Nitrile rubber formulations

Compound ID	NBR-1	NBR-2	NBR-3	NBR-4	NBR-6	NBR-7	NBR-8	NBR-9	NBR-10	NBR-11	NBR-12
INGREDIENTS											
Hycar VT 355 (NBR Rubber)	---	---	---	---	---	100.00	---	---	---	---	---
Paracril CJ (NBR Rubber)	---	---	---	---	---	---	100.00	---	---	---	---
Paracril 1880 (NBR Rubber)	---	---	---	---	---	---	---	100.00	---	---	---
Zetpol 2020 (HNBR Rubber)	100.00	100.00	100.00	100.00	100.00	---	---	---	100.00	100.00	100.00
Zinc Oxide	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	---	2.00	2.00
Stearic Acid	1.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	---	---	---
MPC Black	---	---	---	---	---	---	---	---	---	25.00	20.00
N-110, SAF Black	40.00	45.00	45.00	---	---	---	---	---	---	---	---
N-121, SAF-HS Black	---	---	---	45.00	45.00	45.00	45.00	45.00	50.00	---	---
Cabosil MS-7SD Silica	---	---	---	20.00	---	---	---	---	---	---	---
Z Max MA	---	---	---	---	---	---	---	---	---	35.00	30.00
Santogard PVI	---	---	---	1.25	---	---	1.25	1.25	---	---	---
Agerite Resin D	0.50	---	---	---	---	0.50	0.50	0.50	---	0.50	0.50
Agerite White	0.50	---	---	---	---	0.50	0.50	0.50	---	---	---
Antozite 2	3.00	---	---	---	---	---	---	---	---	---	---
Vanox MTI	---	---	---	---	---	0.50	0.50	0.50	---	---	---
Santoflex 13	1.50	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	---	---
Sulfur	0.50	0.80	0.40	0.80	0.40	0.80	0.80	0.80	0.40	---	---
MBT	0.50	---	---	---	---	---	---	---	---	---	---
TMTD, Methyl Tuads	1.50	---	---	---	---	---	---	---	---	---	---
Butyl Tuads	---	0.70	---	---	---	---	---	---	---	---	---
Octoate Z	---	1.50	---	---	---	---	---	---	---	---	---
Amyl Ledate	---	1.00	---	---	---	---	---	---	---	---	---
Amax	---	1.90	---	---	---	---	---	---	---	---	---
Novor 924	---	---	4.20	4.20	4.20	4.20	4.20	4.20	4.20	---	---
TMTM, Monex	---	---	1.50	1.50	1.50	1.50	1.50	1.50	1.50	---	---
Santocure NS	---	---	0.10	0.10	0.10	0.10	0.10	0.10	0.10	---	---
Di Cup R	---	---	---	---	---	---	---	---	---	1.50	1.30
Formula Weight	154.00	160.90	161.20	182.85	161.20	163.10	164.35	164.35	159.20	164.00	153.80

Table 17b Nitrile rubber properties

Compound ID	NBR-1	NBR-2	NBR-3	NBR-4	NBR-6	NBR-7	NBR-8	NBR-9	NBR-10	NBR-11	NBR-12
Properties											
Mooney Viscometer											
ML +4 at 212 Deg F	75	92	111	155	107	65	65	87	91	26	98
T5 @ 250 Deg F, Minutes	12.4	8	24.7	25	26	37	23	18	120	26	46
Cure Conditions, Minutes/Deg F	30/320	53/320	50/330	40/330	40/320	40/330	30/330	35/330	30/330	45/310	40/330
Original Properties											
Tensile Strength, psi	4080	4543	4440	4140	4193	3090	3500	2730	4763	4400	3960
200% Modulus, psi	900	1017	820	1290	980	650	1250	1130	1300	1230	843
Ultimate Elongation, %	465	443	540	533	507	480	420	330	507	480	570
Hardness, Shore A	70	71	75	85	72	70	76	71	75	86	78
Bashore Rebound, %	26	24	25	24	28	29	5	41	27	32	30
Specific Gravity	1.1337	1.1438	1.1408	1.2145	1.1341	1.1857	1.1517	---	---	---	1.1373
Abrasion Tests											
Taber, Grams/1000 Cycles	0.005	0.0014	0.0025	0.0044	0.003	---	0.0398	0.0397	---	---	0.0015
Pico, Rating	223	653	1094	857	720	132	217	245	---	525	691
Tear Strength Using ASTM Die C											
Unaged, Lb/In	261	322	406	479	408	---	295	255	437	204	449
10 Minutes @ 250 Deg F, Lb/In	103	107	169	220	173	---	147	112	194	230	234
De Mattia Flex Properties											
Unaged Growth Rate, Mils/Minute	47.0	61	12	13	1	22	29	57	13	13	10
Unaged Crack Initiation, Kilocycles	7.0	88	616	---	---	---	---	---	---	---	110
After 70 Hours @ 212 Deg F, Mils/Minute	26	100	16	32	22	29	---	286	---	120	12
Goodrich Flex Properties at 50 Deg C											
External Temperature Rise Rate, Deg C/Min	6	6	7	---	---	---	---	---	---	---	6
Blow Out Time at 141.6 psi, Minutes	8	>120	>120	---	6	13	10	---	---	---	8
Heat Resistance											
Stress Relaxation, F/F0 @ 250 Deg F = 70%	3460	2040	2120	---	3660	650	1680	910	---	---	---
After Heat Aging for 70 Hrs at 250 Deg F											
Elongation Retention, %	62	112	73	50	77	39	33	32	---	---	100
Tensile Retention, %	100	323	100	100	100	62	65	67	---	---	94

Six carboxylated nitrile (XNBR) and one HNBR rubber formulation are presented in Table 18a, and their properties are compared in Table 18b. The HNBR compound (NBR-12) was included in this study for comparison of its properties with those of the XNBR compounds. The NBR-12 material excelled over the XNBR materials in all tests except for heat buildup. An area in which we expected XNBR compounds to excel was wear resistance, but the HNBR compound provided abrasion and cutting and chipping values at least 3 times better than the XNBR compounds.

Table 18a Carboxylated nitrile rubber formulations

Compound ID	NBR-12	XNBR-1	XNBR-2	XNBR-3	XNBR-4	XNBR-5	XNBR-6
INGREDIENTS							
Hycar 1072 Carboxylated Rubber (1)	---	---	---	---	---	---	100.00
Cheigum NX-775 Carboxylated Rubber (1)	---	100.00	---	---	---	---	---
Krynac 110 Carboxylated Rubber (1)	---	---	95.00	---	---	---	---
Krynac 221 Carboxylated Rubber (1)	---	---	---	95.00	---	---	---
Krynac 211 Carboxylated Rubber (1)	---	---	---	---	95.00	---	---
Krynac XC775 Carboxylated Rubber (1)	---	---	---	---		95.00	---
Krynac PA-50 Powdered Nitrile Rubber	---	---	10.00	10.00	10.00	10.00	---
Zetpol 2020, HNBR Rubber	100.00	---	---	---	---	---	---
Zinc Oxide	2.00	5.00	---	---	---	---	---
Stearic Acid	---	3.00	3.00	3.00	3.00	3.00	3.00
N-110, SAF Black	---	40.00	40.00	40.00	40.00	40.00	40.00
MPC Black	20.00	---	---	---	---	---	---
Z Max MA	30.00	---	---	---	---	---	---
Di Cup R	1.30	---	---	---	---	---	---
Unads	---	1.50	1.50	1.50	1.50	1.50	1.50
Sulfur, Spider Brand	---	1.50	1.50	1.50	1.50	1.50	1.50
AZ CNO 85	---	---	---	---	---	---	5.00
Formula Weight	153.30	151.00	151.00	151.00	151.00	151.00	151.00
Notes:							
1. Carboxylated Nitrile Rubber - Butadiene Acrylonitrile Organic Acid Terpolymer							

Table 18b Carboxylated nitrile rubber properties

Compound ID	NBR-12	XNBR-1	XNBR-2	XNBR-3	XNBR-4	XNBR-5	XNBR-6
Properties							
Mooney Viscometer							
ML +4 at 212 Deg F	98	78	91	87	75	56	70
T5 @ 250 Deg F, Minutes	46	7	23	10	10	17	5
Cure Conditions, Minutes/Deg F	40/330	40/330	40/330	40/330	25/330	35/330	20/330
Original Properties							
Tensile Strength, psi	3960	3547	2470	3523	3750	3733	3883
200% Modulus, psi	843	2613	1577	2500	2710	3680	2197
Ultimate Elongation, %	570	270	267	260	263	270	313
Hardness, Shore A	78	84	77	79	80	80	77
Bashore Rebound, %	30	12	16	11	13	12	10
Specific Gravity	1.1373	1.1676	1.1489	1.1717	1.1399	1.1696	1.1660
Abrasion Tests							
Taber, Grams/1000 Cycles	0.0015	0.0083	0.0135	0.0130	---	0.0099	0.0068
Pico, Rating	691	341	189	308	278	282	290
Tear Strength Using ASTM Die C							
Unaged, Lb/In	449	310	250	297	303	270	265
10 Minutes @ 250 Deg F, Lb/In	234	144	115	112	125	142	163
Goodrich Cutting and Chipping							
Diameter Loss, Inches	0.050	---	---	0.468	---	---	0.470
Weight Loss, Grams	0.750	---	---	6.061	---	---	5.901
De Mattia Flex Properties							
Unaged Growth Rate, Mils/Minute	10	333.0	375.0	111.0	111.0	111.0	111.0
Unaged Crack Initiation, Kilocycles	110	1	1	1	1	2	1
After 70 Hours @ 212 Deg F, Mils/Minute	12	448	448	500	500	500	500
Goodrich Flex Properties at 50 Deg C							
External Temperature Rise Rate, Deg C/Min	58	38.0	22.0	19.0	28.0	27.0	28.0

In Table 19a, 9 formulations of natural and HNBR rubber blends, using various curing systems, are provided, and their properties are compared in Table 19b. Compounds NN-5 through NN-7 provided higher tear strength values than that provided by NBR-12 (previously presented in Tables 18b and 17b), but the abrasion values were much lower. All of these compounds used blends with a higher concentration of NR; consequently, additional work needs to be performed with higher concentrations of HNBR rubber. The heat buildup and blowout tests need to be performed on NN-7, because this compound with a low-sulfur curing system provided good abrasion and excellent tear values.

Properties of 19 off-the-road (OTR) commercial tire tread rubber compounds from 6 different suppliers are compared in Table 20 to determine if any of these materials had potential to be used in track pads. OTR-20 and 21 provided excellent tear resistance and fair abrasion resistance values, but the Goodrich flex test results are not available to determine heat buildup and blowout resistance potential. These test results are needed to assess their potential for track pad application. Ten additional pphr of N-110 was added to OTR-2 (forming OTR-2A) in an attempt to increase its abrasion resistance, but only a minor increase was obtained. Based on the results from the carbon black study observed in Tables 10b and 10c, N-299 black should have been used to maximize the abrasion resistant property. N-299 black should be added to OTR-14, OTR-20, and OTR-21 to improve abrasion resistance.

Table 19a Natural and highly saturated nitrile (HNBR) rubber blend: formulations

Compound ID	NN-1	NN-2	NN-3	NN-4	NN-5	NN-6	NN-7	NN-8	NN-9
INGREDIENTS									
Natural Rubber RSS-1	70.00	65.00	65.00	65.00	80.00	80.00	---	---	---
Natural Rubber SMR-L	---	---	---	---	---	---	80.00	80.00	80.00
Vestnamer 8012 (Transoctenamer)	---	10.00	10.00	10.00	---	---	---	---	---
Highly Saturated Nitrile (HNBR) Rubber									
Zetpol 2020	30.00	---	25.00	25.00	20.00	20.00	20.00	20.00	20.00
Zetpol 2010	---	25.00	---	---	---	---	---	---	---
Zinc Oxide	5.00	---	---	---	5.00	5.00	5.00	5.00	5.00
Stearic Acid	1.00	2.00	2.00	2.00	2.00	2.00	2.00	---	---
Struktol A-60	---	---	---	---	---	---	3.00	---	---
Piccopale 100	---	3.50	3.50	3.50	---	---	---	---	---
N-110, SAF Black	43.50	45.00	45.00	45.00	---	---	---	---	---
N-121, HAF-HS Black	---	---	---	---	45.00	45.00	55.00	---	---
MPC Black	---	---	---	---	---	---	---	25.00	20.00
Z Max MA	---	---	---	---	---	---	---	35.00	30.00
Antiox. DQ, Agerite Resin D	0.50	0.50	0.50	0.50	0.50	0.50	0.50	1.50	1.50
Agerite White	0.50	0.50	0.50	0.50	0.50	0.50	0.50	---	---
Antozite 2	3.00	5.00	5.00	5.00	---	---	---	---	---
Vanox MTI	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Santoflex 13	0.45	1.50	1.50	1.00	3.00	3.00	3.00	---	---
Santogard PVI	---	---	---	---	---	---	0.20	---	---
Methyl Ethyl Tuads	---	---	---	---	---	3.00	---	---	---
Methyl Tuads	0.45	---	---	---	---	---	---	---	---
Sulfur, Rubber Makers	1.90	---	---	---	0.40	0.30	1.30	---	---
Santocure	1.05	---	---	---	---	---	---	---	---
MBT	0.15	---	---	---	---	---	---	---	---
Novor 924	---	---	---	---	4.20	---	---	---	---
TMTM, Monex	---	---	---	---	1.50	---	---	---	---
Santocure NS	---	---	---	---	0.10	---	---	---	---
Santocure MOR-90	---	---	---	---	---	5.00	---	---	---
Santocure IPS	---	---	---	---	---	---	3.20	---	---
Drimix Butyl Tuads	---	0.83	---	0.83	---	---	---	---	---
Drimix Octoate Z	---	2.00	---	2.00	---	---	---	---	---
Drimix Amyl Ledate	---	1.33	---	1.33	---	---	---	---	---
Dimix OBTS (Amax)	---	2.68	---	2.68	---	---	---	---	---
Polydox SZ-85F	---	4.70	4.70	4.70	---	---	---	---	---
Polydox S (SS-75), Sulfur	---	1.00	0.53	1.00	---	---	---	---	---
Kenlastic K-36293, Novor 924	---	---	5.60	---	---	---	---	---	---
Kenlastic L-10828, TMTM	---	---	2.00	---	---	---	---	---	---
Kenlastic K-19803, Santocure NS	---	---	0.11	---	---	---	---	---	---
Di Cup R	---	---	---	---	---	---	---	2.50	1.80
Formula Weight	158.00	171.04	171.44	170.54	162.70	164.80	174.20	169.50	158.80

Table 19b Natural and highly saturated nitrile (HNBR) rubber blend: properties

Compound ID	NN-1	NN-2	NN-3	NN-4	NN-5	NN-6	NN-7	NN-8	NN-9
Curing System Type	HS	Novor	Novor	Novor	Novor	LS	LS	Peroxide	Peroxide
Properties									
Mooney Viscometer									
ML +4 at 212 Deg F	42	200	36	200	47	27	60	36	28
T5 @ 250 Deg F, Minutes	4	---	6	---	12	17	7	14	17
Cure Conditions, Minutes/Deg F	20/280	15/290	25/300	30/300	35/320	40/300	40/300	30/300	35/300
Original Properties									
Tensile Strength, psi	3730	2723	3230	2890	3280	3247	3213	4317	4297
200% Modulus, psi	943	600	693	650	980	1090	1320	2040	4560
Ultimate Elongation, %	500	610	617	597	587	513	490	390	430
Hardness, Shore A	80	78	78	77	82	79	83	91	84
Bashore Rebound, %	30	25	31	27	30	25	28	43	51
Specific Gravity	1.3390	1.1045	1.0897	1.1069	1.1068	1.1181	1.1478	1.1534	1.1396
Abrasion Tests									
Taber, Grams/1000 Cycles	0.3445	0.1224	0.1700	0.1517	0.0897	0.3477	0.1729	---	0.4344
Pico, Rating	112	88	83	84	141	135	245	---	221
Tear Strength Using ASTM Die C									
Unaged, Lb/In	453	448	236	438	622	522	575	498	347
10 Minutes @ 250 Deg F, Lb/In	253	152	184	166	288	219	295	216	204
De Mattia Flex Properties									
Unaged Growth Rate, Mils/Minute	17	13	15	14	10	19	19	24	17
Unaged Crack Initiation, Kilocycles	28	33	60	50	---	---	14	---	---
After 70 Hours @ 212 Deg F, Mils/Minute	35	33	17	15	12	33	40	---	38
Goodrich Flex Properties at 50 Deg C									
External Temperature Rise Rate, Deg C/Min	---	5.6	4.7	5.4	---	---	---	---	---
Blow Out Time at 141.6 psi, Minutes	---	52	>120	101	>120	---	---	---	---
Heat Resistance									
Stress Relaxation, F/F0 @ 250 Deg F = 70%	---	---	385	560	260	1800	---	---	---
After Heat Aging for 70 Hrs at 250 Deg F									
Elongation Retention, %	---	52	38	52	45	90	88	88	84
Tensile Retention, %	---	66	39	68	42	69	68	68	72
Notes for Curing Systems Types:									
HS - High Sulfur Curing System									
LS - Low Sulfur Curing System									
Novor - Polyurethane Curing System System Using Novor 924									
Peroxide - Peroxide Curing System Using Di Cumyl Peroxide									

Table 20 Off-the-road tire tread rubber properties

Compound ID	OTR-1	OTR-2	OTR-2A	OTR-3	OTR-4	OTR-5	OTR-6	OTR-7	OTR-8	OTR-12
Supplier	Mc Creary	Goodyear	OTR-2 + 10	Goodyear	Armstrong	Armstrong	Armstrong	Long Mile	Long Mile	Armstrong
Supplier Material ID		Heat Resis	Parts N-11	Abrasion	Nat. Rub	Nat/SBR	SBR/PBD	Synthetic Rub	Nat Rub	Stock 523
Month/Year Supplied	8/83	Tread 8/83	Black ---	Resis Tread 8/83	Tread 8/83	Tread 8/83	Tread 8/83	Stock 650 8/83	Stock 684 8/83	8/84
Properties										
Mooney Viscometer										
ML +4 at 212 Deg F	42	34	42	45	55	46	39	43	---	27
T5 @ 250 Deg F, Minutes	48	34	17	35	21	20	37	55	---	44
Cure Conditions, Minutes/Deg F	25/300	15/310	15/310	35/320	25/300	20/300	25/310	25/300	25/300	40/300
Original Properties										
Tensile Strength, psi	3080	3760	3134	2930	3513	3187	2100	2557	2977	3267
200% Modulus, psi	647	693	1060	510	613	660	490	663	840	617
Ultimate Elongation, %	467	580	463	623	570	547	520	570	527	560
Hardness, Shore A	67	61	74	64	66	67	61	70	68	58
Bashore Rebound, %	44	52	38	28	41	33	23	29	32	43
Specific Gravity	1.1237	1.1163	1.1634	1.1515	1.1261	1.1250	1.1498	1.1607	1.1328	1.1108
Abrasion Tests										
Taber, Grams/1000 Cycles	0.0629	0.0576	0.0914	0.0228	0.0592	---	0.0323	0.0128	0.1802	0.0331
Pico, Rating	116	105	110	123	131	125	137	116	108	86
Tear Strength Using ASTM Die C										
Unaged, Lb/In	310	615	596	330	513	675	245	336	481	557
10 Minutes @ 250 Deg F, Lb/In	228	250	285	166	203	254	173	188	238	304
De Mattia Flex Properties										
Unaged Growth Rate, Mils/Minute	20	15	22	21	7	7	24	27	14	10
Unaged Crack Initiation, Kilocycles	3000	51	21	207	177	152	442	716	1750	24
After 70 Hours @ 212 Deg F, Mils/Minute	16	12	17	16	5	6	19	21	11	8
Goodrich Flex Properties at 50 Deg C										
External Temperature Rise Rate, Deg C/Mi	22.5	13.7	12.5	36.3	35.0	28.5	40.5	37.7	322.0	22
Blow Out Time at 141.6 psi, Minutes	53	>120	>120	20	30	32	11	31	39	21
Heat Resistance										
Stress Relaxation, F/F0 @ 250 Deg F = 70	570	440	387	515	433	460	510	446	300	240
After Heat Aging for 70 Hrs at 250 Deg F										
Elongation Retention, %	56	76	86	94	71	90	89	92	67	43
Tensile Retention, %	14	32	21	45	36	40	28	32	67	8

Table 20 Off-the-road tire tread rubber properties (continued)

Compound ID	OTR-13	OTR-14	OTR-15	OTR-16	OTR-17	OTR-18	OTR-19	OTR-20	OTR-21
Supplier	Armstrong	Armstrong	3rad Ragar	3rad Ragar	3rad Ragar	General Tire	General Tire	General Tire	General Tire
Supplier Material ID	Stock	Stock	Nat Rub	Nat Rub	Nat/SBR	Stock	Stock	Stock	Stock
	524	525	ORLE-1	MSBR-AH	CTA-484	T-354	T-376	T-417	T-428
Month/Year Supplied	8/84	8/84	1/85	1/85	1/85	1/85	1/85	1/85	1/85
Properties									
Mooney Viscometer									
ML +4 at 212 Deg F	40	41	23	21	28	47	45	30	25
T5 @ 250 Deg F, Minutes	17	18	27	49	34	26	35	31	22
Cure Conditions, Minutes/Deg F	40/310	25/310	30/300	30/300	40/300	---	---	---	---
Original Properties									
Tensile Strength, psi	3217	3717	3797	3297	3017	2960	3250	3210	3750
200% Modulus, psi	780	710	720	593	720	400	450	790	780
Ultimate Elongation, %	503	557	563	590	830	660	670	580	600
Hardness, Shore A	67	63	60	64	66	57	58	66	70
Bashore Rebound, %	40	44	44	36	35	39	36	36	44
Specific Gravity	1.1313	1.1288	1.0918	1.1267	1.1210	1.1542	1.1511	1.1641	1.1548
Abrasion Tests									
Taber, Grams/1000 Cycles	0.0307	0.0233	0.3749	0.3530	0.1814	0.4273	0.2153	0.0732	0.3121
Pico, Rating	114	125	72	85	97	88	114	230	194
Tear Strength Using ASTM Die C									
Unaged, Lb/In	530	511	553	526	290	480	503	570	546
10 Minutes @ 250 Deg F, Lb/In	323	258	258	248	194	225	200	315	295
De Mattia Flex Properties									
Unaged Growth Rate, Mils/Minute	7	7	10	1	14	6	7	11	9
Unaged Crack Initiation, Kilocycles	73	52	629	246	251	171	21	51	52
After 70 Hours @ 212 Deg F, Mils/Minute	6	6	8	9	11	4	6	9	7
Goodrich Flex Properties at 50 Deg C									
External Temperature Rise Rate, Deg C/Mi	23.0	17.0	16.0	19.0	25.0	35.0	---	---	---
Blow Out Time at 141.6 psi, Minutes	50	>120	77	51	59	---	---	---	---
Heat Resistance									
Stress Relaxation, F/F0 @ 250 Deg F = 70	327	303	349	381	464	259	192	305	352
After Heat Aging for 70 Hrs at 250 Deg F									
Elongation Retention, %	57	63	64	73	83	76	80	86	83
Tensile Retention, %	12	11	---	---	11	12	29	16	25

4. Summary and Conclusions

In this program a great number of rubber compound formulations were mixed and tested to investigate the effects of different polymers and polymer blends, along with various curing, filler, and antioxidant systems, on the mechanical properties associated with assuring good track pad performance. The polymers used included SBR, Hevea and Guayule natural, synthetic natural, BR, NBR, HNBR, and XNBR rubbers. Blends of NR with SBR, NR with BR, NR with HNBR, and tri-blends of NR/SBR/BR with various curing, filler, and antioxidant systems were also studied.

NR compounds provided excellent tear properties but lacked the necessary abrasion resistance needed for track pad applications. These materials are better suited for bushing and road wheel applications. Texas A&M was successful in making Guayule rubber; however, Butyl Zimate should not be used in the future as an antioxidant during the polymer production. This chemical also acts as an accelerator that limits compounding variations and promotes scorch problems.

When SBR, NBR, BR, and XNBR polymers were used alone in rubber compounds, their properties were not acceptable for track pad applications. Tri-blends of SBR/NR/BR did exhibit potential for future consideration as candidate track pad compounds. Recommended polymers for future tri-blend studies should include SMR-5 NR, UBE Poly VCR 412 polybutadiene, and SBR 1500 rubbers, along with N-234 or N-326 carbon black filler and a high-sulfur curing system.

NBR-12 was selected to fabricate track pads for a counter obstacle vehicle and T-142 track for an M-60 vehicle. Field testing in the 1980s indicated that the NBR-12 material provided a 2- to 3-fold improvement over commercial pads.^{4,8,9} Two US patents (4,843,114 and 5,264,290) based on NBR-12 were obtained in 1989 and 1993.^{1,2} In later field testing with the Bradley and M-1 tanks, this material exhibited excessive heat buildup and the pads failed by blowing out. Additional studies are needed to reduce heat buildup or dissipate the heat faster from the center of the rubber pad. NBR-4, which used the Novor curing system, exhibited excellent laboratory properties but failed by blowouts when tested in the field on the M-60 and Counter Obstacle Vehicle. Very high temperatures were measured in the rubber during the field testing. During the late 1990s, 2 of the critical ingredients for NBR-12 (Z Max MA and MPC black) were discontinued and no longer available. Work would be needed to replace these ingredients to further develop the NBR-12 compound.

The laboratory properties of 50 rubber track pad materials from 16 companies and 16 commercial pad materials from 9 foreign countries were compared to the properties NBR-12 developed at BRDEC. The NBR-12 material provided far more resistance to heat, abrasion, cutting, chipping, and flex fatigue compared to all other commercial materials.

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