ARMY RESEARCH LABORATORY

Elastomers for Tracked Vehicles - Development of Rubber Compounds for Bushings

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ARL-TR-2061

October 1999

Army Research Laboratory
Aberdeen Proving Ground, MD 21005-5069

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Abstract

After development of HNBR12, a patented formulation that doubled the service life of track pads, it has become necessary to improve the service life of bushings and roadwheels. The purpose of the work during FY98 was to increase the service life of bushings and close the gap in service life between pads and bushings, while work during FY99 will address the service life of roadwheels.

A group of natural rubber compounds for bushings was developed to improve the reversion resistance of the conventional cure systems typically used in this application. In order to optimize performance and properties, a factorial experimental design of six factors at two levels for the curing and the antioxidant system was used. Properties deemed important for performance were selected and desirability functions defined for each one, after which a regression analysis was performed on the matrix to optimize the best features. The model was used to develop a set of formulations with enhanced properties. The optimization matrix produced a series of optimized formulations with improved performance properties, of which six were selected for fabrication and testing at the Keweenaw Research Center (KRC).

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1. Introduction

The Army has identified the tanks' track elastomeric components as a major generic cost driver in military tracked vehicles. Continued improvements in tracked ordnance vehicle technology have led to heavier, faster vehicles with a resultant deterioration in the service life of components, such as tank track pads, bushings, and roadwheels. As an initial step in the efforts to reduce operational costs, the U.S. Army Tank-automotive and Armaments Command (TACOM) funded many universities, industries, and Government laboratories in the development of new and improved track pads that have a longer service life, thereby reducing down-time and replacement costs. The Polymers Engineering Team within the U.S. Army Research Laboratory (ARL) has been a central contributor to the technological base for new track and suspension elastomeric materials. Initially, the physical and mechanical characteristics of a pad vendor's elastomer compounds were determined to assemble a database and draft target performance requirements for the tank pads. A great number of compound formulations were then formulated and tested to investigate the effect of different base polymer, vulcanization, filler, and antioxidant systems on the mechanical and performance properties. These studies, using different polymer base, vulcanization, filler, and antioxidant systems have been reported elsewhere [1, 2, 3].

The efforts of the rubber research group, then at Fort Belvoir, VA, produced a patented [4] rubber formulation based on hydrogenated nitrile rubber (HNBR), with a novel curing system that was found to offer unique properties for pad applications [5, 6]. The HNBR compound has demonstrated substantially improved performance over the conventional compounds under MIL-T-11891D [7]. This compound has demonstrated performance two to three times the service life of standard MIL-T-11891D track pad elastomers. Much has been said about the performance of this compound [8], 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.

Total superior performance of the Army's family of tracked vehicles (FTV), such as the M1A2, composite armored vehicle (CAV), Paladin, and Crusader is obviously contingent upon the reliability and life of all track components, especially in view of TACOM's goal to design a track system that would optimally last 5,000 miles. Ideally, equivalent life expectancy for all components must be realized to achieve total system optimization. However, in recent years, it has become apparent that the extension of pad service life is to some extent meaningless if other components, such as the bushings and roadwheels, fail earlier. These components now have become the weak link in the track system. This was demonstrated at Yuma Proving Ground (YPG) when TACOM evaluated the German-made Diehl track. While the track hardware remained serviceable after 2,000 miles, bushings were failing after 1,500 miles. In fact, earlier observations [9], Figure 1, highlighted the failure of bushings at low mileage using thermal imaging techniques. The investigators were able to identify failed bushings by measuring temperature profiles. It is evident then that the longer service life [10] that the HNBR compound provides for the pads would be negated by the continuing need for bushing replacement and to a lesser extent roadwheels. A balance of properties and service life must be accomplished for the bushing and roadwheel elastomeric materials.

Figure 1. Thermogram of Failed Bushing.

These reasons are why the program was initiated—to concentrate on improving the service life of bushings in FY98 and roadwheel compounds during FY99. The principal objective being to improve service life and to reduce current fielded hardware and support costs for bushings and roadwheel elastomers. The project addresses the "*weak links*" in conventional track and roadwheel designs; that is, failure of the rubber components, which ultimately constrain field service life. The project encompasses a broad range of research in new, emerging materials and improved processing techniques. The primary emphasis is materials development with an objective to recommend rubber formulations with increased service life for bushings and roadwheels. Specific milestones toward this goal for FY98 included:

- Establish a database of commercial roadwheel rubber compounds.

- Provide four formulations for bushings.

A central part of the effort for bushings involved a close working relationship with the Michigan Technological University, Keweenaw Research Center (KRC), Houghton, MI, to perform dynamic tests of T-130 bushings. KRC operates three approved Government-furnished equipment (GFE) bushing endurance test machines. These machines simulate stresses and operational conditions of bushings in service and subject the bushings to torsional and compressive stresses. The bushings, Figure 2, can be flexed 30° (±15° from neutral position) at speeds up to 255 c/m at a compressive stress of about 1,500 psi.

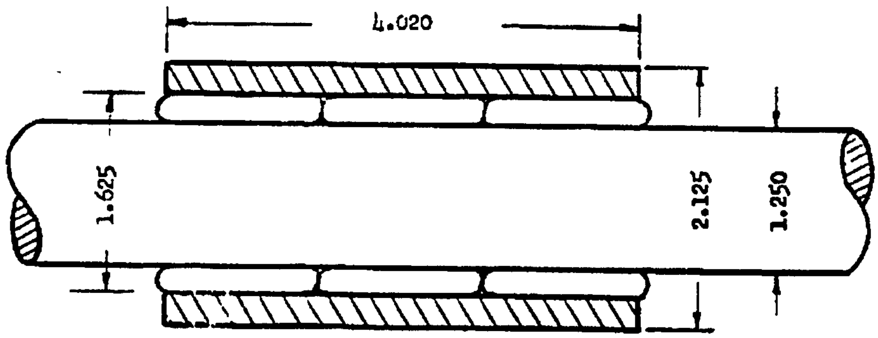


Figure 2. Track Bushing Assembly.

Earlier efforts at improving bushing compounds were hindered by poor adhesion between the rubber and metal of the inserted bushing. Low adhesion resulted in poor performance of the material during dynamic tests, preventing valid information on the performance of the rubber material. Therefore, a secondary goal of the program was to conduct adhesive studies on various candidate materials and to determine minimum required adhesive values to sustain the dynamic bushing tests and field service.

2. Experiments

2.1 Bushings. Traditionally, bushing materials are based on natural rubber formulations with conventional curing systems. Conventional sulfur (high sulfur content) curing systems produce vulcanizates that exhibit high tear strength, good rubber-to-metal adhesion, low heat buildup, and excellent fatigue resistance characteristics, all highly desirable properties for bushings. In many cases, these compounds undergo anaerobic thermal degradation or reversion. 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 introduction of main chain modifications. 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 bushings.

During reversion, several reactions occur, which include:

- *Desulfurization* - This chemistry, which ultimately forms polysulfidic cross-links, continues until the capacity to donate sulfur is depleted.

- *Rearrangement.*

- *Destruction* - Where the original cross-links are destroyed.

Unfortunately for the rubber compounder, the destructive-type reactions tend to predominate during the reversion process, thus leading to a significant reduction in cross-link density, physical properties, and performance characteristics.

To overcome this decrement in physical properties, we initially focused our attention on efficient and semi-efficient vulcanization systems, which are low in sulfur content and high in accelerator. These systems produce more stable networks, rich in monosulfidic and disulfidic cross-links. Consequently, the degree of reversion observed is lower than that observed in conventional formulations. Over the past few years, we have developed a series of compounds—Tables 1–3—with various ratios of sulfur to accelerator. As expected, we noticed that some of the compounds lacked the high tear strength, high metal adhesion, and excellent fatigue properties characteristics of vulcanizates cured using conventional formulations [11]. In order to compensate for this loss in physical properties, we also investigated the use of organic stabilizing agents, also known as vulcanization intermediates, on desulfurization chemistry [12]. These stabilizing agents, 1, 3-bis (citraconimidomethyl), benzene (Perkalink 900), and Hexamethylene-1, 6-bisthiosulpphate disodium salt dihydrate (Duralink HTS), produced a good balance of physical properties, both in optimally cured and overcured compounds. The beneficial effects have been attributed to the formation of hybrid cross-links in the ensuing network [13].

Another group of natural rubber formulations was prepared with different antioxidants and accelerators to determine their effect on oxidative stability and curing characteristics. As testing of physical properties progressed during FY98, properties, such as tear strength, fatigue-to-failure, degree cf reversion, and retention of strength properties after heat aging, were used to select the best candidates for the fabrication of bushings. From the physical properties, we observed that the curing system consisting of Santocure TBBS and sulfur along with a combination of Perkalink 900 and Duralink HTS and a mixture of antioxidants and antiozonants improved the tear and fatigue properties. From the analysis of the formulations and the physical property values for these compounds, we identified trends and then prepared a two-level factorial

Table 1. Bushing Rubber Formulations, Group 96

	NAT-9604B	NAT-9604B-1	NAT-9604B-2	NAT-9604B-3	NAT-9604B-4	NAT-9604B-5	NAT-9604B-6	NAT-9604B-7	NAT-9604B-8	NAT-9604B-9	NAT-9604B-10
NATURAL RUBBER, SMR-L	100	100	100	100	100	100	100	100	100	100	100
NORDEL 1440, EPDM RUBBER											
ZINC OXIDE	5	5	5	5	5	5	5	5	5	5	5
STEARIC ACID	1	1	1	1	1	1	1	1	1	1	1
PEPTIZER 66	2	2	2	2	2	2	2	2	2	2	2
N-330, HAF Black	20	20	20	20	20	20	20	20	20	20	20
N-762, SRF Black	30	30	30	30	30	30	30	30	30	30	30
N-121, Black											
N-339, Black											
N-375, Black (no longer supplied)											
PLASTICIZER LN, NAPHTHENIC	3		3								
AKROWAX 5031	2			2							
SANTOFLEX 6PPD, Antozite 67, Antioxidant PD-2					0.5				0.5	0.5	0.5
ANTIOXIDANT 58, ZMB-2, ZMTI	2					2					
ANTIOXIDANT DQ, TQ, Flectol H, Agerite Resin D	2						2		2	2	2
SANTOCURE MBS, OBT											
SANTOCURE TBBS, BBTS											
VOCOL S, Accelerator VS, Royalac 136											
SULFUR	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	2.5
SANTOCURE IPS (no longer available, use TBSI)	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2			
SANTOCURE TBSI									3.2	3.2	1
SANTIGUARD PVI, CTP	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Sulfasan R, DTDM											
PERKALINK 900, BCI-MX								1		1.5	
DURALINK HTS											

Table 1. Bushing Rubber Formulations, Group 96 (continued)

	NAT-9604B	NAT-9604B-1	NAT-9604B-2	NAT-9604B-3	NAT-9604B-4	NAT-9604B-5	NAT-9604B-6	NAT-9604B-7	NAT-9604B-8	NAT-9604B-9	NAT-9604B-10
PROMIX 4-TEAR											
DI CUP 40 KE											
SARTOMER, SARET 633											
FORMULA WEIGHT	171.70	162.7	165.7	164.7	163.2	164.7	164.7	163.7	165.2	166.7	164.2
PROPERTIES	9604B	9604B-1	9604B-2	9604B-3	9604B-4	9604B-5	9604B-6	9604B-7	9604B-8	9604B-9	9604B-10
ORIGINAL TEAR, LB-IN	449	363	325	314	355	302	346	327	364	351	385
FATIGUE TO FAILURE, CYCLES × 100	333	137	158	171	445	181	333	172	382	380	582
Temperature	300° F	300° F	300° F	300° F	300° F	300° F	300° F	300° F	300° F	300° F	300° F
Scorch t_{s2}, min	9.8	291		3.69	3.6		241	2.53	5.03	5	4.39
M_{h95}, lb-in	24.7	15.47		11.6	13.05		13.7	14.8	17.49	17.46	17.44
M_{fin}, lb-in	25.5	15.21		11.13	12.46		13.26	15.05	18.11	18.37	14.41
Torque Difference, M_{fin}-M_{h95}	0.8	−0.26	0	−0.47	−0.59	0	−0.44	0.25	0.62	0.91	-3.03
Peak Rate, lb-in/min	1.75	3.7		28	3		3.8	5.03	4.9	5	3.3

Table 2. Bushing Rubber Development, 9606–9607 Formulations

	NAT-9606B	NAT-9606B-1	NAT-9606B-2	NAT-9606B-3	NAT-9606B-4	NAT-9606B-5	NAT-9607B	NAT-9607B-1	NAT-9607B-2	NAT-9607B-3	NAT-9607B-4	NAT-9607B-5
NATURAL RUBBER, SMR-L	100	100	100	100	100	100	100	100	100	100	100	100
NORDEL 1440, EPDM RUBBER												
ZINC OXIDE	5	5	5	5	5	5	5	5	5	5	5	5
STEARIC ACID	2	2	2	2	2	2	2	2	2	2	2	2
PEPTIZER 66	2	2	2	2	2	2	2	2	2	2	2	2
N-330, HAF Black	20	20	20	20	20	20	20	20	20	20	20	20
N-762, SRF Black	30	30	30	30	30	30	30	30	30	30	30	30
N-121, Black												
N-339, Black												
N-375, Black (no longer supplied)												
PLASTICIZER LN, NAPHTHENIC	3						3					
AKROWAX 5031	2						2					
SANTOFLEX 6PPD, Antozite 67, Antioxidant PD-2	0.5					0.5						0.5
ANTIOXIDANT 58, ZMB-2, ZMTI	2					2	2					2
ANTIOXIDANT DQ, TQ, Flectol H, Agerite Resin D						2	2					2
SANTOCURE MBS, OBT							1.15	1.15	1.15	1.15	1.15	1.15
SANTOCURE TBBS, BBTS	2	2	2	2	2	2						
VOCOL S, Accelerator VS, Royalac 136	1.2	1.2	1.2	1.2	1.2	1.2						
SULFUR	1.4	1.4	1.4	1.4	1.4	1.4	3	3	3	3	3	3
SANTOCURE IPS (no longer available, use TBSI)												
SANTOCURE TBSI												
SANTIGUARD PVI, CTP				0.1								
Sulfasan R, DTDM												
PERKALINK 900, BCI-MX							1		1	3		1.5
DURALINK HTS	1.5		1.5		3	3						

Table 2. Bushing Rubber Development, 9606–9607 Formulations (continued)

	NAT-9606B	NAT-9606B-1	NAT-9606B-2	NAT-9606B-3	NAT-9606B-4	NAT-9606B-5	NAT-9607B	NAT-9607B-1	NAT-9607B-2	NAT-9607B-3	NAT-9607B-4	NAT-9607B-5
PROMIX 4-TEAR												
DI CUP 40 KE												
SARTOMER, SARET 633												
FORMULA WEIGHT	172.6	163.6	165.1	163.7	166.6	171.1	173.15	163.15	164.15	166.15	171.15	169.15
PROPERTIES	9606B	9606B-1	9606B-2	9606B-3	9606B-4	9606B-5	9607B	9607B-1	9607B-2	9607B-3	9607B-4	9607B-5
ORIGINAL TEAR, LB-IN	218	327	333	345	345	321	257	354	355	342	312	354
FATIGUE TO FAILURE, CYCLES × 100	607	144	115	145	143	322	441	82	97	99	72	446
Temperature	300° F	300° F	300° F	300° F	300° F	300° F	300° F	300° F	300° F	300° F	300° F	300° F
Scorch t_{s2}, min	2.13	2.26	1.56	1.53	1.45	2.34	4.01	3.38	3.38	3.45	3.79	3.77
M_{h95}, lb-in	12.81	15.07	13.88	13.78	13.35	14.63	15.98	17.11	15.41	15.41	17.62	17.88
M_{fin}, lb-in	13.43	15.81	14.59	14.74	14.03	15.35	14.6	16.12	16.48	16.48	16.82	17.09
Torque Difference, M_{fin}-M_{h95}	0.62	0.74	0.71	0.96	0.68	0.72	−1.38	−0.99	1.07	1.07	−0.8	−0.79
Peak Rate, lb-in/min	4.9	4.9	6.8	8.2	6	4.9	2.5	4.3	3.9	3.5	3.3	2.7

Table 3. Bushing Rubber Development, Group 97 Formulation

	NAT-9701B	NAT-9701B-1	NAT-9701B-2	NAT-9702B	NAT-9703B
NATURAL RUBBER, SMR-L	100	100	100	100	100
NORDEL 1440, EPDM RUBBER					
ZINC OXIDE	5	5	5	5	5
STEARIC ACID	2	2	2	1	1
PEPTIZER 66	2	2	2	2	
N-330, HAF Black					
N-762, SRF Black	30	30	30		
N-121, Black	20	20	20		
N-339, Black					
N-375, Black (no longer supplied)				50	50
PLASTICIZER LN, NAPHTHENIC					
AKROWAX 5031					
SANTOFLEX 6PPD, Antozite 67, Antioxidant PD-2	0.5	0.5	0.5	0.5	0.5
ANTIOXIDANT 58, ZMB-2, ZMTI	2	2	2	2	2
ANTIOXIDANT DQ, TQ, Flectol H, Agerite Resin D	2	2	2	2	2
SANTOCURE MBS, OBT					
SANTOCURE TBBS, BBTS				0.6	1
VOCOL S, Accelerator VS, Royalac 136					
SULFUR	2.5	2.5	2.5	2.4	1.2
SANTOCURE IPS (no longer available, use TBSI)					
SANTOCURE TBSI	1	1	1		
SANTIGUARD PVI, CTP	0.2	0.2	0.2		
Sulfasan R, DTDM					0.6
PERKALINK 900, BCI-MX		1			
DURALINK HTS			1.5		
PROMIX 4-TEAR					
DI CUP 40 KE					
SARTOMER, SARET 633					
FORMULA WEIGHT	167.2	168.2	168.7	165.5	163.3
PROPERTIES	9701B	9701B-1	9701B-2	9702B	9703B
ORIGINAL TEAR, LB-IN	328	319	323	329	578
FATIGUE TO FAILURE, CYCLES × 100	717	725	738	1066	878
Temperature	300° F	300° F	300° F	300° F	300° F
Scorch t_{s2}, min	6.54	6.59	7.12	3.84	3.97
M_{h95}, lb-in	16.41	16.01	14.79	18.59	16.53
M_{fin}, lb-in	14.1	14.87	13.64	16.6	13.53
Torque Difference, M_{fin}-M_{h95}	-2.31	-1.14	-1.15	-1.99	-3
Peak Rate, lb-in/min	1.6	1.6	1.2	1.7	3

experimental design to investigate the effect of the reversion stabilizers, curing system, and antioxidant system on the performance properties.

2.2 Experimental Design. The traditional approach to developing formulations for rubber products combines the expert compounder's experience with some experimental work on one or two ingredients and a few trials. Sometimes the compound meets the target properties specified and is a relative success. At other times, results do not meet the expectations due to possible variation in materials or variations in processing (e.g., time, temperature, and mold variations). At this time, the expert compounder must reformulate many of the times under time constraints in order to complete a project or meet production demands. Sometimes the compounder must once again reformulate, and sometimes the expert formulator cannot find a solution given the constraints he or she has to meet.

The logical way to approach this situation is by using the design of experiments (DOX) and desirability methodologies. These techniques have been available for some time [14] but are seldom used by the rubber compounder; however, the advent of the personal computer, the increased processing power, and targeted software are likely to change this scenario. The advantages are obvious, the derivation of extensive meaningful data from a minimum amount of actual compounding and physical testing. There are four major steps to the use of DOE techniques for the development of rubber compounds targeted to specific performance: the design, establishing the desirabilities, regression analysis, and the final optimization. The software title used to develop the experimental design and analysis of the data is PROOPT,* which implements a multivariate/multiresponse optimization methodology. By applying these methodologies to the development of a rubber compound, we can investigate the variable levels, which produce the best combination of property values.

As mentioned previously, we investigated the use of reversion stabilizers, the curing system—sulfur and accelerators—and the effect of the antioxidant. The experiment contained

*PROOPT - Developed and distributed by L. R. Good & Son, Alexandria, OH.

6 variables (ingredients) at 2 levels—to run all possible combinations would require 64 experiments (2^6), but only 16 of these were actually run. The DOX is symbolized mathematically as 2^{6-2}, a factorial design of six variables at two levels. From the 16 formulations, we get information on all of the main effects and nearly all of the two-factor interactions. Table 4 shows the ingredients' minimum and maximum values of the design. The experimental matrix, which includes center points, as shown in Table 5, offers a very important statistical property called ***orthogonality***, which means that the factors are not correlated.

Table 4. Ingredients Investigated and Their Levels

Name	Minimum	Maximum
Santoflex6PPD	1	3
Resin D	1	3
Perka900	1	3
Sulfur	1	3
Santocure TBSI	1	3
Santocure TBBS	1	3

Table 5. Factorial Experimental Design Matrix

Row	Santoflex 6PPD	Agerite Resin D	Perkalink 900	Sulfur	Santocure TBSI	Santocure TBBS
1	1.5	1	1	3	1	1
2	0.5	3	1	3	1	1
3	0.5	1	3	3	1	1
4	1.5	3	3	3	1	1
5	1.5	1	1	1	3.5	1
6	0.5	3	1	1	3.5	1
7	0.5	1	3	1	3.5	1
8	1.5	3	3	1	3.5	1
9	1.5	1	1	1	1	3
10	0.5	3	1	1	1	3
11	0.5	1	3	1	1	3
12	1.5	3	3	1	1	3
13	1.5	1	1	3	3.5	3
14	0.5	3	1	3	3.5	3
15	0.5	1	3	3	3.5	3
16	1.5	3	3	3	3.5	3

This is important, especially when variables are more correlated (i.e., they move in the same direction with the property investigated), since the error in estimation of their effects becomes larger and larger.

2.2.1 The Design. The first step of this process consisted of obtaining the experimental design. This involved a number of trials where the level of each material was varied and the resulting properties measured. PROOPT has a design module that produces the experimental design based on the compounder's inputs of the material levels. In design of experiment terms, the software produces a linear fractional factorial design for screening key variables. This permits the compounder to eliminate the less important variables and to choose the more important ones for further testing.

Table 4 lists the levels of the 6 materials used for the 16 runs; Table 6 shows the full formulations for the experimental matrix; Table 7 lists the property values used in the experimental design to evaluate the compounds obtained after the 16 experimental trials were mixed, cured, and tested; and Table 8, shows a full set of test property values used to evaluate the materials.

2.2.2 Establishing Desirabilities. The second step is to establish a desirability for each final property. This is another point where the compounder's judgment is brought to bear. Desirability methodology is a way of unifying a compound's various and often competing properties. The range of values of each property is mapped into a zero-to-one desirability scale, where zero represents unacceptable values, nonzero values cover the increasingly more desirable property range, and one denotes the most desirable property value or range. PROOPT uses mappings of four general shapes.

- Minimize: where the most desirable level of the property is toward its lower values.

- Peak and Knoll: where the most desirable level of the property is selected in the midrange—the peak is a single value, while the knoll has a range of values.

- Maximize: where the most desirable level of the property is toward its higher values.

Table 6. Experimental Matrix Formulations

	NAT-9813B	NAT-9813B-1	NAT-9813B-2	NAT-9813B-3	NAT-9813B-4	NAT-9813B-5	NAT-9813B-6	NAT-9813B-7
NATURAL RUBBER, SMR-L	100	100	100	100	100	100	100	100
ZINC OXIDE	5	5	5	5	5	5	5	5
STEARIC ACID	1	1	1	1	1	1	1	1
PEPTIZER 66	2	2	2	2	2	2	2	2
N-330, HAF Black	20	20	20	20	20	20	20	20
N-762, SRF Black	30	30	30	30	30	30	30	30
SANTOFLEX 6PPD, Antozite 67, Antioxidant PD-2	1.5	0.5	0.5	1.5	1.5	0.5	0.5	1.5
ANTIOXIDANT DQ, TQ, Flectol H, Agerite Resin D	1	3	1	3	1	3	1	3
SANTOCURE TBBS, BBTS	1	1	1	1	1	1	1	1
SULFUR	3	3	3	3	1	1	1	1
SANTOCURE TBSI	1	1	1	1	3.5	3.5	3.5	3.5
PERKALINK 900, BCI-MX	1	1	3	3	1	1	3	3
DURALINK HTS								
PROMIX 4-TEAR								
FORMULA WEIGHT	166.50	167.5	167.5	170.5	167	168	168	171

	NAT-9813B-8	NAT-9813B-9	NAT-9813B-10	NAT-9813B-11	NAT-9813B-12	NAT-9813B-13	NAT-9813B-14	NAT-9813B-15
NATURAL RUBBER, SMR-L	100	100	100	100	100	100	100	100
ZINC OXIDE	5	5	5	5	5	5	5	5
STEARIC ACID	1	1	1	1	1	1	1	1
PEPTIZER 66	2	2	2	2	2	2	2	2
N-330, HAF Black	20	20	20	20	20	20	20	20
N-762, SRF Black	30	30	30	30	30	30	30	30
SANTOFLEX 6PPD, Antozite 67, Antioxidant PD-2	1.5	0.5	0.5	1.5	1.5	0.5	0.5	1.5
ANTIOXIDANT DQ, TQ, Flectol H, Agerite Resin D	1	3	1	3	1	3	1	3
SANTOCURE TBBS, BBTS	3	3	3	3	3	3	3	3
SULFUR	1	1	1	1	3	3	3	3
SANTOCURE TBSI	1	1	1	1	3.5	3.5	3.5	3.5
PERKALINK 900, BCI-MX	1	1	3	3	1	1	3	3
DURALINK HTS								
PROMIX 4-TEAR								
FORMULA WEIGHT	166.5	167.5	167.5	170.5	171	172	172	175

Table 7. Test Property Values for Experimental Design Matrix

Row	Tensile Strength	Tear Strength	Fatigue/ Energy	Heat Build-Up	Compression Set	Hot Tear Strength (250 °F)	Energy After Aging	Rebound	Mh95 (lb-in)
1	3523.95	383.43	128	12.5	1.7	197	0.27000000	54	22.16
2	3203.38	358.02	107.2	15.5	2.49	219.4	0.20999999	52	22.16
3	3762.1	339.26	113	17.33	2.63	227.6	0.18	53	22.84
4	3117.08	363.5	181.2	19.5	5.89	204.5	0.2	43	20.27
5	3077.75	328.98	148.6	18.5	1.6	162.2	16.1	56	18.59
6	3091.4	337.5	125.2	22	2.15	208.7	11.9	50	12.75
7	3175.61	340.41	100.7	20	2	181.3	14.8	52	18.3
8	2896.49	337.89	95.6	20.5	2.66	186.7	25.6	48	17.09
9	2896.18	353.63	170.9	16	1.65	192.3	19.3	54	17.39
10	2978.54	342.53	125.1	18.5	2.5	196.2	21.8	49	17.01
11	2782.32	340.1	87.1	19.5	2.35	205.4	16.7	52	17.72
12	3086.17	338.43	115.4	21.5	2.95	176.8	43.2	49	15.97
13	894.33	130.73	0	29	2.4	45.5	0	54	32.96
14	1051.33	157.16	0	31	2.85	51.6	0	48	35.54
15	998.43	120.85	0	26.5	2,45	43.6	0	53	30.34
16	1194.06	98.16	0	29	4.1	36.9	0	52	28.23

Figure 3(a) shows the desirability graph for the heat buildup property. It is a minimize type. It exhibits a steep negative slope toward 0.0 as temperature increases to 40° C. Any value in the range of 15° to about 35° C is acceptable. Also, anything below 15° C is acceptable at a desirability of 1, the highest value. Any value over 37° C is unacceptable since the desirability would be zero. The desirability graph for the cure level, MH95, is of the target type (peak/knoll type). The acceptable range is 10–30 lb-in. The most desirable value is 20 (the desirability value is 1 at this point). Any value lower than 10 or greater than 30 is unacceptable. The tear strength property on the other hand is of the maximize type. It rises steeply from 300 at 600 lb/in, reaching an optimum desirability at 600. Anything below 300 is unacceptable. Anything above 600 is perfectly acceptable with the highest desirability of 1.

Figure 3(b) illustrates a generic description of the desirability function proposed by Harrington of Monsanto and detailed in ***Industrial Quality Control - April 1968***.

Note from Figure 3(a) that the desirability curves can be concave, convex, or straight. This is controlled in PROOPT by selecting a number for right and left shape in the range of 0.01 to 1.0 to 100. A shape of 1 produces a straight line, a number greater than 1 produces a concave upward curve, and a number less than 1 produces a convex upward curve.

Table 8. Physical (Full Set) Property Values for Experimental Design Matrix

PROPERTIES	NR 9813B	NR 9813B-1	NR 9813B-2	NR 9813B-3	NR 9813B-4	NR 9813B-5	NR 9813B-6	NR 9813B-7
FATIGUE TO FAILURE								
Energy at Extension Ratio = 2 in-lb	5.13	4.44	4.89	3.74	2.9	2.92	3.41	3.18
ORIGINAL, CYCLES × 100	657	476	553	678	431	366	343	304
Cycles/Energy × 100	128.0	107.2	113.0	181.2	148.6	125.2	100.7	95.6
AFTER AGED 20 HR @ 250° F								
Energy at Extension Ratio, in-lb	7.5	7.1	6.7	7.9	4.4	5.7	5.7	4.2
ORIGINAL, CYCLES × 100	2.0	1.5	1.2	1.6	70.5	67.4	84.2	108.0
Cycles/Energy × 100	0.3	0.2	0.2	0.2	16.1	11.9	14.8	25.6
Temperature	290° F	290° F	290° F	290° F	290° F	290° F	290° F	290° F
Scorch t_{s2}, min	5.22	5.4	5.37	4.97	7.66	6.91	7.18	6.79
M_{h95}, lb-in	22.16	22.16	22.84	20.27	18.59	12.75	18.3	17.09
M_{fin}, lb-in	21.29	21.63	23.47	20.54	19.56	13.39	19.23	17.98
Torque Difference, M_{fin}-M_{h95}	−0.87	−0.53	0.63	0.27	0.97	0.64	0.93	0.89
Peak Rate, lb-in/min	6.9	6.8	6.9	6.1	2.8	2.5	3	2.8
Die C Tear, lb/in	383.43	358.02	339.26	363.50	328.98	337.50	340.41	337.89
Die C Tear, lb/in 10 min @ 250° F	197.00	219.40	227.60	204.50	162.20	208.70	181.30	186.70
Tensile Strength, psi	3524.0	3203.4	3762.1	3117.1	3077.8	3091.4	3175.6	2896.5
Modulus @ 200% Elongation, psi	1809.6	1552.0	1724.6	1788.9	1555.4	1432.9	1536.2	1341.8
Ultimate Elongation, %	360.9	353.4	400.8	314.1	325.9	358.9	347.4	351.1
Energy at Break, in-lb	311.8	256.5	389.5	229.7	225.7	249.7	253.1	228.6
AFTER 70 HR @ 212° F								
Tensile Strength, psi	2156.2	1947.1	2167.4	2148.1	2197.3	2276.4	1994.2	2339.4
Modulus @ 200% Elongation, psi					1766.9	1696.1	1776.6	1635.7
Ultimate Elongation, %	178.2	179.1	170.2	187.6	234.8	253.4	216.3	266.0
Energy at Break, in-lb	86.1	79.2	84.0	90.8	112.3	128.5	96.7	138.1
Compression Deflection, % at 600 psi								37.6
Compression Set, % 22 hr @ 160° F								21.8
Hardness, Shore A	69	69	69	64	64	66	66	66
Rebound, %	54	52	53	43	56	50	52	48
AFTER 70 HR @ 212° F								
Hardness, Shore A	71	72	74	75	64	67	67	69
Rebound, %	52	52	53	48	55	50	54	51
Heat Buildup, Internal, δ°C	70.50	74.00	85.00	85.00	80.00	94.00	88.00	40.00
Heat Buildup, External, δ°C	12.50	15.50	17.33	19.50	18.50	22.00	20.00	20.50
Heat Buildup, Compression Set, %	1.70	2.49	2.63	5.89	1.60	2.15	2.00	2.66

Table 8. Physical (Full Set) Property Values for Experimental Design Matrix (continued)

PROPERTIES	NR 9813B-8	NR 9813B-9	NR 9813B-10	NR 9813B-11	NR 9813B-12	NR 9813B-13	NR 9813B-14	NR 9813B-15
FATIGUE TO FAILURE								
Energy at Extension Ratio = 2 in-lb	2.89	2.71	2.96	2.87	0	0	0	0
ORIGINAL, CYCLES × 100	494	339	258	331				
Cycles/Energy × 100	170.9	125.1	87.1	115.4				
AFTER AGED 20 HR @ 250° F								
Energy at Extension Ratio, in-lb	4.6	4.5	4.2	3.9				
ORIGINAL, CYCLES × 100	88.0	97.8	70.6	169.8				
Cycles/Energy × 100	19.3	21.8	16.7	43.2				
Temperature	290° F	290° F	290° F	290° F	290° F	290° F	290° F	290° F
Scorch t_{s2}, min	7.01	7.45	7.03	6.24	5.27	5.06	5.21	4.81
M_{h95}, lb-in	17.39	17.01	17.72	15.97	32.96	35.54	30.34	28.23
M_{fin}, lb-in	18.29	17.89	18.63	16.8	34.68	37.39	31.91	29.71
Torque Difference, M_{fin}-M_{h95}	0.9	0.88	0.91	0.83	1.72	1.85	1.57	1.48
Peak Rate, lb-in/min	4.9	4.5	4.9	4.8	17.8	17.5	16.1	15
Die C Tear, lb/in	353.63	342.53	340.10	338.43	130.73	157.16	120.85	98.16
Die C Tear, lb/in 10 min @ 250° F	192.30	196.20	205.40	176.80	45.50	51.60	43.60	36.90
Tensile Strength, psi	2896.2	2978.5	2782.3	3086.2	894.3	1051.3	998.4	1194.1
Modulus @ 200% Elongation, psi	1329.5	1169.1	1334.4	1187.3				
Ultimate Elongation, %	336.7	381.4	340.8	390.9	74.7	72.5	83.1	76.7
Energy at Break, in-lb	221.3	248.9	205.4	269.0	15.6	18.7	19.6	30.2
AFTER 70 HR @ 212° F								
Tensile Strength, psi	2005.5	2380.1	2013.6	2186.0	899.0	951.4	895.9	877.2
Modulus @ 200% Elongation, psi	1634.8	1493.2	1649.2	1562.1				
Ultimate Elongation, %	230.2	281.9	233.0	257.9	56.3	50.4	60.0	57.0
Energy at Break, in-lb	101.3	153.0	106.0	127.3	12.3	11.7	13.2	12.4
Compression Deflection, % at 600 psi		38.85						
Compression Set, % 22 hr @ 160° F		20.7						
Hardness, Shore A	61	63	65	64	76	80	76	76
Rebound, %	54	49	52	49	54	48	53	52
AFTER 70 HR @ 212° F								
Hardness, Shore A	63	65	67	66	78	80	78	79
Rebound, %	55	49	54	49	53	47	52	49
Heat Buildup, Internal, $^{\delta}$°C	79.00	36.50	86.50	88.50	101.00	110.50	105.00	108.50
Heat Buildup, External, $^{\delta}$°C	16.00	18.50	19.50	21.50	29.00	31.00	26.50	29.00
Heat Buildup, Compression Set, %	1.65	2.50	2.35	2.95	2.40	2.85	2.45	4.10

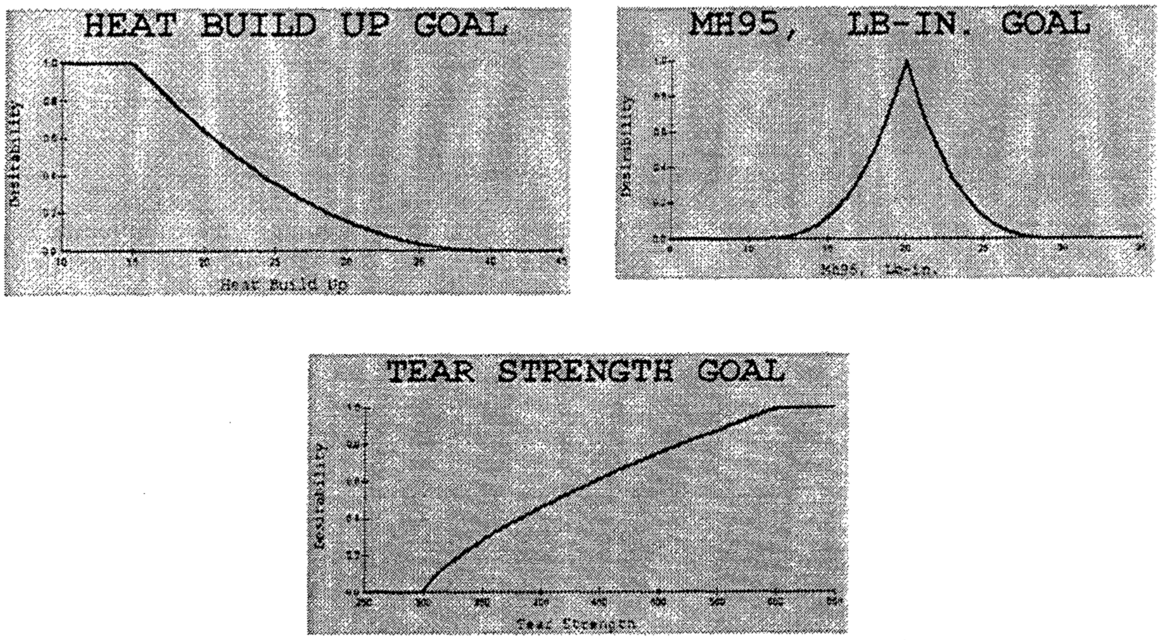
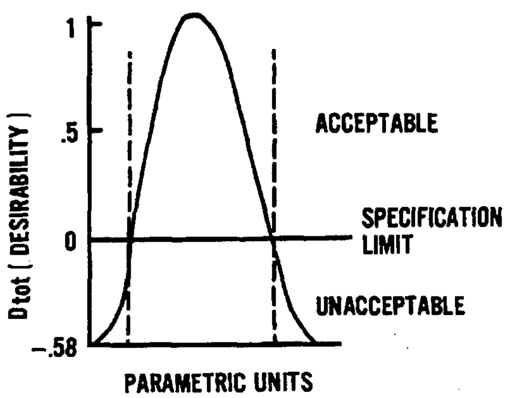


Figure 3(a). Desirability Function Forms.

DESIRABILITY FUNCTION

1. TRANSFORMS AND EQUATES VARIOUS UNIT MEASUREMENTS OF PERFORMANCE IN TERMS OF A UNIFIED DESIRABILITY VALUE.

2. COMPUTES A TOTAL RELATIVE DESIRABILITY FOR EACH SYSTEM BASED ON CONSIDERATION OF ALL PERFORMANCE FACTORS.



INDIVIDUAL DESIRABILITY

$$d_n = \left[e^{(-e^{-y})} - e^{-1}\right] / \left[1 - e^{-1}\right]$$

TOTAL DESIRABILITY

$$D_{tot} = \sqrt[n]{d_1 d_2 d_3 \text{----} d_n}$$

e = LOGARITHMIC CONSTANT

y = LINEAR TRANSFORMATION OF PARAMETER VARIABLE

Figure 3(b). Generic Desirability Function [14].

*2.2.3 **Regression Analysis.*** In the third step, PROOPT performs a series of mathematical operations to find an equation for each physical property, which relates it to each process variable under investigation. For the six ingredients investigated, this equates to a multiple linear regression. We need not pay much attention to these relationships since PROOPT uses them to carry out the next steps to obtain the optimized formulations. But they are available if necessary.

*2.2.4 **Optimization.*** The next step is optimization. This is the key step that leads to the optimized formulation. In this step, PROOPT performs a tradeoff among the desirabilities for each of the properties to achieve the highest value of composite desirability. The letter D is used to represent this, referred to as "big D." Its peak value is referred to as "D." This mathematical technique is called a hill-climbing routine. Composite desirability is the geometric mean of all the property desirabilities. By using the geometric mean, PROOPT performs tradeoffs that produce a value for each property within its acceptable range (individual property desirability greater than zero) whenever the composite desirability value is greater than zero. After running the optimization algorithm, a series of optimum formulas are produced. Four of these were selected to fabricate a bushing for qualification testing at KRC, along with two from the experimental test matrix. Table 9 shows the optimized formulations.

As was mentioned, PROOPT performs a tradeoff or balancing of all the properties. The individual desirabilities of the properties for any optimum formulation are somewhere in the range from 0–1. The letter d is used to represent them, referred to as "little d." The desirability value of each property results from the mathematical tradeoff methodology in the program. PROOPT provides a graph of the values of the desirability for each of the properties.

These materials will be tested at KRC on the previously described fatigue testing machines. As described earlier, the cyclic torsional deflection is from −15° to +15° ± 15° 1/4°. The angle of twist α is determined by the diameter of the sprockets and is at its greatest value at the leading or drive sprocket with an angel of 12°–14°, which is the current configuration at KRC. From communications with KRC personnel, the torsional and radial stiffness of the experimental compounds should be used to screen-out materials for dynamic testing. The capability to

Table 9. Optimized Formulations Physical Properties and Target Values

PROPERTIES	NR 9813B-7	NR 9813B-9	NR 9813B-16	NR 9813B-17	NR 9813B-18	NR 9813B-19	Desired Property
FATIGUE TO FAILURE							
Energy at Extension Ratio = 2 in-lb	3.18	2.71	3.74	3.38	3.37	3.41	
ORIGINAL, CYCLES × 100	304	339	442	417	615	586	
Cycles/Energy × 100	95.6	125.1	118.3	123.2	182.6	171.7	
AFTER AGED 20 HR @ 250° F							
Energy at Extension Ratio, in-lb	4.2	4.5	3.3	2.8	3.1	3.4	
ORIGINAL, CYCLES × 100	108.0	98.8	335.5	331.0	270.0	212.7	
Cycles/Energy × 100	25.6	21.8	102.9	117.0	87.9	63.3	
Temperature	290° F	290° F	290° F	290° F	290° F	290° F	
Scorch t_{s2}, min	6.79	7.45	5.48	5.45	6.4	6.6	
M_{h95}, lb-in	17.09	17.01	17.36	17.62	17.52	17.85	
M_{fin}, lb-in	17.98	17.89	18.26	18.51	18.43	18.77	
Torque Difference, M_{fin}-M_{h95}	0.89	0.88	0.9	0.89	0.91	0.92	
Peak Rate, lb-in/min	2.8	4.5	6.3	6.5	5.9	5.7	
Die C Tear, lb/in	337.89	342.53	387.56	413.15	428.89	419.22	>300
Die C Tear, lb/in 10 min @ 250° F	186.70	196.20	206.7	225.8	225.5	242	>175
Tensile Strength, psi	2896.5	2978.5	3133.9	3127.4	3423.0	3384.9	>2700
Modulus @ 200% Elongation, psi	1341.8	1169.1	1172.7	1114.0	1197.9	1249.8	>700
Ultimate Elongation, %	351.1	381.4	426.4	442.9	440.2	435.2	>350
Energy at Break, in-lb	228.6	248.9	295.2	311.2	306.5	324.7	
AFTER 70 HR @ 212° F							
Tensile Strength, psi	2339.4	2380.1	2560.9	2585.5	2863.1	2452.6	
Modulus @ 200% Elongation, psi	1635.7	1493.2	1551.0	1555.6	1650.5	1603.0	
Ultimate Elongation, %	266.0	281.9	308.7	317.1	306.5	324.7	
Energy at Break, in-lb	138.1	153.0	178.2	188.4	188.8	152.7	
Compression Deflection, % at 600 psi	37.6	38.85	37.57	38.76	40.43	39.77	33–41
Compression Set, % 22 hr @ 160° F	21.8	20.7	19.1	20.3	19.8	25.5	<25
Hardness, Shore A	66	63	69	68	64	64	65–75
Rebound, %	48	49	45	46	53	50	
AFTER 70 HR @ 212° F							
Hardness, Shore A	69	65	73	72	66	67	
Rebound, %	51	49	47	49	55	53	
Heat Buildup, Internal, Δ°C	40.00	36.50	57.3	55.33	41.67	37.67	<50
Heat Buildup, External, Δ°C	20.50	18.50	26.3	24.33	19.67	18.33	<25
Heat Buildup, Compression Set, %	2.66	2.50	4.12	3.8	2.89	2.55	
BLOWOUT TIME, MIN	>120	>120	>120	>120	>120	>120	
Blowout 2	10.90	53.10	15.67	27	32.3	45.3	
DEMATTIA FLEX FATIGUE, Unaged	10.90	14.10	16.4	17.2	13.6	15.1	<25
212° F Growth Rate, mils/min	24.20	32.40	19.5	20	19.8	22.9	<200
20 HR @ 250° F, Growth Rate, mils/min							

Table 9. Optimized Formulations Physical Properties and Target Values (continued)

PROPERTIES	NR 9813B-7	NR 9813B-9	NR 9813B-16	NR 9813B-17	NR 9813B-18	NR 9813B-19	Desired Property
RADIAL STIFFNESS, lb-in × 100							
ORIGINAL	79.22	74.83	53.82	66.43	69.64	65.57	>115
4 hr @ 250° F, 4 hr	72.04	72.53	63.77	64.56	60.20	70.70	
AFTER AGING 4 HR at 250° F							
TORSIONAL STIFFNESS, lb-in/RAD							
ORIGINAL, 7°	2184.07	3006.67	2881.8/1	2729.99	2131.33	2521.56	<2100
@ 250° F, 7 °	1977.24	572.62	1627.16	1841.35	1955.32	919.44	
ORIGINAL, 14°	1810.98	2314.81	2163.93	2073.75	1892.94	1949.83	
@ 250° F, 14°	1608.23	1095.00	1220.02	1674.85	1676.93	1248.43	
ADHESION, PEEL ON T130 BUSHING							
ORIGINAL, lb-in	54.22	39.42	39.27	36.84	37.41	4.41	>35
ENERGY, lb-in	292.88	233.43	250.69	199.16	203.82	216.76	

determine these properties is valuable in screening candidate formulations prior to sending bushings to KRC for simulated bushing testing. Test parameters, such as degree of torsion and compressive load, were obtained from KRC to ensure that tests performed in-house would correlate with those conducted at KRC. Additionally, KRC provided guidelines for minimum adhesion requirements. Table 9, lists the property values for the optimized formulations compared to target values for physical properties.

2.3 Roadwheels. As with the bushings, failure of roadwheels has become increasingly more significant as other components last longer. As indicated before, ideally, the service life of all components would be the same; but such is not the case, thus affording us the opportunity to improve the materials.

This effort was limited during FY98. The plan was to evaluate some of the commercially available compounds and the failure mode of some roadwheels from Red River Army Depot (RRAD). In spite of efforts to obtain as many compounds as possible from industry, we have only received two compounds from industry and one from RRAD. Nonetheless, we intend to continue this effort in FY99 and will continue to formulate for this requirement however small the baseline obtained. Perhaps the major drawback at this point is that there is no U.S. Army Tank-Automotive Research, Development, and Engineering Center (TARDEC)-sponsored field test scheduled for roadwheels. Feedback from field service is critical to monitor and correlate performance properties with formulations and laboratory test results. This may be an area for future collaboration between ARL's Weapons and Materials Research Directorate (WMRD) and TARDEC.

The mode of failure for roadwheels seems to be similar in principle to that of the bushings, both experience thermo-mechanical degradation leading to blowouts, never by abrasion as can be the case for track pads. In this regard, we have also evaluated the effect that the curing system exerts on the thermal stability of the compound. Adhesion to metal and tear strength resistance also appears to be properties that are important for both applications. But we are also investigating the crack growth resistance and fatigue resistance of the compounds. Close examination of roadwheels shows that small stones and road debris get embedded into the rubber work their way through. We may postulate that such foreign objects create cracks that eventually reach a critical stress value causing the roadwheel to tear and, in some cases, to delaminate from the metal wheel. To investigate this wear mechanism, we need to determine tearing strength, especially at high temperature. Since most roadwheel compounds are based on natural rubber, which experiences strain-induced crystallization, there is a need to quantify the tearing energy available for crack growth [15, 16].

Figures 4–7 show various types of roadwheel failures and wear patterns, which provide insight into which physical properties are necessary for improvement. Certainly, from this series of pictures, we can establish that compounding development efforts should be concentrated to improve tear strength, adhesion to metal (which may be affected by the curing system), flex fatigue, and crack growth resistance.

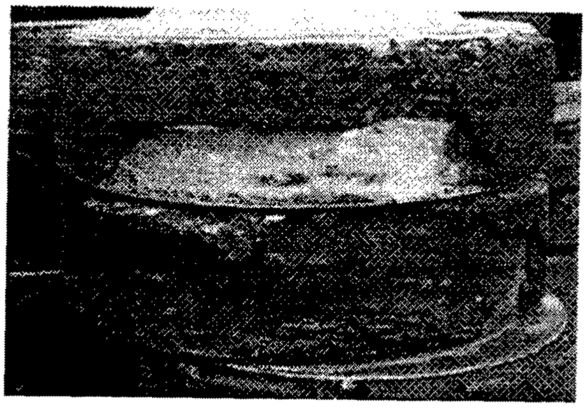


Figure 4. Roadwheel Wear.

Figure 5. Roadwheel Wear.

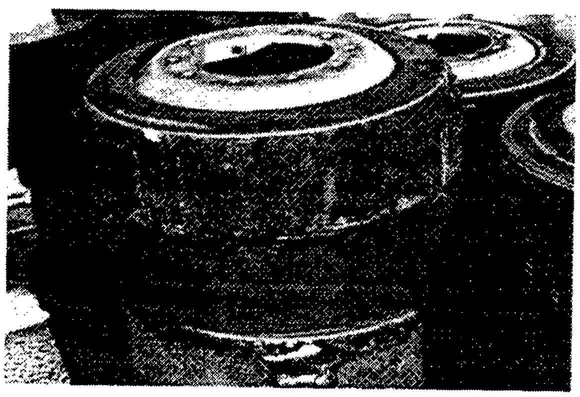


Figure 6. Roadwheel Wear.

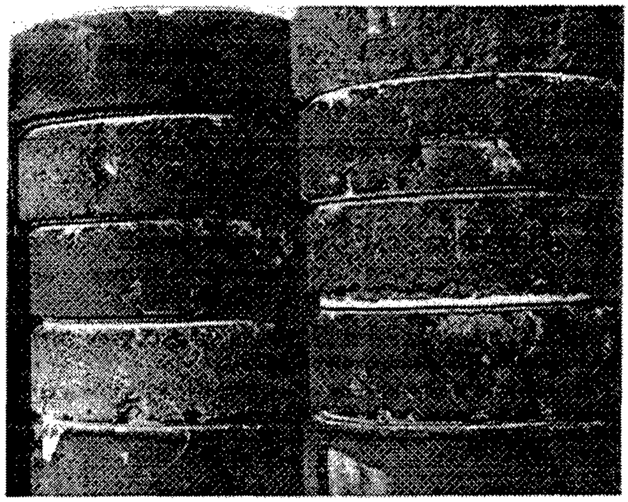


Figure 7. Roadwheel Wear.

3. Results and Discussion

The task of assembling a definitive set of target performance requirements for a given application is by no means a trivial one. Apart from specific requirements, many times we must rely upon detailed knowledge of the application, experience, and intuition. The last column of Table 9 includes a list of target values for desired properties that collects years of experience compounding rubber for dynamic applications, observations, and analysis of test results. Target values for adhesion, torsional, and radial stiffness were suggested by Mr. Glenn Simula of KRC.

The optimization of a rubber compound is always a compromise. We have discussed earlier how some desirable physical properties are compromised when we attempt to reduce reversion, or how we decrease adhesion to metal when the amount of sulfur is reduced in the vulcanization system. As a minimum, candidate experimental compounds should outrank materials currently in use for bushings. The use of the experimental design and desirability methodologies simplified this task and produced the best compromise of properties.

Commercial bushing compounds were obtained from industry. The rubber was then molded and tested side by side to the experimental compounds. A baseline of physical property values based on the commercial compounds was used to compare progress for the experimental formulations. The optimized experimental formulations developed are shown in Table 10. The physical properties for these commercial materials are depicted in Table 11. A variety of compounding ingredients, such as polymers, fillers, and curing agents, were evaluated to determine their effect on physical properties. Specific compounding ingredients were selected in an effort to optimize heat resistance, flex fatigue, resilience, crack growth, and permanent set after prolonged stress. Six in-house formulations have been tested with emphasis on torsional and radial stiffness properties before and after heat aging.

Table 10. Bushing Rubber Development—Optimization Results

	NAT-9813B-7	NAT-9813B-9	NAT-9813B-16	NAT-9813B-17	NAT-9813B-18	NAT-9813B-19
NATURAL RUBBER, SMR-L	100	100	100	100	100	100
ZINC OXIDE	5	5	5	5	5	5
STEARIC ACID	1	1	1	1	1	1
PEPTIZER 66	2	2	2	2	2	2
N-330, HAF Black	20	20	20	20	20	20
N-762, SRF Black	30	30	30	30	30	30
SANTOFLEX 6PPD, Antozite 67, Antioxidant PD-2	1.5	0.5	1.5	1.5	1.07	1.278
ANTIOXIDANT DQ, TQ, Flectol H, Agerite Resin D	3	3	2.38	3	1	1
SANTOCURE TBBS, BBTS	1	3	2.53	2.51	2.179	2.1
SULFUR	1	1	1	1	1	1.09
SANTOCURE TBSI	3.5	1	1	1	1	1
PERKALINK 900, BCI-MX	3	1	3	2.38	1	1
DURALINK HTS						
PROMIX 4-TEAR						
FORMULA WEIGHT	171	167.5	169.41	169.39	165.249	165.468

Theoretically, to obtain optimum bushing performance, the radial stiffness should be maximized and the torsional stiffness minimized. Increasing radial stiffness will decrease overall track tension. Low torsional stiffness will generate less heat during service, therefore minimizing degradation of material properties. Based on the typical commercial material, baseline values are 115,000 lb-in for radial stiffness and 2,100 in-lb/radian for torsional stiffness.

Table 11. Commercial Bushing Compounds

PROPERTIES	Desired Property	BUSH 7	BUSH 8	BUSH 10
FATIGUE TO FAILURE				
Energy at Extension Ratio = 2 in-lb		3.65	3.82	3.23
ORIGINAL, CYCLES × 100		557.00	555.75	734.20
Cycles/Energy × 100		152.6	145.5	227.3
AFTER AGED 20 HR @ 250° F				
Energy at Extension Ratio, in-lb		3.70	3.17	4.40
ORIGINAL, CYCLES × 100		1.7	1.5	160.5
Cycles/Energy × 100		0.5	0.5	36.5
Temperature		290° F	290° F	290° F
Scorch t_{s2}, min		5.6	5.5	3.9
M_{h95}, lb-in		16.4	20.8	15.0
M_{fin}, lb-in		15.7	20.9	13.5
Torque Difference, M_{fin}-M_{h95}		-0.73	0.08	-1.51
Peak Rate, lb-in/min		1.8	2.0	5.2
Die C Tear, lb/in	>300	354.00	516.00	521.00
Die C Tear, lb/in 10 min @ 250° F	>175	137.00	218.00	244.00
Tensile Strength, psi	>2700	3910.0	3730.0	3410.0
Modulus @ 200% Elongation, psi	>700	1190.0	1420.0	1040.0
Ultimate Elongation, %	>350	450.0	440.0	480.0
Energy at Break, in-lb				
AFTER 70 HR @ 212° F				
Tensile Strength, psi		1116.97	1489.2	2228.97
Modulus @ 200% Elongation, psi				1789.45
Ultimate Elongation, %		131.98	141.79	244.57
Energy at Break, in-lb		37.33	54.88	126.26
Compression Deflection, % at 600 psi	33–41	40.99	35.39	42.97
Compression Set, % 22 hr @ 160° F	<25	27.8	25.4	29.7
Hardness, Shore A	65–75	69.0	71.0	70.0
Rebound, %		42.0	43.0	37.0
AFTER 70 HR @ 212° F				
Hardness, Shore A		65	74	49
Rebound, %		41	38	38
Heat Buildup, Internal, $^{\delta}$°C	<50	76	46.3	43.7
Heat Buildup, External, $^{\delta}$°C	<25	20	23	30.4
Heat Buildup, Compression Set, %		38.7		
BLOWOUT TIME, MIN		75.9	18.9	49
Blowout 2				
DEMATTIA FLEX FATIGUE, Unaged	<25	11.5	23	9.375
212° F Growth Rate, mils/min	<200	30.5		
20 HR @ 250° F, Growth Rate, mils/min		300000	3000	110.91

Table 11. Commercial Bushing Compounds (continued)

PROPERTIES	Desired Property	BUSH 7	BUSH 8	BUSH 10
RADIAL STIFFNESS, lb-in × 1000				
ORIGINAL	>115	69.28	66.33	54.87
4 HR @ 250° F, 4 hr		48.41	58.20	51.23
AFTER AGING 4 HR at 250° F				
TORSIONAL STIFFNESS, lb-in/RAD				
ORIGINAL, 7°	<2100	2343.05	1150.07	2347.50
@ 250° F, 7 °		1786.22	2106.63	1980.68
ORIGINAL, 14°		1858.04	1519.50	1789.61
@ 250° F, 14°		1496.67	1716.43	1558.75

When comparing the experimental compounds with the commercially available compounds, first we look at the reversion. This is calculated by subtracting the cure torque—M_{h95}—from the final torque. The cure curve is produced by the Monsanto moving die rheometer. A negative value means the compound exhibits reversion. From Table 11, we see that two of the compounds exhibit reversion and the compound designated as BUSH 8 is marginal at best and may exhibit some reversion at the higher temperatures encountered in the bushing housing. The optimized formulations shown in Table 9 are all resistant to reversion.

The optimized formulations show excellent tear strength even after heat aging at 250° F. Perhaps more notable of the improved curing system are the results for heat buildup, blowout, compression set after 22 hr at 160° F, and the compression deflection % at 600 psi, a specification requirement. The heat buildup test is conducted according to ASTM D-623 [17] using a 17.5% dynamic strain and a load to exert 141.7 psi on the samples. To produce blowout conditions, we changed the strain to 30%, still with the same stress of 141.7 psi. However, if a sample lasted more than 2 hr, we then proceeded to increase the stress on the samples to 262 psi. This set of conditions we call Blowout 2. It is notable to see that the commercial compounds (Table 11) all had blowout times of less than 120 min, while the optimized formulations in Table 9 all lasted over 2 hr. Moreover, even under the more stringent conditions of Blowout 2, most notably, compounds NR-9813-9 and NR-9813-19 produced very high resistance to blowout with times of 53 and 45 minutes, respectively. This performance is orders of magnitude better than commercial compounds. Very seldom have the investigators seen this type of performance for a natural rubber compound.

It is interesting to note that none of the commercial bushing compounds met the specification requirements for Compression Set or Compression Deflection at 600%. Again, the optimized formulation exhibited excellent compression set and deflection characteristics.

De Mattia flex fatigue at room temperature and at 212° F was within the target values for both the commercial compounds and the optimized formulations; however, the values for the optimized compounds in Table 9 were more consistent within the Weibel statistical distribution characteristic of this test.

Bushing elastomers for military tracked vehicles perform under very tough conditions. The rubber is prestressed by compression into a housing, which does not allow for heat dissipation. They are then dynamically loaded axially and in torsion, thus developing hysteretic heat. As the bushing is flexed in torsion, it is easy to visualize that an important characteristic for these compounds must be the Fatigue to Failure. Again, the optimized formulations shown in Table 9 show excellent Fatigue to Failure when compared to the commercial bushings (Table 11). At first glance, it looks like the commercial compounds exhibit very high values of Fatigue to Failure, ranging from 55,575–73,420 cycles. However, these compounds are harder (see Hardness values) when the results are normalized by the energy at the strain level at which the test is performed, the values drop dramatically and are more in line with those of the experimental optimized compounds in Table 9. Here is where the more thermally stable curing systems of the optimized compounds really shine.

After heat-aging the samples for 20 hr at 250° F, the Fatigue-to-Failure of the commercial compounds BUSH-7 and BUSH-8 dropped to 55 cycles, while BUSH-10 produced 3,650 cycles. A look at Table 9 shows that our experimental compounds produced values ranging from 2,180–11,700 cycles, evidence of the increased thermal stability of these compounds, making them better candidates for bushings than the commercial materials.

4. Summary and Conclusions

Results from this project produced a group of formulations with improved thermal stability eliminating the reversion exhibited by most sulfur-cured natural rubber compounds. The use of the experimental design and desirability methodologies proved extremely useful in the development of rubber compounds, techniques that when properly applied provide meaningful results while reducing the time of investigation by reducing the number of experiments. The compounds developed exhibited performance property values that exceeded those of commercially available bushing compounds.

The use of antioxidants, vulcanization stabilizers, and hybrid cross-linking agents was optimized to improve the tendency to reversion in natural rubber conventional sulfur cure formulations, while maintaining acceptable tear resistance, fatigue life, and reduced compression set.

The guidelines provided by KRC on desired torsional and radial stiffness were key to the compounding efforts. Although torsional and radial stiffness appear to be relevant in predicting which material will perform best in dynamic tests, those properties may not indicate how well (quantitatively) a given material will perform. Bushings were fabricated for simulation testing at KRC. The funding to complete the qualification tests is still an issue that needs resolution. It is recommended that TARDEC provide the necessary funding to accomplish this task.

During FY99, the investigators are dedicating their efforts to improve the wear characteristics of the rubber compounds used in roadwheels; however, the bushing formulation efforts would benefit from a program that takes in account the measurement of dynamic mechanical properties. These properties, Storage Modulus G', Loss Modulus G", and Tan δ, control deformation, heat buildup, and ultimately, the service life of these components. This relationship between heat buildup in an elastomer component subjected to high dynamic stresses and frequencies, as in bushings and roadwheels, is well known [18].

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REPORT DOCUMENTATION PAGE

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1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	October 1999	Final, Sep 97 - Dec 98

4. TITLE AND SUBTITLE
Elastomers for Tracked Vehicles - Development of Rubber Compounds for Bushings

5. FUNDING NUMBERS
JONO: 98M412

6. AUTHOR(S)
Gumersindo Rodriguez, Paul Touchet, Alan R. Teets, and David P. Flanagan

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Research Laboratory
ATTN: AMSRL-WM-MA
Aberdeen Proving Ground, MD 21005-5069

8. PERFORMING ORGANIZATION REPORT NUMBER
ARL-TR-2061

9. SPONSORING/MONITORING AGENCY NAMES(S) AND ADDRESS(ES)

10.SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

After development of HNBR12, a patented formulation that doubled the service life of track pads, it has become necessary to improve the service life of bushings and roadwheels. The purpose of the work during FY98 was to increase the service life of bushings and close the gap in service life between pads and bushings, while work during FY99 will address the service life of roadwheels.

A group of natural rubber compounds for bushings was developed to improve the reversion resistance of the conventional cure systems typically used in this application. In order to optimize performance and properties, a factorial experimental design of six factors at two levels for the curing and the antioxidant system was used. Properties deemed important for performance were selected and desirability functions defined for each one, after which a regression analysis was performed on the matrix to optimize the best features. The model was used to develop a set of formulations with enhanced properties. The optimization matrix produced a series of optimized formulations with improved performance properties, of which six were selected for fabrication and testing at the Keweenaw Research Center (KRC).

14. SUBJECT TERMS
elastomers, tracked vehicles, bushings, tank pads, design of experiments, natural

15. NUMBER OF PAGES
39

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500
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