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ELECTRICAL PROPERTIES OF TANK PAD RUBBER: A FEASIBILITY STUDY

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The purpose of this work is to investigate the feasibility of electrical measurements for improving the life and reliability of tank track pad rubber. Immediate goals are to determine if electrical measurements can be used to distinguish various types of rubbers used in tank track pads, to obtain more fundamental information about the electrical properties of the rubber, and to make recommendations.

Our principal results are:

1. The electrical resistance of carbon black loaded rubber increases when the rubber is under compressional stress and tends to relax if the stress is maintained. Subsequent release of the stress results in another jump in resistance, followed by relaxation.

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2. Each of seven rubber compositions supplied by Ft. Belvoir, VA has its own distinct resistance relaxation characteristic, i.e., a "fingerprint" exists for each type of rubber.

3. For both types of relaxation, resistance varies linearly with the logarithm of time. This is similar to the time dependences seen for mechanical stress relaxation and creep, and can be described by a rectangular relaxation time distribution function.

4. The resistance of carbon black filled rubber is extremely sensitive to pressure and, in fact, varies approximately exponentially with pressure.

5. Electrical resistance relaxation under stress, and the subsequent resistance spike upon stress removal, can be attributed to a healing of disrupted links, and rerupture of those same links, respectively.

6. The electrical resistance changes, and certain mechanical parameters such as stress softening and set, are probably due to common bonding mechanisms in the rubber.

7. Slower relaxation occurs under stress rather than following release because it is easier for a disrupted link to rebond in the latter case.

8. For the Ft. Belvoir samples, electrical differences between the NR-1 and NR-42 types can be attributed to low structure black used in NR-42.

9. A fraction of the resistance increase remains after one month, but initial values can be restored by heating for 16 hours at 70°C.

10. A variety of measurements (current-voltage, thermal voltage, and frequency dependent impedance) identify the electron as the major charge carrier that contributes to electrical conduction.

11. Contact resistance on samples cut from track pads was identified and modelled using frequency dependent impedance measurements; contact resistance can be nearly eliminated using Aquadag contacts.

12. The frequency dependent impedance characteristics (capacitance and conductance) and the current-voltage characteristics vary for the different rubber types (samples were cut from pads or supplies by Ft. Belvoir). However, none of those measurements provide the unique "fingerprints" that are seen in the resistance relaxation characteristics.

13. Electrical measurements (the resistance relaxation ones in particular) can be used to fingerprint samples, depend on the history of the sample and can be correlated with certain mechanical properties of the visco-elastic material. Hence, our main program objective, to validate the usefulness of electrical measurement on carbon black loaded rubber samples, has been achieved.

14. Recommendations are made for future work, and in summary, are related to: i) increased stress levels inorder to simulate actual track pad conditions; ii) temperature dependence of resistance increase/relaxation; iii) stress performance resistance tests with no attached contacts, i.e. letting pressure contacts also provide electrical contact; iv) correlation of resistance relaxation characteristics with wear and lifetime characteristics.

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1.0. INTRODUCTION

This is the final report for U.S. Army Contract No. DAAE07-83-K-R007, performed at Virginia Polytechnic Institute and State University, regarding the feasibility of electrical measurements on tank track pad rubber. We determined that certain electrical measurements depend strongly on composition and history of carbon black filled rubbers. Such measurements should have direct diagnostic value when applied to tank track pads.

2.0. OBJECTIVES

The long term objective is to improve the life and reliability of tank track pad rubber. Over the course of this nine month program, our main goal was to determine if electrical measurements would be useful in this task. The shorter term objectives of this "feasibility study" can be summarized as follows:

- To determine if electrical measurements can be used to distinguish various types of rubbers used in tank track pads and to distinguish between various pads directly (for different vendors, different service histories);

- To obtain more fundamental information about the electrical properties of the rubber, and if possible to correlate these with mechanical properties;

- To make recommendations as to the feasibility of electrical measurements toward improving the reliability of tank track pad rubber, and make recommendations for future work.

3.0. CONCLUSIONS

This program consisted of an investigation of the feasibility of using electrical measurements to gain useful information related to tank track pad rubber. Our most important results were related to the effects of pressure on resistance, and resistance relaxation. Each of six different compositions measured had its own resistance increase-relaxation fingerprint. Samples of the same composition had nearly identical fingerprints. A major asset of the pressure-resistance relaxation measurement is that it couples mechanical and electrical properties of the rubber. A correlation between electrical relaxation and certain mechanical parameters such as creep and set recovery was made. The resistance relaxation phenomena can be attributed to various bond breakages and repairs, which can also be related to mechanical properties.

We feel that the main objectives of this contract have been achieved. Certain electrical measurements can result in useful information related to tank track pad types of rubber. For the resistance relaxation measurement to be developed further toward its full potential, recommendations for further study are also given.

4.0. RECOMMENDATIONS

There are several areas directly related to pressure induced resistance change and resistance relaxation that should be investigated:

- Compressive stresses should be increased to 200 $lb/in.^2$ and higher, to be closer to those experienced by an actual track pad in service;
- The temperature dependence of resistance increases and relaxations should be investigated in an effort to determine thermal activation energies for bond breakage and recovery;
- Tests of this type should be performed on blocks cut from track pads, and on pieces obtained from Ft. Belvoir without permanent electrodes (electrodes for current continuity would be provided by a pressure jig);
- An attempt should be made to correlate the stress/relaxation characteristics of various compositions with their wear/lifetime characteristics. Stress/relaxation and Flexometer tests, for example, could be done on similar pieces.

5.0. DISCUSSION

5.1. Background

The electrical parameters of carbon black loaded rubber that we have measured are resistance (including contact resistance), capacitance, and dependence of resistance on pressure and time[1] None of these parameters is well understood theoretically, since each depends on complicated processes in the rubber. The general model is that electrical conduction and capacitance are governed for the most part by the amount, type and distribution of carbon

[1] Temperature effects will be investigated in the future.

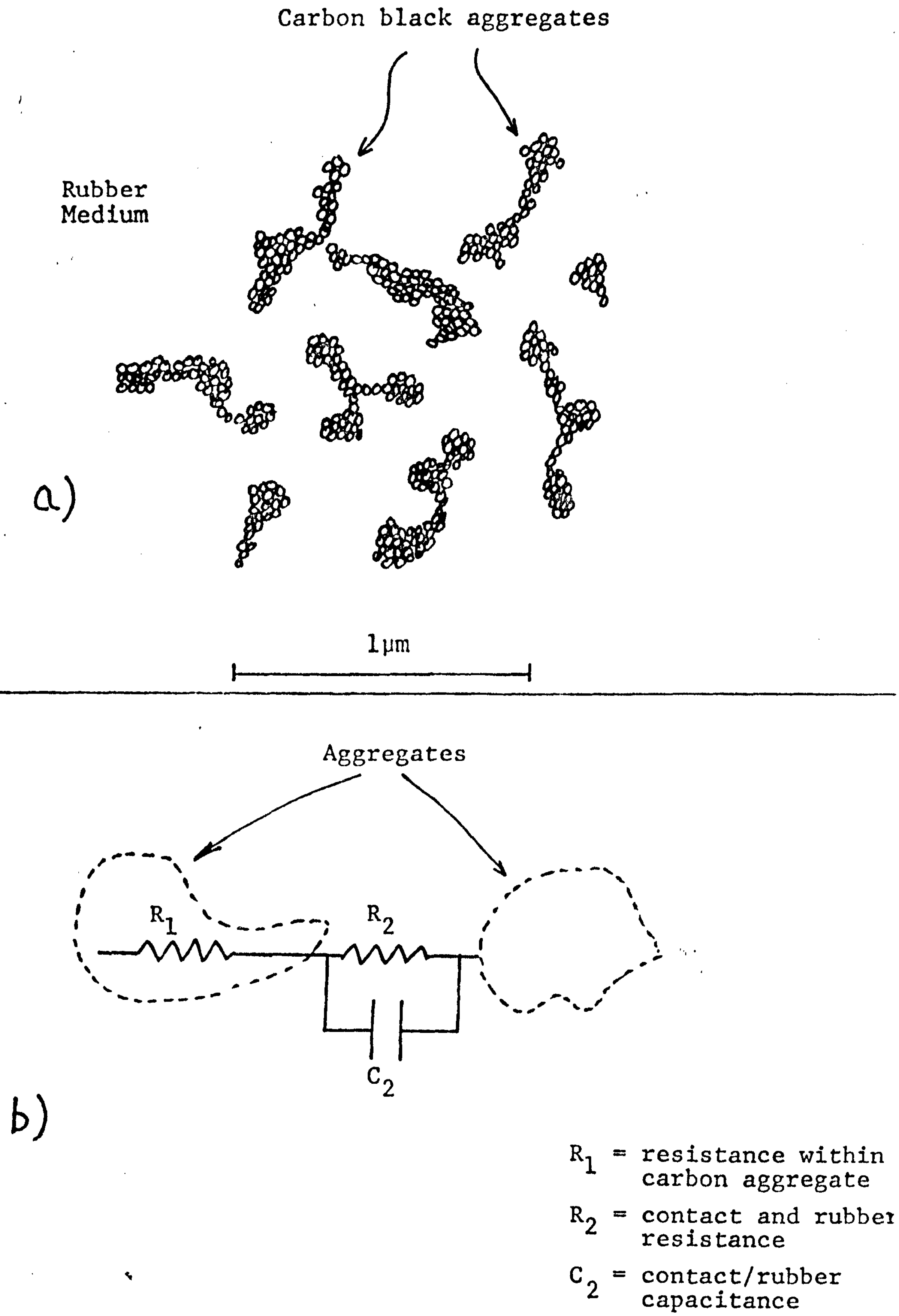

Figure 5-1. a) Carbon black aggregates in rubber medium;
b) Electrical Model

black in the rubber.[1] This is illustrated in Figure 5-1.

The carbon black particle size and structure are key factors in determining both electrical and mechanical properties. Additional factors are other additives (such as sulfur), the possibility of charge layers surrounding the aggregates, tunnelling between the aggregates, and ionic conduction.

It is also highly probable that the same bonds determine both mechanical and electrical properties of the rubber. These include carbon black particle to particle bonds, carbon to polymer bonds, polymer cross links, polymer chain bonds, and vander Waals forces between carbon black aggregates and between the carbon black and the matrix. Electrical conduction can therefore monitor disruptions suffered by these bonds when subjected to mechanical stress, as we have verified in this research.

We would anticipate also that electrical measurements might be a very sensitive tool for distinguishing between different types of rubbers and, as described below, this has indeed turned out to be the case.

A variety of electrical measurements have been used over the years on carbon black loaded rubbers, both to monitor fabrication processes and to gain more fundamental information about the complicated electromechanical system. A major application of electrical measurements (mainly DC resistance or its inverse, conductance) has been to monitor mixing conditions and the effects of composition [1-11]. In addition, studies of the physics of charge transport have been reported [1,12-15]. An example is the PTC (Positive Temperature Coefficient) materials, which are based on the rise of electric resistance with temperature [16,17].

One aspect of electrical conductance in carbon black filled rubbers that has been reported, although not extensively investigated or well understood, is the dependence of conduction on externally applied stress, which may be time dependent [9,18-20]. The DC resistance (or conductance), and its time dependence--both under periodic loading or as a sample--is stressed and released, are very sensitive to sample type and history. In fact, this has turned out to be our most sensitive electrical measurement. It has the additional advantage that the electrical resistance, being modulated mechanically, can be correlated with certain mechanical properties of the same sample (such as creep and set). This will be discussed further below.

5.2. Experimental Techniques

We have measured two groups of rubber samples: a) those cut directly from track pads and b) those made specifically for this program at Ft. Belvoir, VA. (These will be referred to as the "track pad" and "Ft. Belvoir" samples, respectively.)

The "track pad" samples were cut from pads supplied by TACOM. Electrical contacts were applied by bonding wires to two faces (or ends for longer samples) using a conducting epoxy or paste. Silver epoxy, Aquadag, and Electrodag were the main ones tested, the latter two being carbon black suspensions. Contact resistance (resistance at the epoxy-rubber interface) was encountered in most cases. It was less severe for Aquadag than for the other two. This will be discussed further in the next section.

The pads were supplied by TACOM, and were manufactured by three vendors (designated as Types A, B and C in the report, and identified in the Addendum).

The formulations and mechanical properties of the Ft. Belvoir samples are contained in the Ft. Belvoir progress reports. We concentrated our measurements on four sample types of known composition, and two commercial ones for comparison purposes.

Compositions are shown in Table 5.1. Two of these used a styrene-butadiene (SBR) base, the other two used natural rubber (NR).

Table 5.1. Four of the Ft. Belvoir Sample Compositions

Ingredients (PPHR)	SBR-2	SBR-26	NR-1	NR-42
SBR (Firestone FRS-1500)	100			
SBR (Copolymer 1500)		100		
Natural Rubber (RSS#1)			100	100
SAF Black (N110)	45	45	45	
NAF-LS Black (N326)				45
Zinc Oxide (Kadox 15)	4	4	4	4
Stearic Acid (#1 rubber grade)	2	2	2	2
Agerite Resin D	0.5	0.5	0.5	0.5
Agerite White	0.5	0.5	0.5	0.5
Antozite 2	3	3	3	3
Sulfur (rubber maker)	2.0	2.0	2.5	2.5
Santocure	1.5	1.5	0.8	0.8

All compounds were mixed in a Banbury mixer at a speed of 77 rpm, followed by a final mill mix. SBR pieces were cured for 30 minutes at 310°F (154°C), and NR pieces for 20 minutes at 300°F (149°C).

Two additional commercial "off-the-road" compositions were mixed and cured in addition to the SBR and NR samples. Even though these compositions are proprietary, the samples were measured for comparison to the other types.

Sample dimensions are 0.5 in. thickness, 1 in^2 area. Brass plates of the same area as the sample faces, and 1/16 in. thick, were bonded to the faces during curing in order to minimize contact resistance [21]. Wires were silver epoxied to the brass plates for electrical contact.

AC measurements (mainly capacitance and conductance versus frequency) were made using a Hewlett-Packard Model 4192A Impedance Analyzer over the frequency range 10Hz - 13MHz.

DC resistances were measured directly by digital multimeters, or by passing known current through the sample and measuring voltage. For pressure tests on the Ft. Belvoir samples, a current of 0.1mA was maintained in the sample and the voltage across the sample was displayed on a strip chart recorder. Stress was applied using a small arbor press, and measured by means of a pressure transducer under the sample. Pressure was applied for less than 100 seconds, typically 70 seconds, since this was sufficient time to determine a relaxation rate. A second relaxation rate was determined following release of the load. All measurements were done at room temperature (20 $\pm$ 1 C).

For the Ft. Belvoir samples, DC current was measured as a function of voltage over the current range 10μA to 1 mA. This range was used because it straddles the current used in the relaxation tests (0.1 mA), and the I-V characteristics in that region could thus be determined. These characteristics are ohmic, and will be discussed further below.

Thermoelectric measurements were made on each Ft. Belvoir sample in order to determine the sign of the charge carrier. One side of the sample (i.e. brass plate) was heated gently with a soldering iron, and the polarity of the thermal voltage recorded. The sign of the thermal voltage was negative in all cases, indicating that the dominant charge carrier is also negative.

5.3. Results

5.3.1. Electrical Resistance Relaxation.

Our most significant results are related to the dependence of electrical resistance on external stress, and to resistance time dependence. These are the most significant measurements for two reasons:

a) Each of the six sample types has its own definitive resistance relaxation signature;

b) Resistance increase and relaxation can be correlated directly with certain analogous mechanical parameters.

Three samples of each type were provided by Ft. Belvoir. Resistance values for the 18 samples are shown in Table 5.2. These values are averages of five measurements. The measurements were made after the "A" set had been subjected to some preliminary stress tests; those values are therefore somewhat larger for six of the seven types.

Table 5.2. Resistance Values for 18 Ft. Belvoir Samples (each is average of five measurements)

Sample	Resistance (KΩ)
NR 1-A	0.135
B	0.060
C	0.054
NR 42-A	17.815
B	4.590
C	33.700
SBR 2-A	4.347
B	1.588
C	3.278
SBR 26-A	1.004
B	0.269
C	0.222
OTR 5-A	0.251
B	0.092
C	0.104
OTR 6-A	0.471
B	0.219
C	0.303

The dependence of electrical resistance on stress was noted early in the program, and reported in the first monthly report dated August 24, 1983. This was first seen on samples cut from track pads, and it was noted that resistance increased for several types of stress: compression, tension and torsion. Similar effects were seen in the Ft. Belvoir samples, which could be studied in greater detail due to their better electrical contacts and the fact that the entire sample body could be placed under compressional stress applied directly to the contacts. Therefore, only resistance relaxation curves for the Ft. Belvoir samples are discussed below.

Resistance parameters that pertain to the relaxation curves are shown in Figure 5-2. When the load is applied to the sample, resistance increases from R_o to R_1. While under constant load, the resistance relaxes from R_1 to R_2. When the load is removed, the resistance increases suddenly from R_2 to R_3, and then again relaxes.

Resistances versus time for four types of Ft. Belvoir samples (for the "A" set) are shown in Figure 5-3, and for the two commercial types in Figure 5-4. (The curves are laterally displaced slightly to avoid overlap.) The load applied was 60 lb., over 1 in^2 area, except for sample NR-42 which received only 30 lb. due to its greater sensitivity.

Resistance values, and the ratios R_1/R_0, R_3/R_0 and R_3/R_2, are given in Table 5.3. Each entry is an average of three measurements.

Table 5.3. Resistance Parameters (in kΩ) and Ratios

Sample	R_0	R_1	R_2	R_3	R_1/R_0	R_3R_0	R_3/R_2
SBR-2	6.64	132	80.3	168	19.9	25.3	2.09
SBR-26	0.40	9.63	8.90	10.4	24.0	25.9	1.17
NR-1	0.12	1.51	1.46	1.51	12.9	12.9	1.03
NR-42	15.41	460	444	444	29.9	28.8	1.00
OTR-5	0.23	3.23	2.49	4.67	14.3	20.7	1.88
OTR-6	0.40	4.48	1.71	11.12	11.2	27.7	6.51

When the resistances are plotted as functions of the logarithm of time, over 30 second time intervals, linear curves result. These are shown in Figure 5-5. (For times longer than several minutes, the curves become somewhat, although not highly, nonlinear as the resistances relax back toward their initial values.)

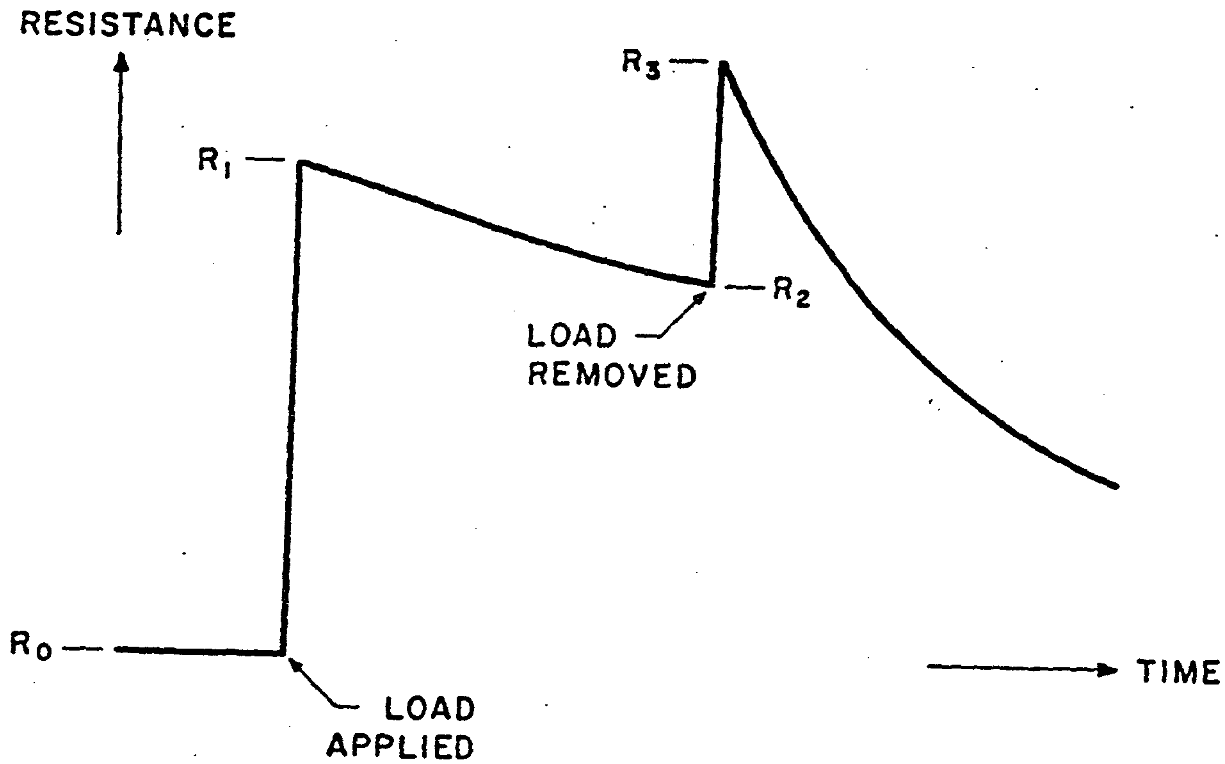

Figure 5-2. Generic resistance vs time curve defining resistance parameters

The resistance relaxation rates can be expressed as percent decrease per decade of time (in seconds) and are listed in Table 5.4. The first column pertains to the change in resistance when the sample is under load, the second column identifies the load after it is removed. (These correspond to the left and right hand parts of Figure 5-5).

We found the increase is resistance depends not only on the sample type, but very strongly on the applied pressure. The dependence of the initial resistance increase (R_1) on applied pressure is shown in Figure 5-9 for six samples (set "A"). The very strong near-exponential dependence of resistance on pressure is evident. Four of the types lie very close together. However, their resistance relaxation characteristics are quite distinguishable (Figures 5-3 and 5-4).

Table 5.4. Resistance Relaxation Rates (% decrease per decade)

Sample	Loaded	Released
SBR-2	19.6	38.0
SBR-26	3.2	26.3
NR-1	4.3	23.0
NR-42	1.4	26.3
OTR-5	13.2	32.4
OTR-6	37.3	31.7

Following resistance relaxation tests on the Ft. Belvoir samples, resistances did not relax back totally to the initial values, after 1 month storage at room temperature. However, they may be thermally restored to near-initial values by heating at 70°C for several hours. This is illustrated in Table 5.5. Following this type of thermal healing treatment, resistance values (R_0) appear to remain constant indefinitely if the sample is not stressed.

Table 5.5. Resistance Values Illustrating Relaxation and Thermal Healing (KΩ)

Sample	R_0	R_{max}	R_1	R_0'
SBR-2	4.21	132	6.89	4.82
SBR-26	0.37	9.60	0.92	0.39
NR-1	0.11	1.51	0.34	0.14
NR-42	12.9	490	36.4	17.7

R_0 = "initial" value following 16 hours aging at 70°C

R_{MAX} = maximum value under 60 lb pressure

R_1 = value after 1 month storage at room temperature

R_0' = value after aging 16 hours at 70°C.

This indicates that whatever bond-rupture is occurring during stress is not permanent, and can be repaired. This, however, may not be the case for more severe stress such as that encountered when a track pad is in service. Further investigations at higher pressures would be required to resolve this question.

The resistance increase and relaxation characteristics that immediately follow a thermal "healing" exhibit several interesting features in addition to those already discussed (see Figure 5-7 and compare it to Figure 5-3.) First, the average resistance values increase slightly following each pressure-release cycle. This is expected since it is known that electrical and mechanical properties depend strongly on history. Second, the initial resistance increase following thermal healing has a form unlike those that appear in subsequent loading. This seems to indicate that the initial electrical bond breakage includes a type that is of a different nature than ones broken during later loading. This bond may be largely responsible for the apparent permanent increases in resistance that exists following a series of pressure tests. Third, as average resistance values increase during the pressure cycles, so do the relaxation rates (such as those seen in Figure 5). This is reasonable since the larger the number of electrical links broken under stress, the larger the number that heals during a given period following release.

Even though the average resistance and relaxation rates increase with the number of loading cycles, the shapes of the pressure-release characteristics (such as those of Figures 5-3 and 5-4) are unique for each of the different samples types. (A second set of supposedly identical samples gave characteristics nearly identical to those shown here.) It therefore appears that such characteristics can be used as "signatures" for given carbon black filled rubber types.

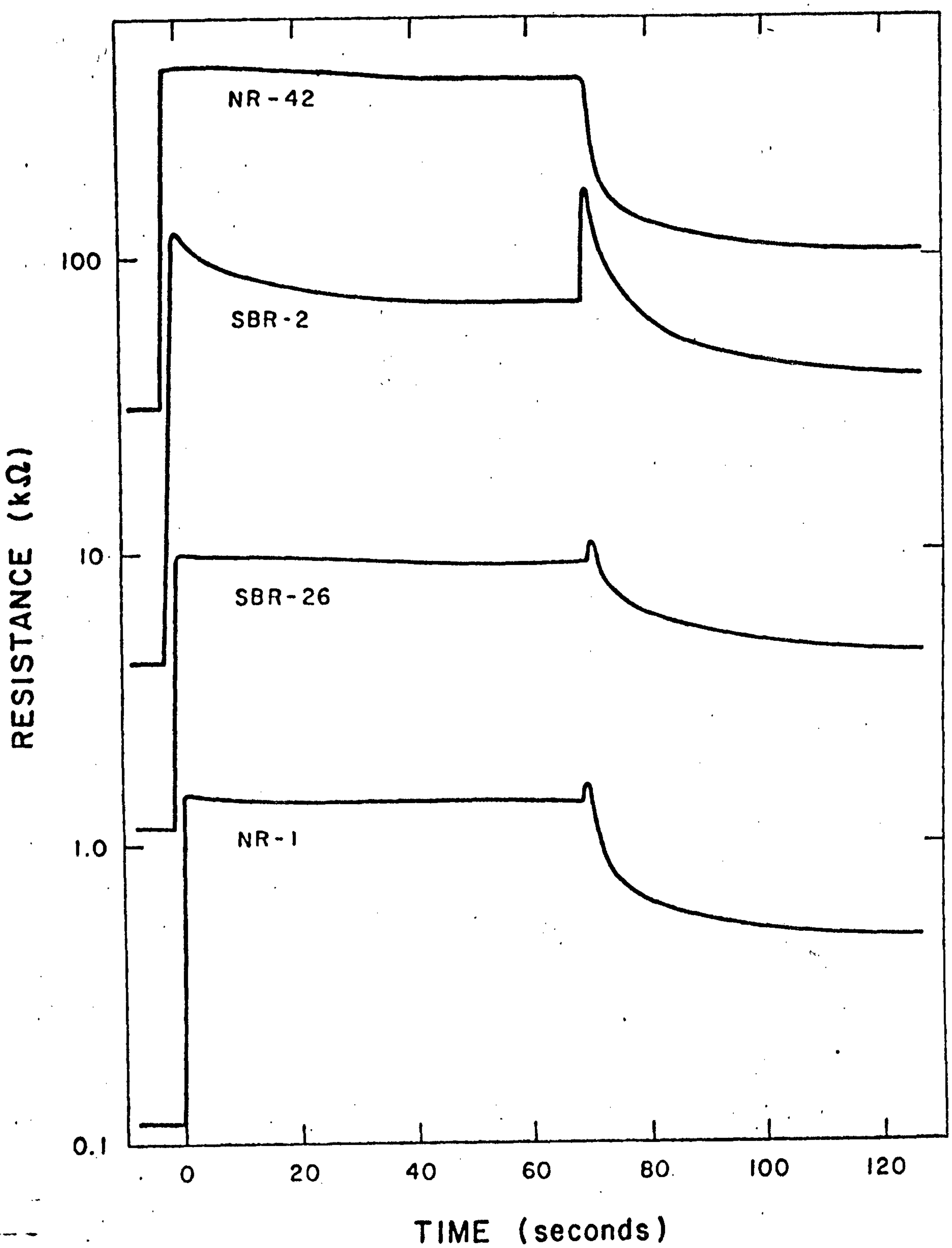

Figure 5-3. Typical resistance increase and relaxation curves for pressure applied at t=0 and removed at t=70 sec. (Curves displaced slightly for clarity)

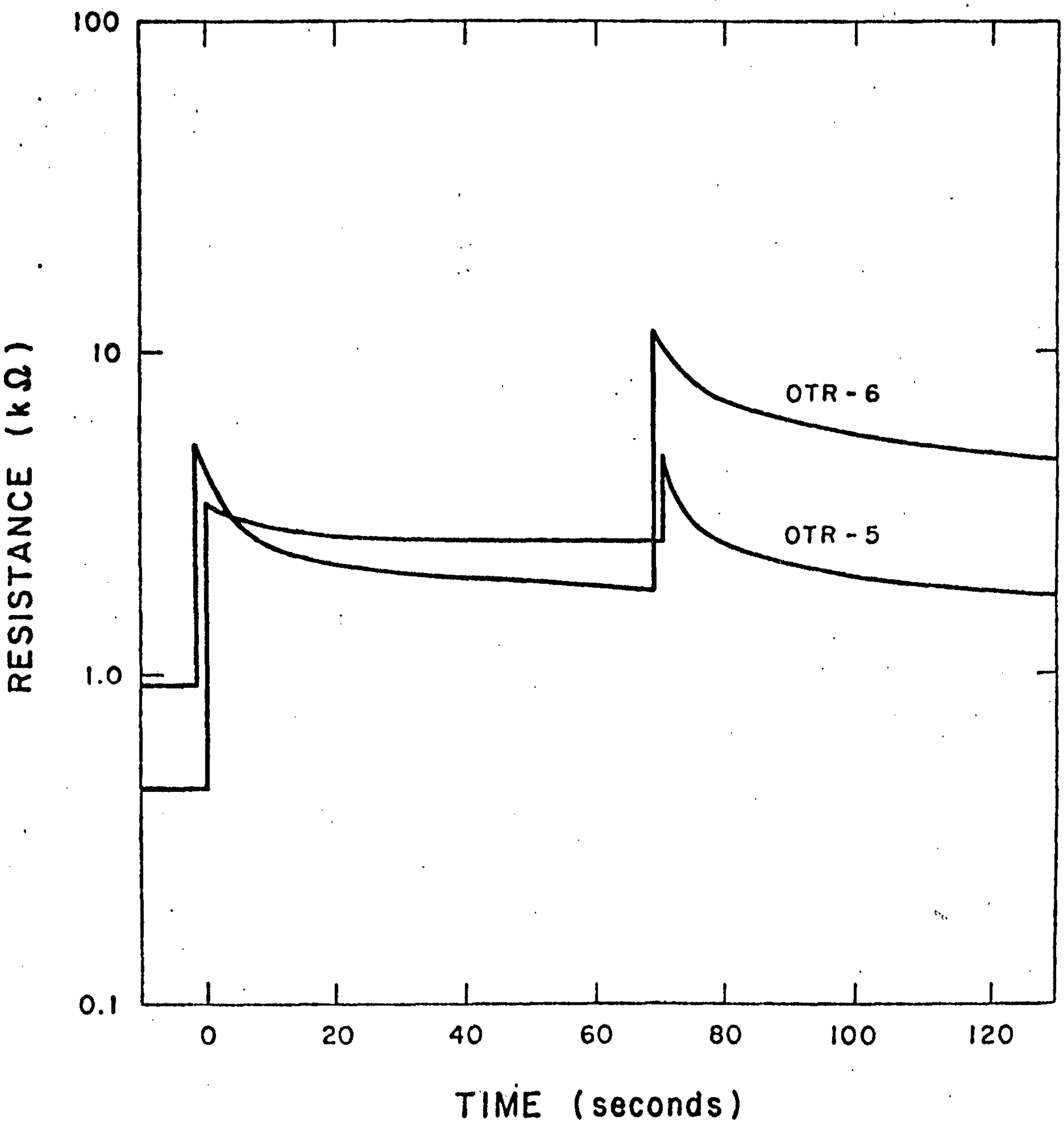

Figure 5-4. Resistance increase and relaxation curves for OTR samples

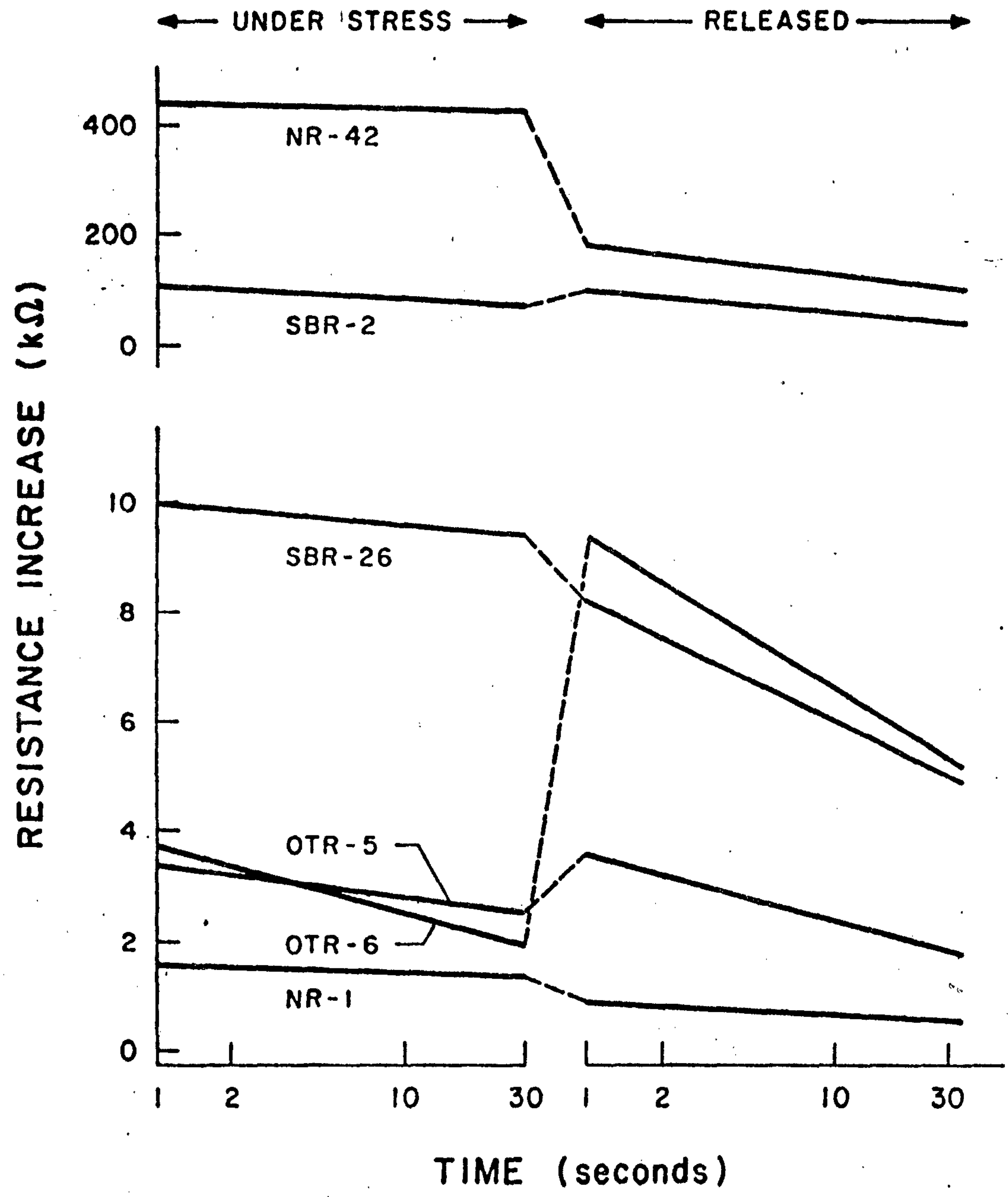

Figure 5-5. Relaxations during stress and following release, on logarithmic time scale (From Figure 2 and 3 data)

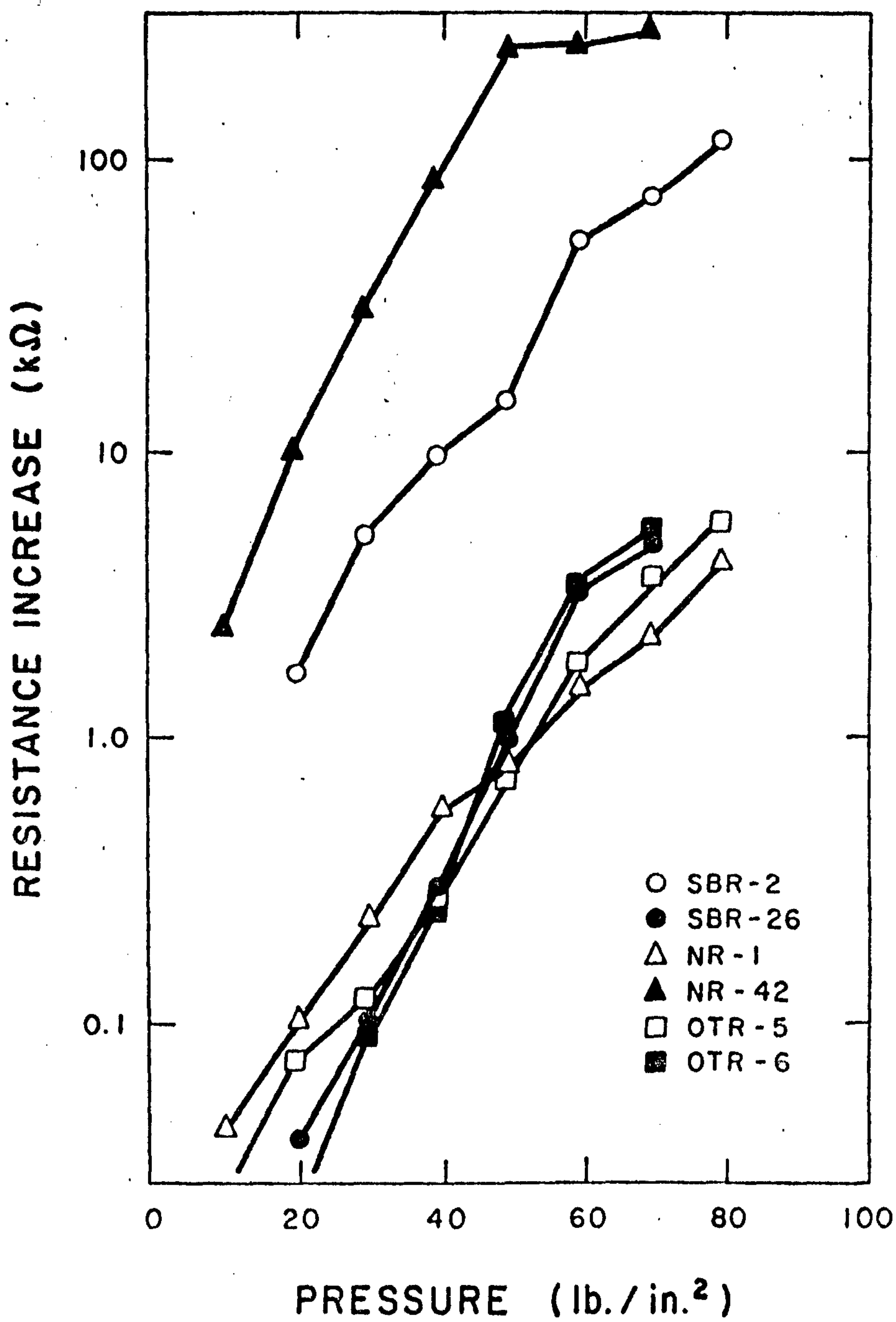

Figure 5-6. Resistance increase (R_1) versus applied pressure

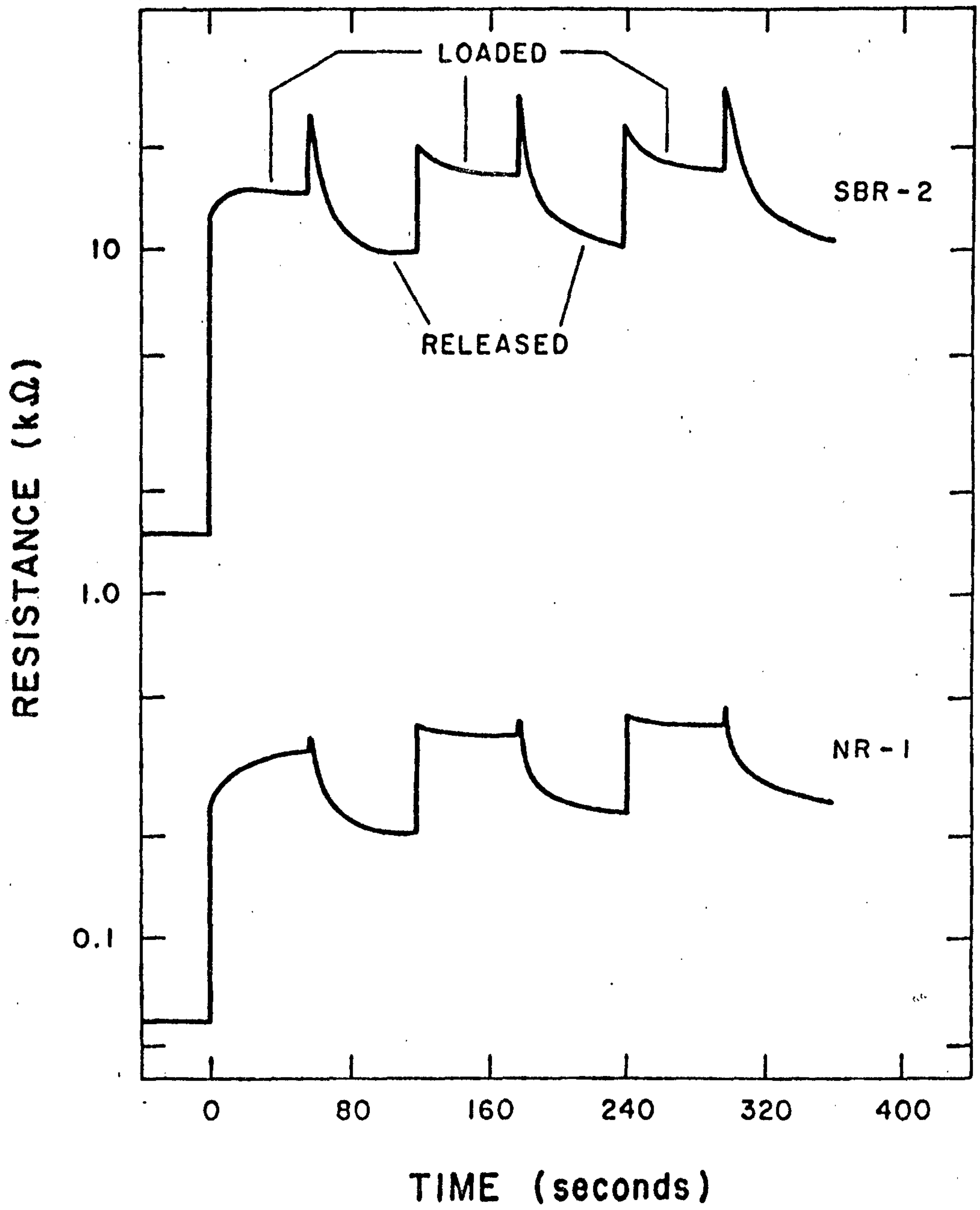

Figure 5-7: Increase-relaxation characteristics for two samples immediately following thermal anneal at 70°C

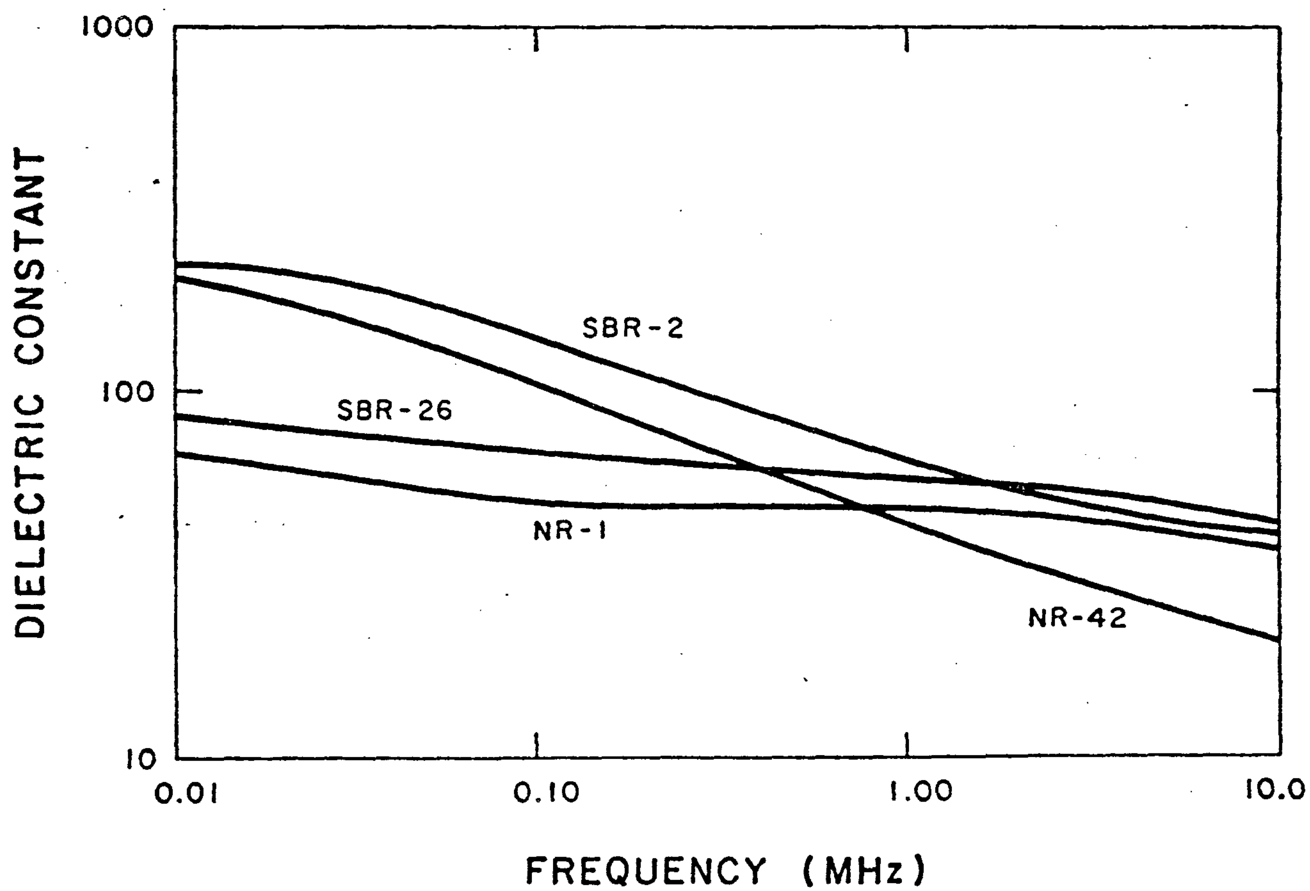

Figure 5-8. **Dielectric constants versus frequency**

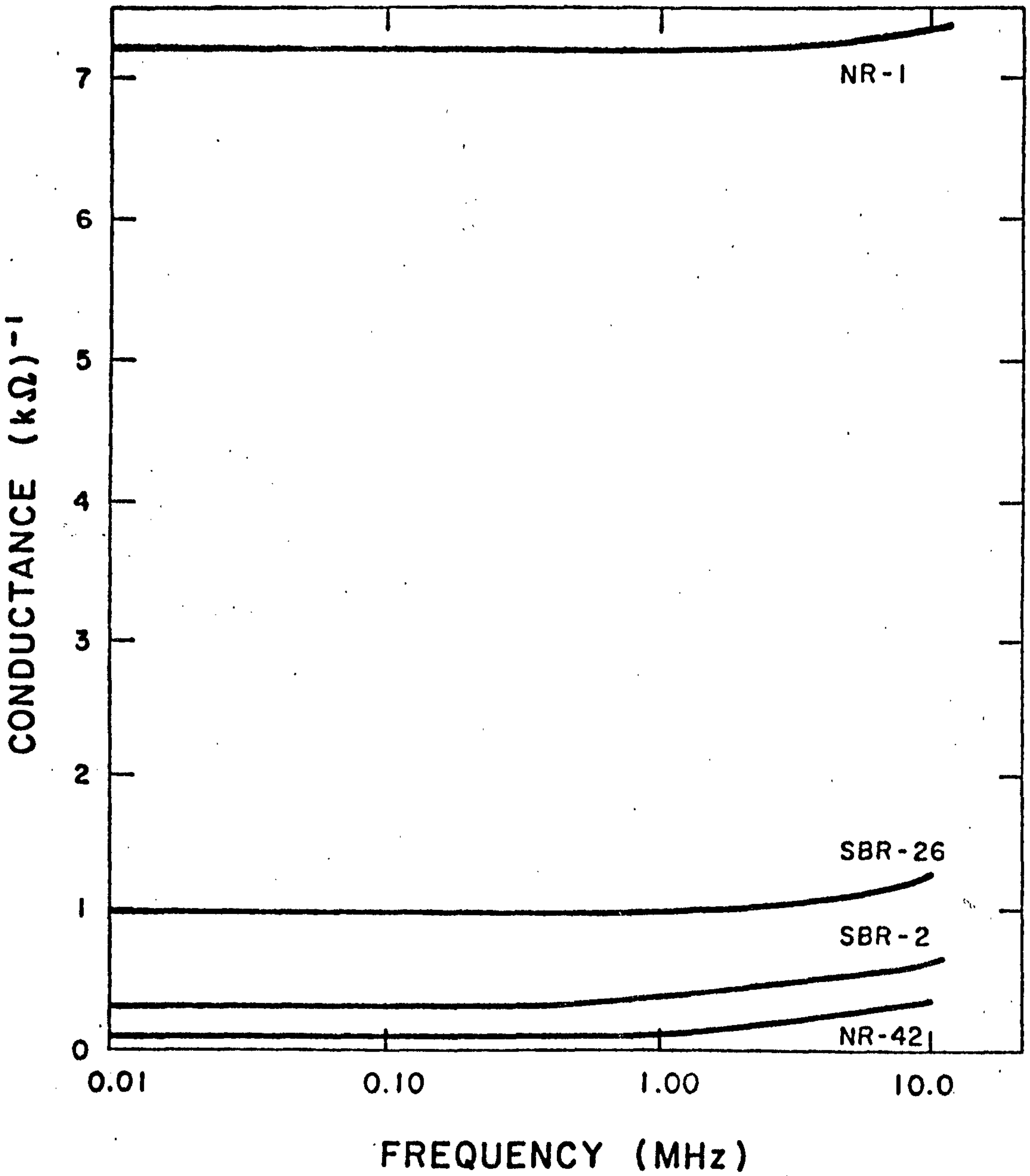

Figure 5-9. Conductance versus frequency

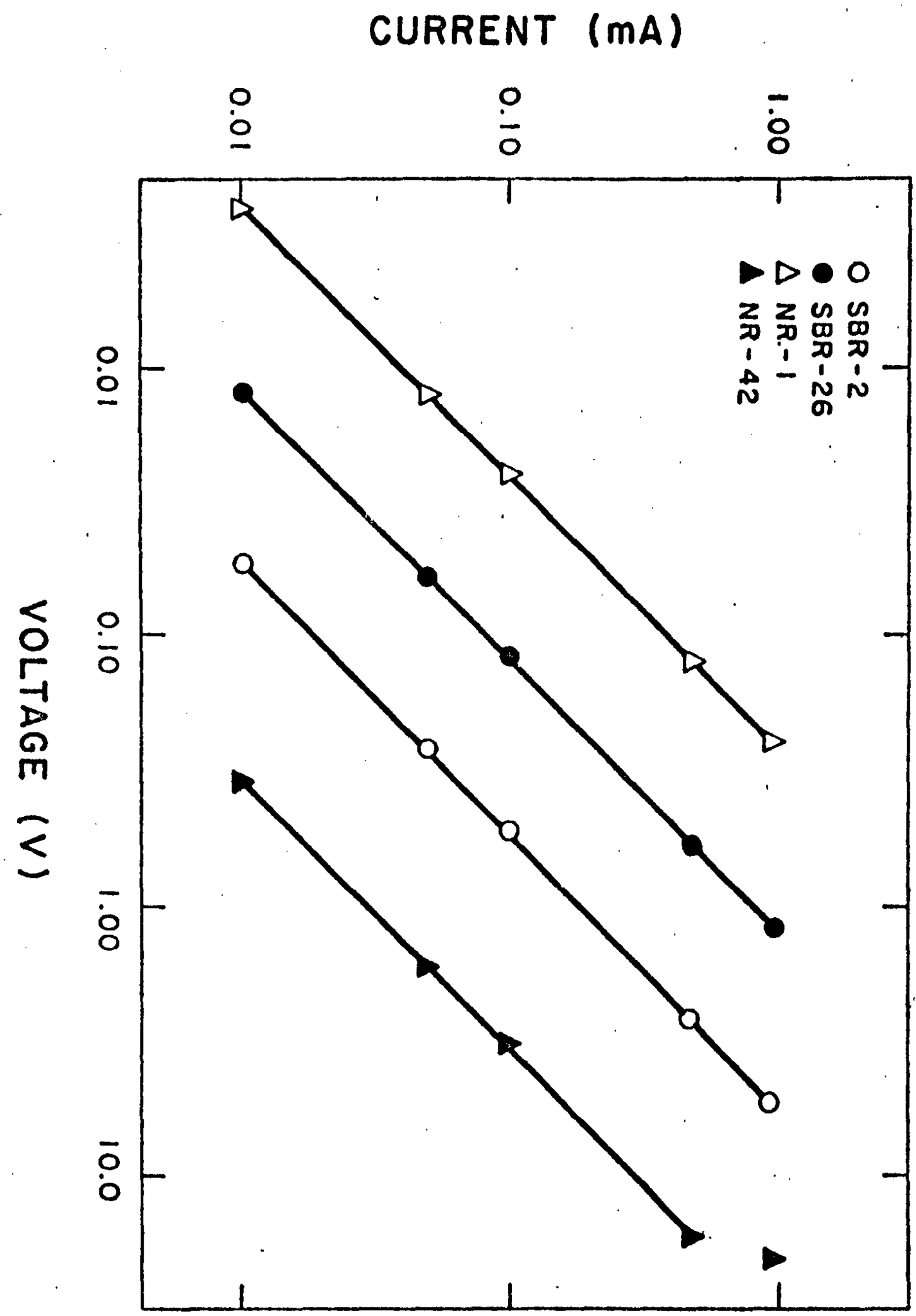

Figure 5-10. Current-voltage characteristics

The amount and type of carbon black and its spatial distribution are the key factors relating to electrical conduction in these materials. Transport between carbon black particles, amount of sulfur [1,2], carbon-elastomer bonds [22], chemical state of black particle surface [19], and other additives also probably affect the conductivity to varying degrees in the unstressed state.

In order to better understand the electrical conduction mechanisms, several additional electrical measurements were made on those samples with known composition.

Relative dielectric constants ε_r were deduced from the relation $C = \varepsilon_r \varepsilon_0 A/d$ where C = capacitance, A = area (1 in.^{2}=6.45 cm^2), d = thickness (0.5in.=1.27cm) and $\varepsilon_0 = 8.85 \times 10^{-14}$ F/cm. (Fringing effects were neglected.) These are shown in Figure 5-8 over the 10 KHz - 10 MHz frequency range (see Figure 5-).

Resistances versus frequency over the same frequency range are shown in Figure 5-9.

Current (I)-voltage(V) measurements for each sample are shown in Figure 5-10. (The 1 mA point for NR-42 is probably high due to localized heating in the sample.)

Only the polarities of the thermoelectric voltage were of interest, in order to deduce the sign of the charge carrier. These voltages were negative for all samples, indicating that the dominant charge carrier is negative.

The mechanisms of charge carrier transport are not clear in the literature. Various types have been reported for different samples made under different conditions. Ionic carriers have been reported for carbon black loaded cis-polybutadiene [14], for polyester polymer-carbon black compositions [20], and for certain PTC materials [17].

Current-voltage behavior has been described in terms of space charge limited currents [12,13], and electric field assisted currents, including Schottky, field emission and tunnelling [1,13-15]. These modes of current are all superlinear in voltage, varying as V^2 for space charge current, and exponentially for the others.

Our currents are ohmic in nature ($I \propto V$), as seen in Figure 5-10. This means that the dependence of conduction on stress is probably not caused by modulation of the carbon-carbon gap (which would apply to tunnelling current). Nor is it caused by pressure modulation of a local electric field (say at the tip of a carbon black aggregate) because this would apply to the field dependent current noted above.

This can be seem more clearly by comparing samples NR-42 and SBR-2 in Figure 5-3. NR-42 resistance increases by a factor of about 30 when pressure is applied, but then relaxes very little. This indicates a slow repair of ruptured bonds and chains that contribute to the conductivity. Therefore, upon release of the pressure, there are few "repaired" bonds to be "reruptured" so no resistance spike is seen ($R_3=R_2$). Only relaxation back toward the unstressed value appears. However, for SBR-2, resistance relaxation under stress does occur, and therefore a resistance spike ($R_3=2.1R_2$) appears when stress is removed, as the repaired bonds rerupture. This accounts for the similar shapes of the left ("loaded") and right ("released") parts of the Figure 5-3 curves (except for the increased resistance at t>70 second, which is analogous to a mechanical "set").

Thus, the increase in resistance when a sample is under stress is proportional to the number of bonds or chains broken. The relaxation rate and subsequent resistance spike when the stress is removed are both proportional to the number of bonds or chains repaired.

Some of these electrical relaxation characteristics can be related directly to certain mechanical properties of the samples. The linear relation between resistance and the logarithm of time is the same as that reported for mechanical creep and for carbon black filled rubber [9,24,25]. In such a material, the relaxation can be described by a relaxation function, $G(\tau)$, that is a rectangular versus log of time.

$$G(\tau)d(\log \tau) = G_0 = \text{constant} \qquad a < \tau < b.$$

Thus, we can describe resistance relaxation as a similar spread in relaxation times, although the exact relaxation mechanisms have not been identified.

The apparent increase in resistance following stress, which does not decay to zero over a time period of one month, is analogous to the mechanical "set" of vulcanized rubber, which has been reported to disappear after 24 hours [25]. Thus, it appears that a certain fraction of the mechanical links that give rise to conductivity are permanently or near-permanently disrupted during stress. As noted in Table 5.5, these can be restored by heating at 70°C.

The near-exponential dependence of the resistance maximum on applied pressure (Figure 5-9) is much stronger than the compressional deflection reported for vulcanized SBR [25], where the strain was proportional to the 2/3 power of pressure. The compressional strains experienced by our samples were not measured. However, they were probably less than 10 percent, corresponding to concurrent resistance increases over an order of magnitude. This illustrates the great sensitivity of the resistance to pressure.

Changes in electrical conductivity and shear modulus aren't expected to occur in exactly the same fashion when a sample is under pressure, even though both are strongly dependent on the carbon black network [9]. That is, these parameters are both high when the carbon black network is intact, and reduced when it is broken down by mechanical stress. In this regard, resistance increase can be correlated with stress softening and resistance relaxation with the mechanical recovery from set. Resistance and resistance relaxation should thus be applicable to monitoring changes that occur in, and during subsequent recovery of, mechanical properties such as these.

Thus, carbon black filled rubber acts as a pressure transducer, with sensitivity and relaxation characteristics depending on the sample type and history.

DC current is attributed to electron flow. Resistance increases resulting from compressional stress are due to a disruption of the electrical conduction network. Resistance relaxation under stress, and the subsequent resistance spike on stress removal, are attributed to a healing of disrupted links, and rerepture of those same links. Relaxation occurs more slowly under stress than after the removal because it is easier for a disrupted link to rebond at its unstressed site.

Such resistance increase-relaxation characteristics are unique for each sample type measured and can be used to define a signature for each type.

We anticipate that such measurements will be directly applicable to tank track rubber for diagnostic and perhaps even screening purposes.

5.3.2. Other Electrical Measurements

The previous section described electrical measurements on samples with vulcanized brass plates supplied by Ft. Belvoir. Additional electrical measurements were made somewhat earlier in the program on samples cut from track pads.

An example is shown in Figure 5-11, where current (I) is plotted as a function of voltage (V) for six samples, as indicated in the figure. These samples were cut from new pads, and pads with 1500 mile service. They were made by three vendors, as identified in the Addendum.) Electrical resistivity values (in Ω-cm) are indicated for each sample,

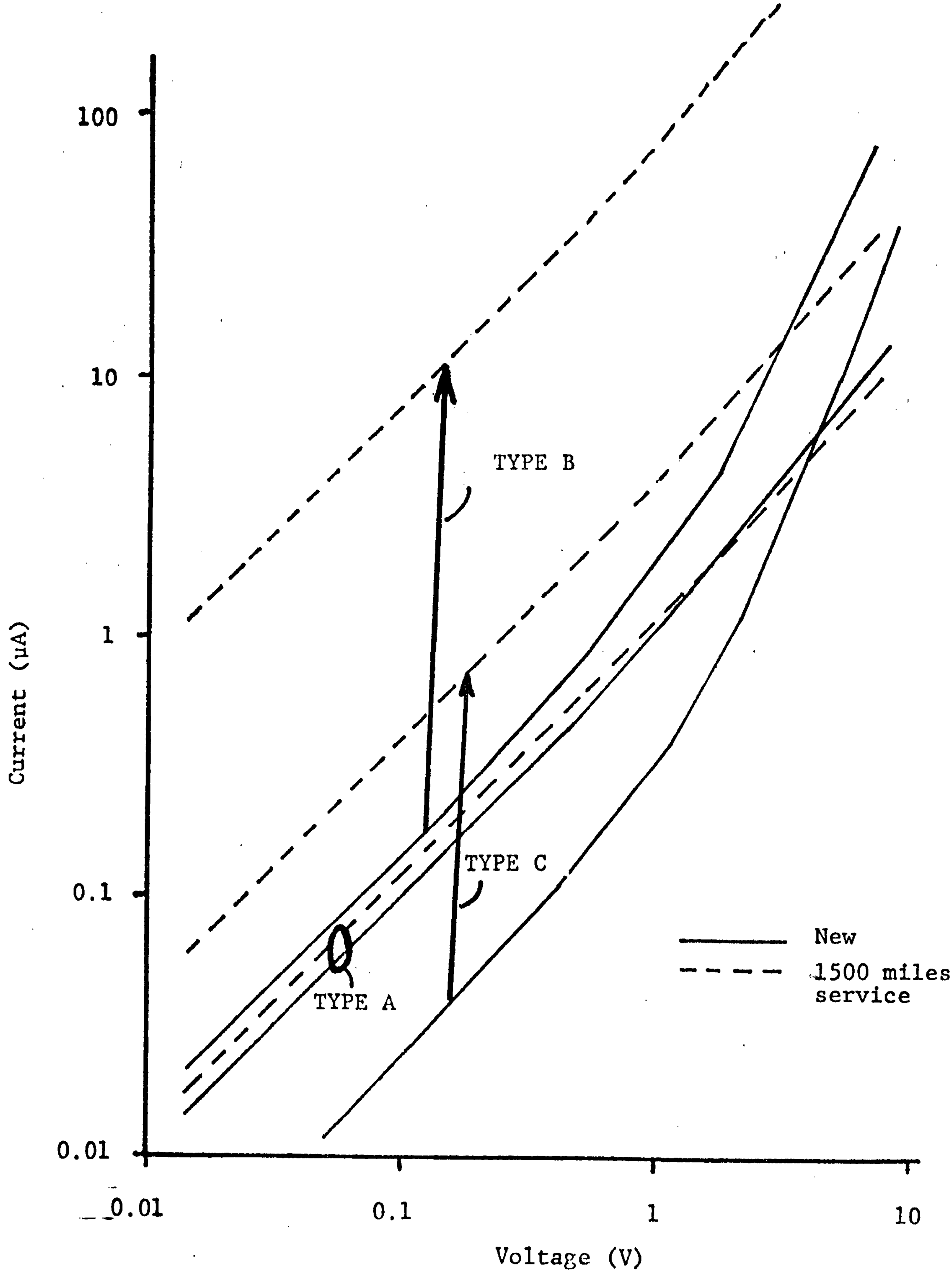

Figure 5-11. Current-voltage characteristics for samples cut from six pads (Identified in Addendum.)

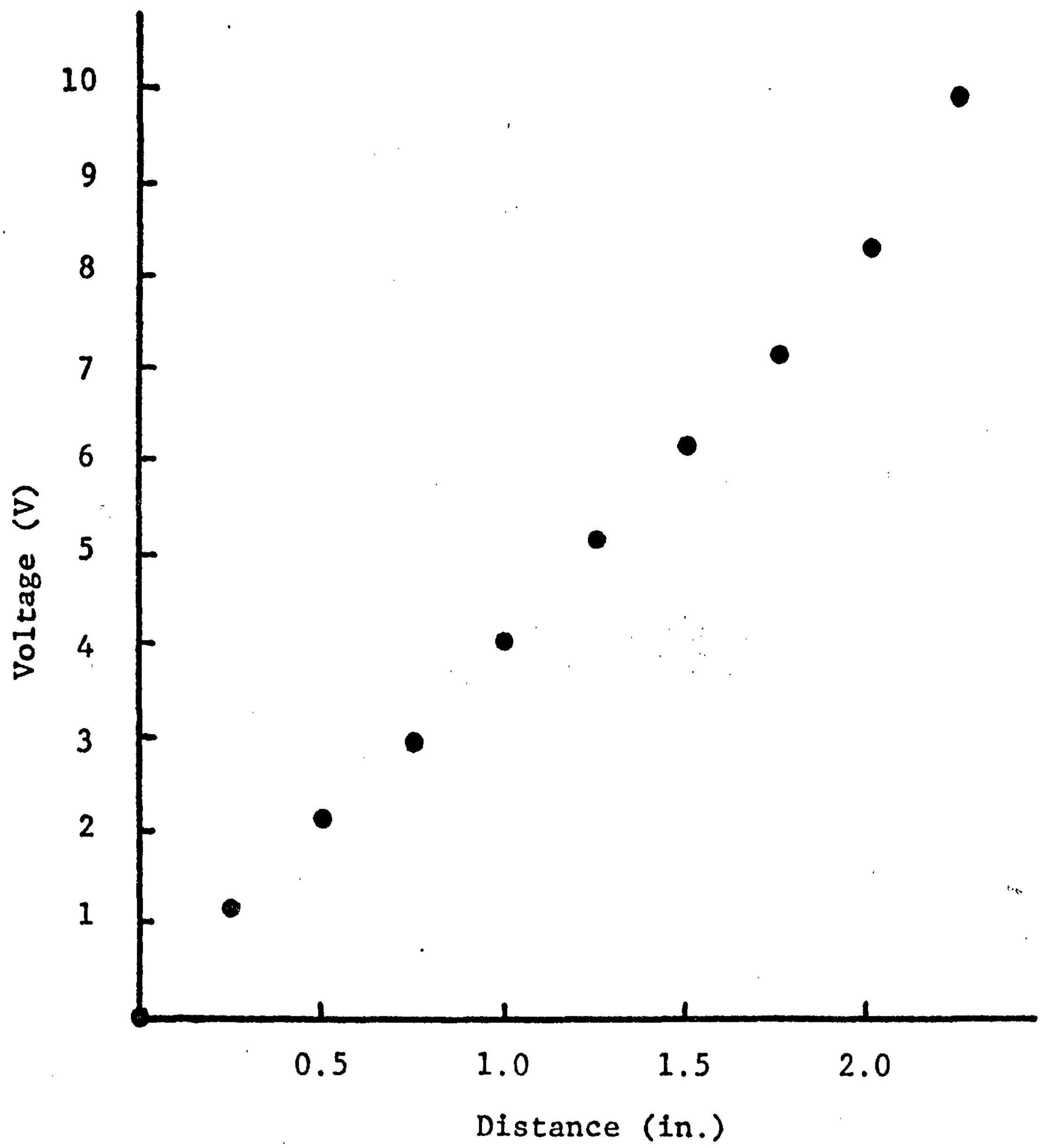

Figure 5-12. Voltage versus distance along a strip cut from Type A pad (Aquadag contacts)

corresponding to the linear region of the I-V curve. The Type B pad resistance decreased by about two orders of magnitude, the Type C sample decreased by about one order, and the Type A sample remained relatively unchanged following 1,500 miles of wear. It appears that the Type A pad should probably exhibit the better wear characteristics, assuming that its mechanical properties can be correlated with the resistance. This correlation should be investigated further.

The rising slope of the I-V curves for the new Type B and Type C samples is not understood, but may be in part to nonohmic electrical contacts. (The electrical contact problem will be discussed shortly.)

Figure 5-11 indicates the following:

- Resistances vary by an order of magnitude for the new samples. Probably an even wider variation would be seen if a larger number of samples were measured.

- 1,500 miles of wear results in two orders of magnitude change in one type (Type B) and almost no change in another (Type A).

The contact resistance problem made some of the earlier resistance measurements questionable since it was not known what fraction of the resistance was due to the contacts. (This was discussed in several of the early monthly reports.)

If contact resistance exists, it will appear as a voltage drop at the contact when a current is passed through the sample. Several contacting techniques were tried; the main ones were the attachment of wires to the ends of approximately 2 inches long rubber strips using silver epoxy, Electrodag, or Aquadag. The contact resistance was not completely eliminated in any case, but was lowest for Aquadag contacts. This is illustrated in Figure 5-12 for a rubber strip cut from a Type A pad. A small DC current was passed through the sample, and the voltage drop was probed along the length of the sample. The slightly sharper voltage jumps seen near the ends are due to a fairly small contact resistance contribution. Thus, even though contact resistance has not been eliminated, it can be reduced to a level no larger than about 10 percent of the sample, for contacts applied after vulcanization. We assume, according the reports of Norman [21], that an even further reduction (and--in fact the only case where contact resistance is reduced to zero) is when brass contacts are attached during vulcanization. This was the case for the Ft. Belvoir samples discussed earlier.

A frequency dependent impedance model for contact resistance is discussed in the appendix of this report. From this model and the above measurements, several summary comments should be made relating to contact resistance:

- It is severely detrimental for Ag epoxy or Electrodag contacts but much less so for Aquadag;
- It can be modelled using frequency dependent impedance measurements;
- It is not of major concern for our most important measurement, resistance relaxation, for several reasons: a) bulk rubber resistance increases drastically when under compressive stress, reducing the importance of contact resistance; b) if brass plates are not vulcanized directly onto the samples, contacts can be placed on the ends and pressure can be applied in the center, with the resulting large resistance increase in the center swamping contact resistance; c) as noted in the Recommendations section of this report, pressure-resistance relaxation tests should be conducted where electrical contact is made by pressure along (i.e., no epoxies or in-situ brass plates). This would ease the requirements for attached contacts (and hence sample preparation) and would be more conducive to a rapid testing/screening of a large number of samples.

ACKNOWLEDGEMENTS

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ADDENDUM

Identification of manufacturers of tank track pads measured in this program.

Designation in Report	Manufacturer
Type A	Firestone
Type B	Standard Products
Type C	Monarch

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APPENDIX

We have verified, at least for a certain set of samples, that contact resistance is not as severe a problem above frequencies of 50-100 KHz, even if it is severe at lower frequencies. This is seen by representing the contacted sample as a lumped conductance-capacitance model as shown in Figure A-1.

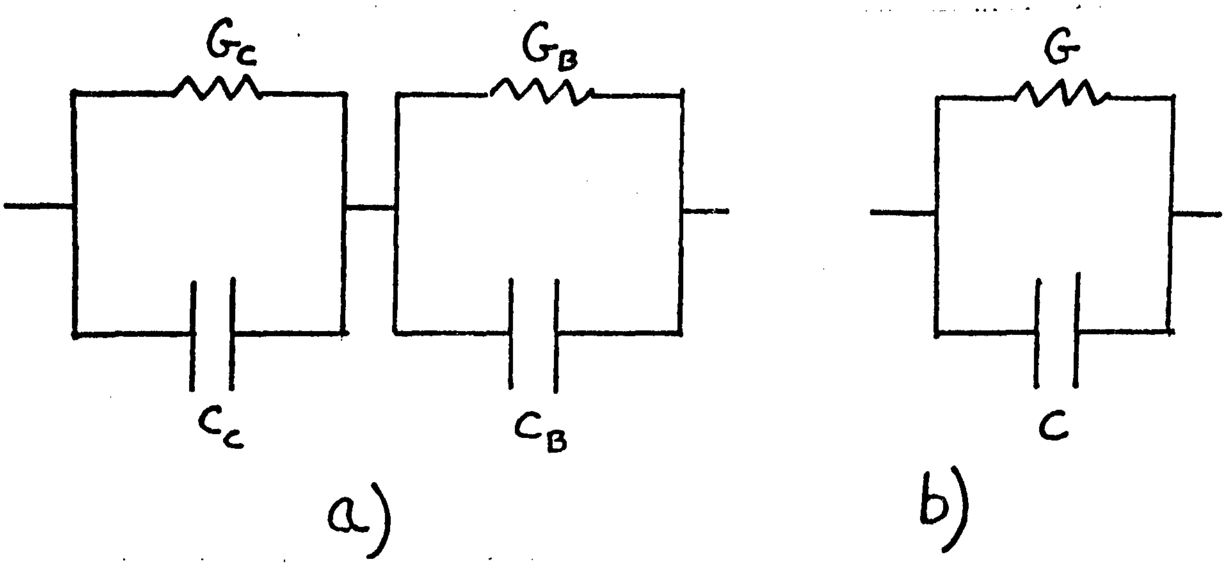

Figure A-1. a) Lumped model for rubber and contacts; b) Parallel combination read out on the Impedance Analyzer

In this model, G_c and C_c are the contact conductance (inverse of resistance) and capacitance respectively. G_B and C_B are the bulk rubber parameters. The Impedance Analyzer reads out only net values G and C (Figure A-1(b). The network transformation equations at frequency ω are

$$C = \frac{(C_cG_B+C_BG_c)(G_B+G_c)-(G_cG_B-\omega^2C_cC_B)(C_B+C_c)}{(G_B+G_c)^2+\omega^2(C_B+C_c)^2}$$

$$G = \frac{(G_cG_B-\omega^2C_cC_B)(G_B+G_c)+\omega^2(C_cG_B+C_BG_c)(C_B+C_c)}{(G_B+G_c)^2+\omega^2(C_BC_c)^2}$$

At low frequencies these can be approximated by

$$C = \frac{C_B + (G_B/G_C)^2 C_C}{(1 + G_B/G_C)^2} \qquad G = \frac{G_C\ G_B}{G_C + G_B}$$

and at high frequencies by

$$C = \frac{C_C\ C_B}{C_C + C_B} \qquad G = \frac{C_C^2 G_B + C_B^2 G_C}{(C_B + C_C)^2}$$

These limiting cases indicate that if contact resistance is large (G_C is small) the net (measured) capacitance will be higher at low frequencies than with zero contact resistance. At high frequencies, measured capacitance is independent of contact resistance because the capacitors shunt the resistors.

This model was verified quantitatively by measuring two samples with differently prepared contacts. One sample (C4) had silver epoxy contacts, the other (C3) had Aquadag contacts placed on faces that were slightly charged to raise the carbon content. Capacitances versus frequency for these two samples is shown in Figure A-2a. Two additional samples of different thickness (sample A1 at 1mm and A3 at 6mm) were also prepared using silver epoxy on the as-cut faces. Their capacitance values are shown in Figure A-2(b).

In Figure A-2, the trends predicted by the model are verified. In Figure 14a, sample C3 (with lower contact resistance) has lower capacitance at low frequencies. Above about 100 KHz, the capacitance values becomes nearly identical, as predicted.

In Figure A-3(b), for samples of different thickness which have the same type of contacts (high resistance) the capacitance values are nearly identical at lower frequencies, where the capacitance is governed almost entirely by the contact. At higher frequencies, the thinner sample has significantly higher capacitance as expected, since capacitance is inversely proportional to thickness.

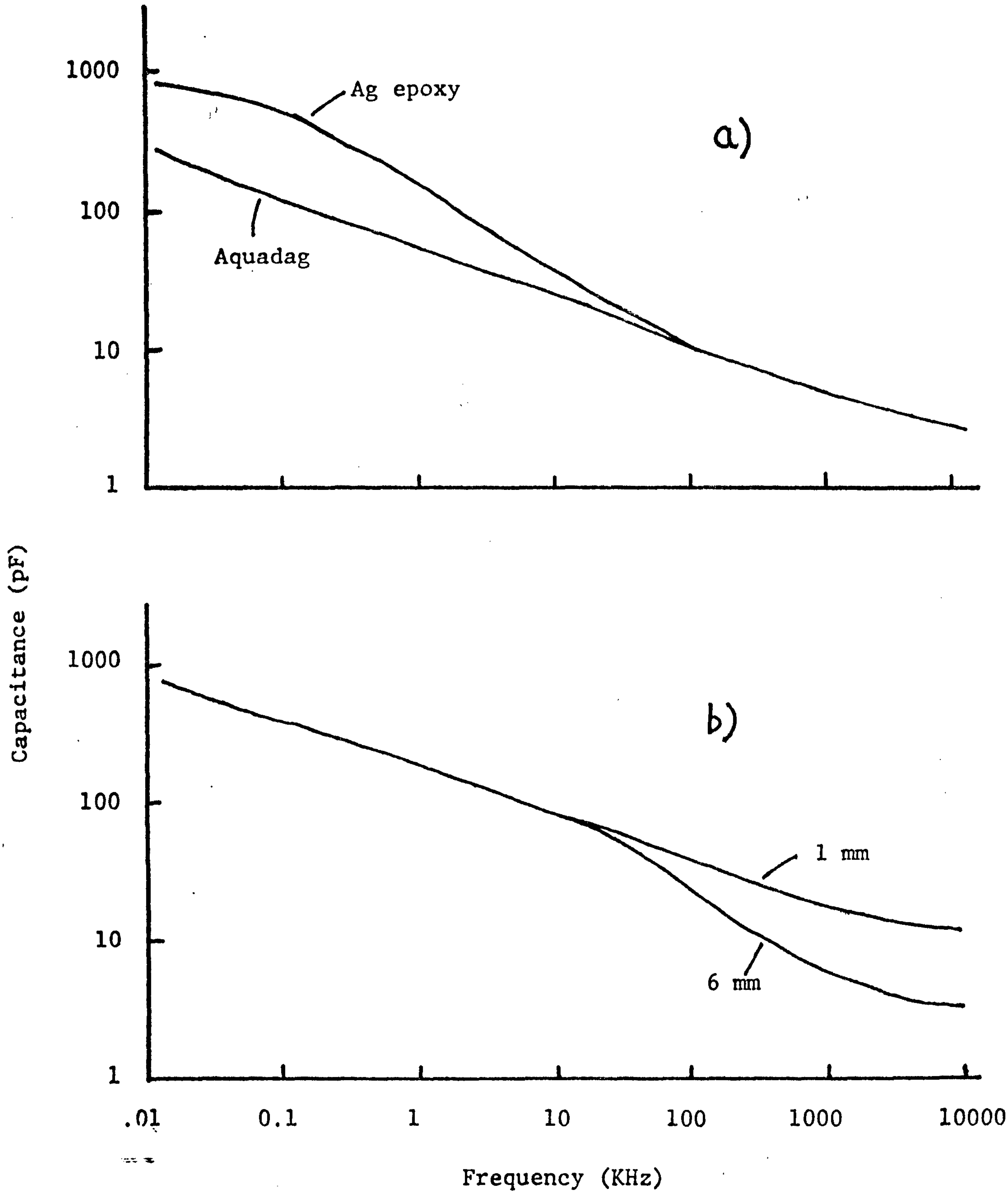

Figure A-2. Capacitance versus frequency for samples with a) different contacts (same thickness); b) different thickness (same contacts)

From the limiting low and high frequency values of Figure A-2(a) (and from conductance measurements which were also taken), sample C4 can be represented as shown in Figure A-3.

For this sample, the contact resistance is nearly as large as the bulk rubber resistance. The contact capacitance is much larger than that of the bulk rubber, which is not so detrimental as it appears, since $C = \frac{C_c\, C_B}{C_c + C_B}$ C_B if $C_c >> C_B$.

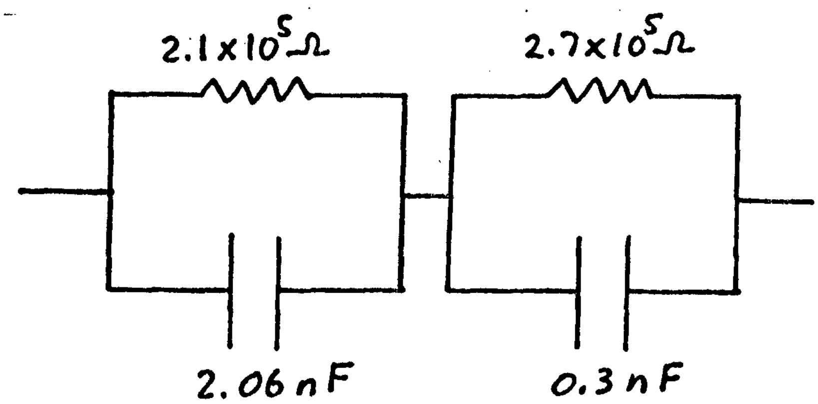

Figure A-3. Model for sample C4 derived from C and G measurements and the above equations.

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