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APPLICATIONS STUDY OF ELECTROADHESIVE DEVICES

by Richard P. Krape

Prepared by
CHRYSLER CORPORATION SPACE DIVISION
New Orleans, La.
for Langley Research Center

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Prepared under Contract No. NAS 1-7303 by
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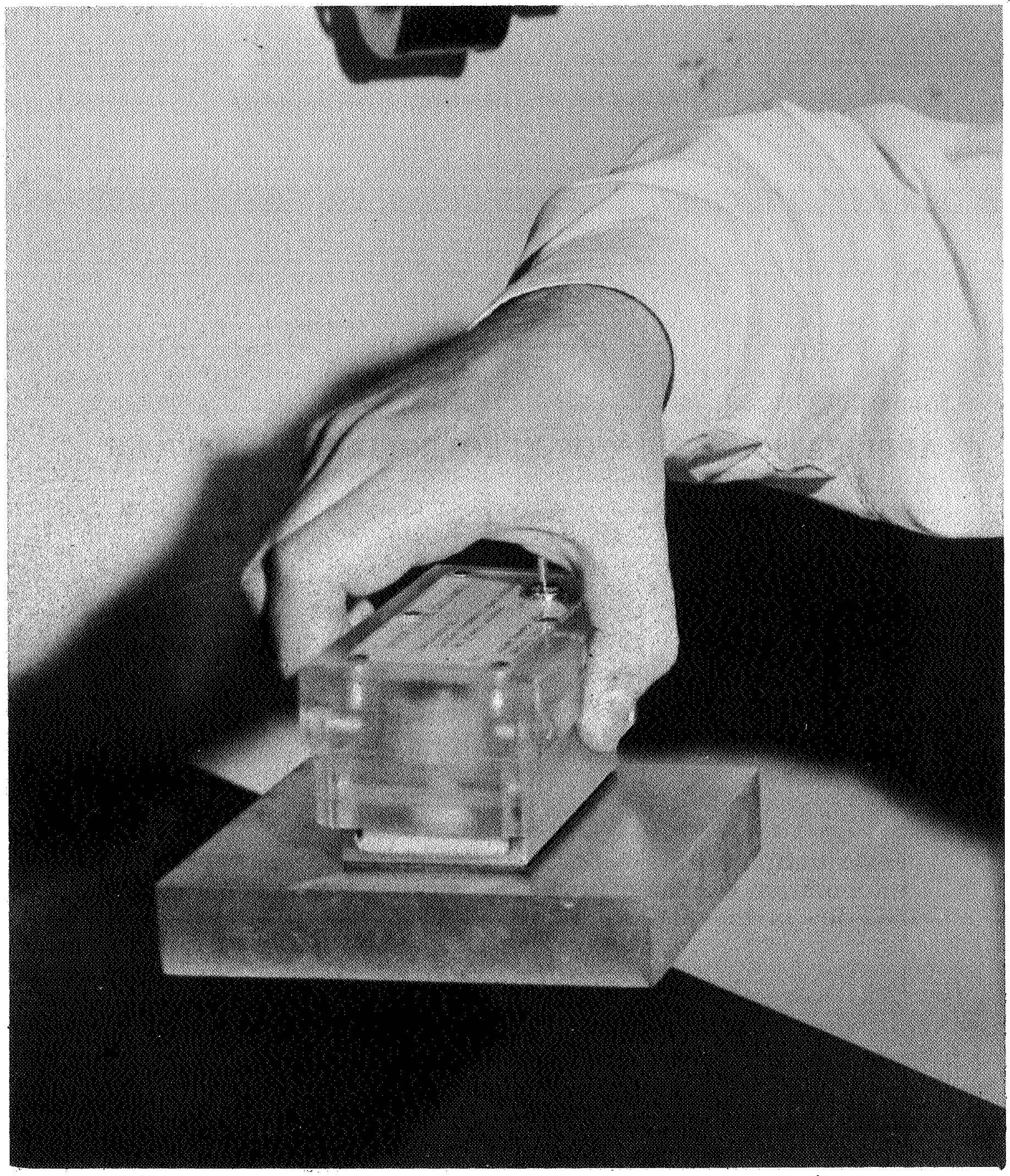

FRONTISPIECE - Hand Model Electroadhesor Shown Lifting a 3-lb. Aluminum Plate

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APPLICATIONS STUDY OF ELECTROADHESIVE DEVICES

By Richard P. Krape *

SUMMARY

Chrysler Corporation Space Division is engaged in development of prototype equipment utilizing the principle of electrostatic adhesion. This work is a logical extension of Chrysler's basic research program dealing with electrostatic principles and phenomena and recognizes the growing awareness of the potential usefulness of electroadhesor equipment in the aerospace environment.

Electroadhesors are devices which utilize electrostatic "surface effect" to produce attractive forces between two objects. In Figure 1, the basic components of a typical contact-type device are identified as (1) a D. C. power source, (2) a control switch, (3) two conductive electrodes, and (4) an insulating material having special dielectric and physical properties.

The phenomenon of electroadhesion occurs when a relatively high voltage differential exists between the charged electrodes and the adhering object while at the same time a very small electrical current is passed from one to the other through the insulator. The high charge density within the electrodes causes the formation of image charges (of opposite polarity) on the surface of the adhering material, and the attractive force between the charges of opposite sign effects a bond.

Under NASA Contract NAS 1-7303 (Langley Research Center), Chrysler Space Division was authorized to conduct a three-phase research and development program involving the following sequential activities:

Phase I	Analysis of Electroadhesive Phenomenon
Phase II	Study of Techniques for Application of the Electroadhesive Principle
Phase III	Test and Evaluation

This report presents the results of work performed under this contract.

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* Phase I theoretical treatise and power supply studies were authored by Dr. D.N. Veith, Research Projects Staff, who acted as scientific consultant for these work efforts.

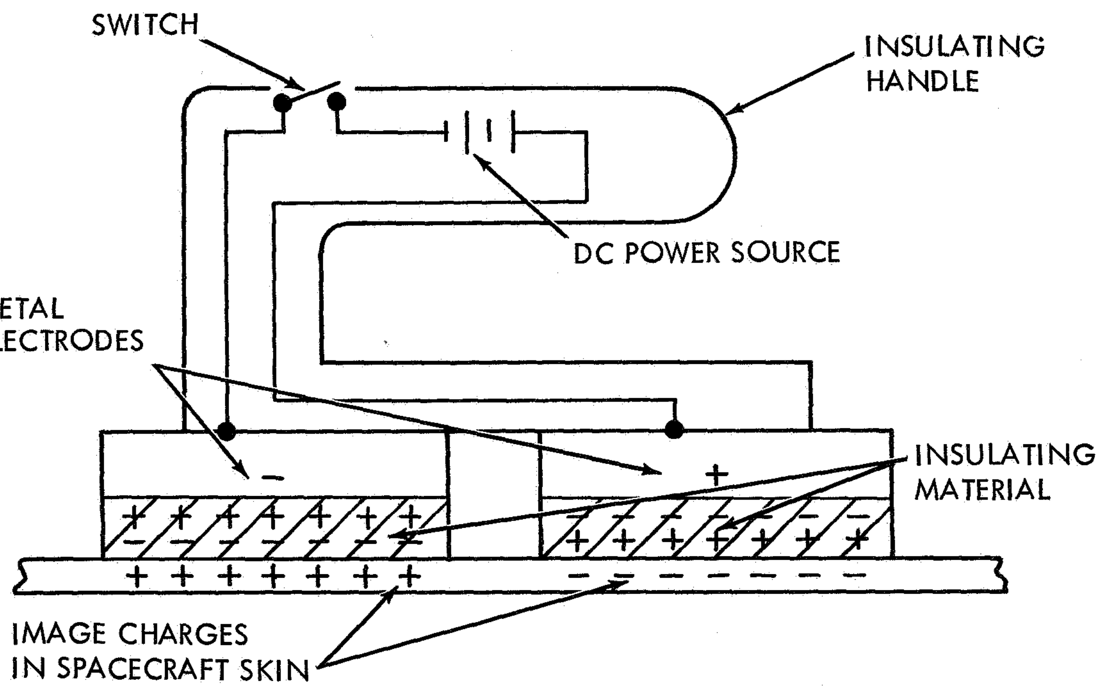


Figure 1 - Two-Pole Electroadhesor

INTRODUCTION

During the recently completed Gemini space flights, considerable attention was given to the problem of astronaut orientation and stability in the zero-gravity environment. From EVA and related ground experiments, the problems associated with human locomotion in the space environment have been well established. These problems have created interest within the engineering community for development of methods and devices which will aid future astronauts in the performance of flight experiments.

Chrysler Space Division engineering personnel, engaged in basic research work on electrostatics, initiated studies to determine the feasibility of using "electroadhesion" as a means for aiding astronauts in the performance of on-board and EVA experiments. These studies eventually led to work performed under this contract and the establishment of the following related electrostatic development objectives:

Spacecraft Electroadhesor Worktable

Spacecraft Electrostatic Windshield Wipers

Electrostatic Object Retrieval Devices

Spacecraft Electrostatic Docking Assist System

Related Electroadhesor Equipment

Under NASA Contract NAS 1-7303, Chrysler engaged in a concerted effort to define electroadhesion, investigate key environmental and operational parameters affecting its performance, study techniques for aerospace application, and to develop prototype models useful for further test and evaluation. This work constituted a meaningful step toward advancing electroadhesor technology, and in particular, the establishment of experimental data useful in assessing factors or conditions which either promote or reduce electroadhesive performance.

Phase I, Analysis of Electroadhesive Phenomenon, consisted of mathematical analysis and experimental research necessary to define electroadhesion and the factors that control or affect the electroadhesion phenomenon. The work was organized under a series of tasks, each investigating a particular parameter and its correlation with other parameters. The parameters analyzed were:

1. Resistivity of the electroadhesive coating

2. Thickness of the coating

3. Current density at the adhering interface

4. Effects of surface condition (roughness, etc.)

5. Polarity of applied voltage

6. Environment

    a. Air at sea level
    b. Orbital vacuum
    c. Gases at spacecraft cabin pressures

        (1) Pure O_2
        (2) Oxygen and nitrogen mixtures
        (3) Oxygen-Helium mixtures

7. Temperature

8. Time (build-up and die-out of force)

9. Dependence on chemical identity of adhering materials

Under Phase II, Study of Techniques for Application of the Electroadhesive Principle, studies were made to investigate approaches to the design of electroadhesor devices and to determine what could be accomplished with the application of the electroadhesive principle and the ultimate uses of devices operating on this principle. The work involved investigation of five types of electroadhesor mountings, a study of power supply requirements, and techniques for controlling electroadhesor operation.

Under Phase III, Test and Evaluation, three prototype electroadhesor models were designed, fabricated, and tested to establish preliminary operational data. Prototype evaluation included tests for static pull force, skid force, and battery longevity.

Chrysler, in presenting the results of the above noted activity, recognizes the research and developmental nature of the work and the need for assessing reported information and data from this standpoint. In those areas where results of work performed warrant firm conclusions, such conclusions are presented. Conversely, where results of work performed did not warrant similar treatment, or where specific tests produced unexpected results (and led to requirements for further investigations outside the scope of this contract), conclusions are not firmly stated. In these cases, engineering interpretation of the observed condition is presented as a matter of interest or clarification.

PHASE I - ANALYSIS OF ELECTROADHESIVE PHENOMENON

Any personal observation of electroadhesion invites curiosity as to the mechanism(s) which produce attractive forces and the influence of variables in promoting or reducing the electroadhesive effect. A standard procedure for investigating phenomena of this type normally involves two sequential steps: (1) theoretical analysis and mathematical computation and (2) physical experimentation in support of the theoretical analysis.

Analysis. - The force on a charged conductor in an electric field is given by the expression (Reference 1-page 86) (in rationalized M.K.S. Units)

$$F_p = \int_S \frac{\vec{D}\ \vec{E}}{2}\ \hat{p}\bullet\hat{n}\ d\ S \tag{1}$$

where F_p is the force in the direction of the unit vector $\hat{p}$, $\vec{D}$ is the electric displacement, $\vec{E}$ is the electric field intensity, $\hat{n}$ is a unit vector normal to the surface, and the integration is carried out over the surface area, S .

In the case of two plane parallel charged conductors, the field will be uniform and normal to the surfaces, neglecting fringe effects at the edges. Therefore, the force will be normal to the surfaces, and $\hat{p}\bullet\hat{n} = 1$. It is reasonable to assume in most cases that the medium is isotropic, and in this case

$$\vec{D} = \epsilon\vec{E} \tag{2}$$

where ϵ is the capacivity of the medium. Therefore,

$$\vec{D}\bullet\vec{E} = \epsilon E^2 \tag{3}$$

Equation (1) then reduces to

$$F = \frac{\epsilon E^2}{2} \int_S d\ S \tag{4}$$

or,

$$\frac{F}{A} = \frac{\epsilon E^2}{2} \tag{5}$$

where A is the area of one conducting surface.

In the case of plane, parallel conductors,

$$E = \frac{V}{d} \tag{6}$$

where V is the potential difference between the plates, and d is their separation.

Finally, then

$$\frac{F}{A} = \frac{\epsilon V^2}{2d^2} \tag{7}$$

The force, then, between two given conductors with a given spacing increases with the square of the voltage applied between them. This voltage cannot be increased without limit, however, because the dielectric medium between the plates breaks down and discharge occurs. Under ordinary circumstances this discharge occurs at a voltage too low for the force to be large. This is the reason that electrostatic forces are generally considered to be rather weak. It is also generally thought that a given dielectric has a value of dielectric strength which is more-or-less independent of its thickness. That is, there is a maximum field strength which the material can withstand without breaking down. For this reason, there would seem to be nothing gained by reducing the thickness of the dielectric material, despite the fact that Equation 7 shows that the force increases inversely as the square of the plate separation. Following this reasoning, the breakdown voltage decreases with the spacing, and no increase in force is gained.

This reasoning, at least for the case of gaseous dielectrics, is not completely correct. The breakdown voltage is dependent not only on the nature of the gas and on the electrode spacing, but on the gas pressure as well. In fact the breakdown voltage, V_b depends on the pressure, P, and electrode separation only through their product Pd, or $V_b = f\ (Pd)$. This fact is known as Paschen's Law, (Reference 2-page 86). The function, f, cannot easily be expressed analytically, but can best be depicted graphically. Such a graph is given in Figure 2. It can be noted in this figure that the breakdown voltage has a minimum value for some value of the product Pd. At other values of Pd, V_b is greater, whether Pd has been increased or decreased. This can be explained by a consideration of the nature of the electric discharge. The discharge is a cascade of events. In a volume of gas there will occur a few free charges (ions and electrons) due to more-or-less random ionizing events, such as cosmic ray interactions and photoelectric effect phenomena. These charged particles will be accelerated by the field in the gap until they collide with a gas atom. The average distance traversed before such a collision is the mean free path, and it is dependent on the nature of the gas and its pressure. If the charged particle has acquired sufficient energy from the field before the collision takes place, the atom will be ionized, creating more charge carriers, and

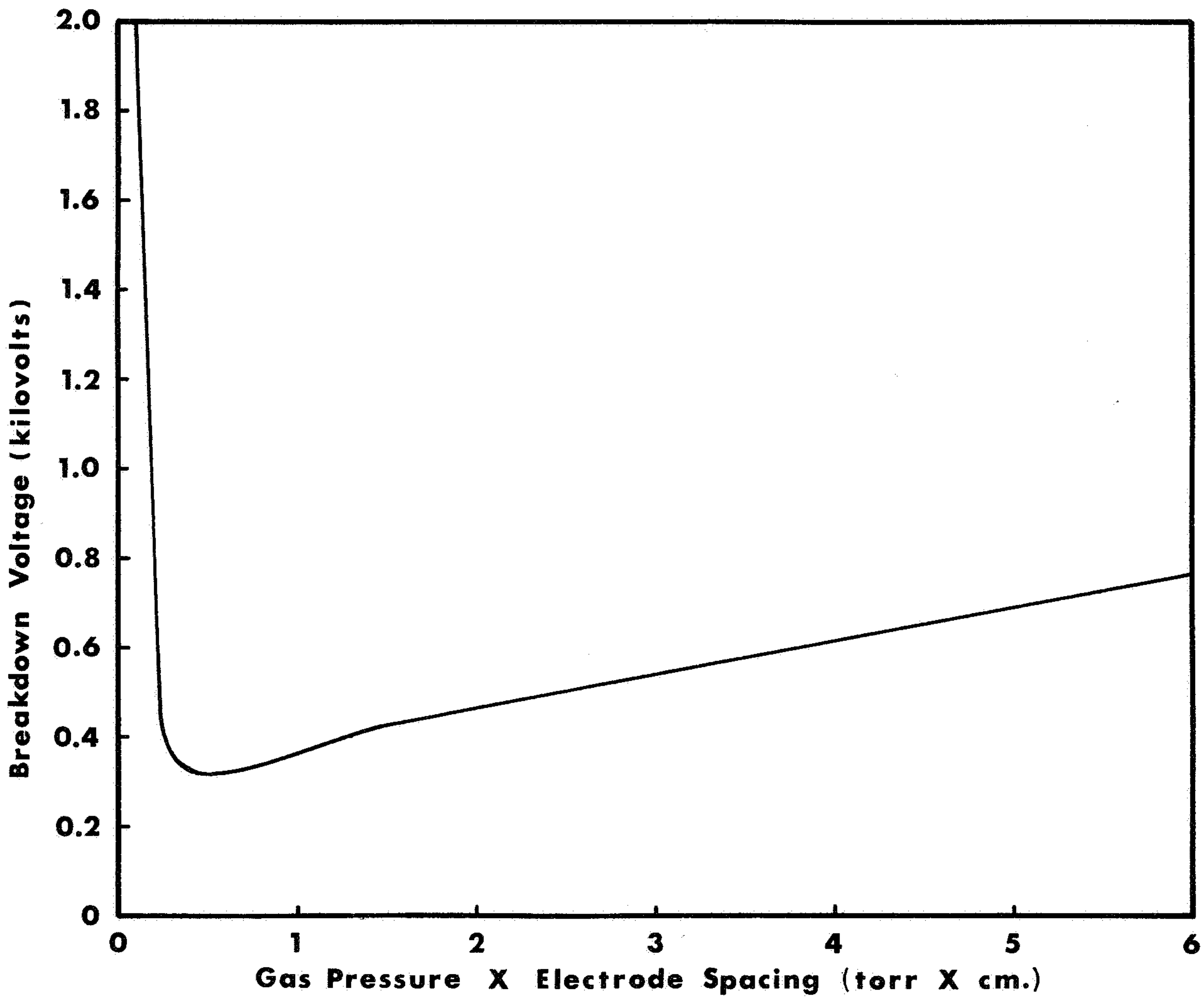


Figure 2 - Breakdown Voltage vs. Gas Pressure-Electrode Spacing Product in Air, Illustrating Paschen's Law

the process repeats itself, resulting in a discharge. On the other hand, if the collision takes place before the charged particle has acquired sufficient energy, ionization will not occur, and the particle's energy will simply be absorbed.

The maximum attractive force which can be developed between two electrodes is limited by how strong an electric field can be sustained without having breakdown. Breakdown involves cascades of ions, each ion developing enough energy in one path to create another ion pair, and thus causing multiplication of ions without limit and complete short-circuiting of the gap. For ordinary values of Pd, the field strength at which this occurs depends on the gas pressure alone, since pressure determines the mean free path. In air at sea level, for example, the maximum electric field is around 30,000 volts per centimeter. All this assumes that there will be a sufficient number of mean free paths between electrodes for unlimited multiplication of ions to occur. If the pressure or spacing is reduced sufficiently, a region is arrived at where the number of mean free paths between electrodes is limited, and a higher multiplication rate, requiring a stronger field, is necessary to maintain a short-circuiting discharge. If this point is reached by reducing the spacing, the potential required to produce a stronger field is also reduced.

When two surfaces of ordinary smoothness (not optically flat) are brought together, ohmic contact will occur at isolated points and over the entire balance of the area; the two surfaces will be separated by a film of air (or vacuum). If both surfaces are good conductors, these points of contact will short out the two surfaces and no potential difference can be maintained. However, if at least one of the surfaces is a poor conductor, charges will tend to build up on opposite sides of the film faster than they drain off to points of contact. If the film is then so thin that there is no room for ion cascades, there will be very little conduction across it, and a large concentration of surface charge will build up. This, in combination with the close spacing, will produce the very high electric fields which account for the phenomenon of electroadhesion. Obviously there is some optimum electrical resistance; however, the materials must be conductive enough to allow the charges to reach the surface, but resistive enough to prevent them from migrating immediately to points of contact.

Until this point, it has been assumed that plane, parallel electrodes were being considered, and that the voltage was applied between them. For most applications, however, this is not practical. For example, if a tether device for attachment to the exterior of a spacecraft hull were desired, this system would require that one output terminal of the power supply be connected to the hull, which is obviously undesirable. To overcome this difficulty, the two-pole electroadhesor was devised (see Figure 1). In this device, there are two co-planar electrodes and the voltage is applied between them, causing one electrode to be positively charged and the other negatively charged. When this pair of electrodes is placed near a plane conducting body, image charges are induced in that body, with positive image charges opposite the negative electrode and vice-versa. There is then an attractive force between the charges on each electrode and the image charges. Therefore, the attractive force is produced without electrical connection to the spacecraft hull. The insulating material may be applied to either the hull or the electrodes. In fact, it need not be attached to either, but may simply be sandwiched between the hull and the electrodes. This latter fact is particularly useful for testing materials.

It is to be expected that, if a gas is present between the electrodes of an electroadhesive device (either single or two pole), the force developed will be dependent on the gas pressure. This is true because the current carried by the gas tends to neutralize the charge on the plates, and the current is pressure dependent. Some typical curves which verify these predictions are presented in Figure 3. These curves show that the electroadhesive force increases with applied voltage until a plateau is reached, and that the lower the ambient air pressure, the higher the plateau. They also show that, for a given applied voltage, the lower the ambient air pressure the lower the current.

According to Loeb (Reference 3, page 86), the current due to a uniform electric field in a gas is given by

$$i = n_o q_o e^{\alpha d} \tag{8}$$

where n_o is the density of free electrons at the grounded plate, q_o is the electronic charge and α is a parameter of the gas called the first Townsend coefficient. (This expression is correct only for voltages below the breakdown values). The first Townsend coefficient, α, represents the number of new electrons and positive ions created by ionization by a single electron traversing 1 cm of path in the field in the gas. It depends on a number of factors, including the nature of the gas, the gas pressure, and the electric field strength. A typical curve for air, illustrating this variation is given in Figure 4. Since α/P and E/P are plotted in this single curve, it actually represents a family of curves of α vs E for different pressures. It then shows at once the variation of α with both E and P.

This information can be presented in a slightly different form, which is more useful in the present context. Again according to Loeb

$$i = n_o q_o e^{\eta V} \tag{9}$$

where V is the applied voltage and η is defined to be equal to α/E. Equation 9 then gives the nature of the dependence of current on applied voltage.

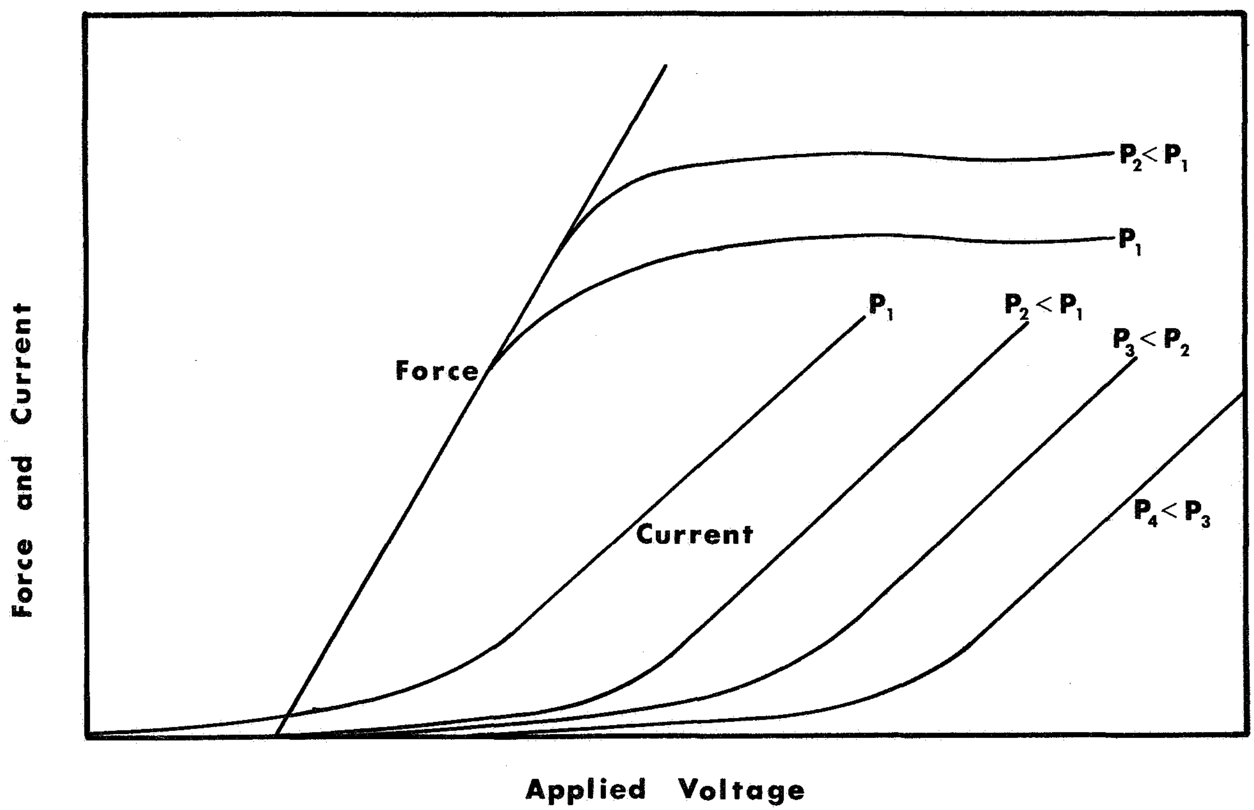


Figure 3 - Typical Force and Current Characteristics of Electroadhesor

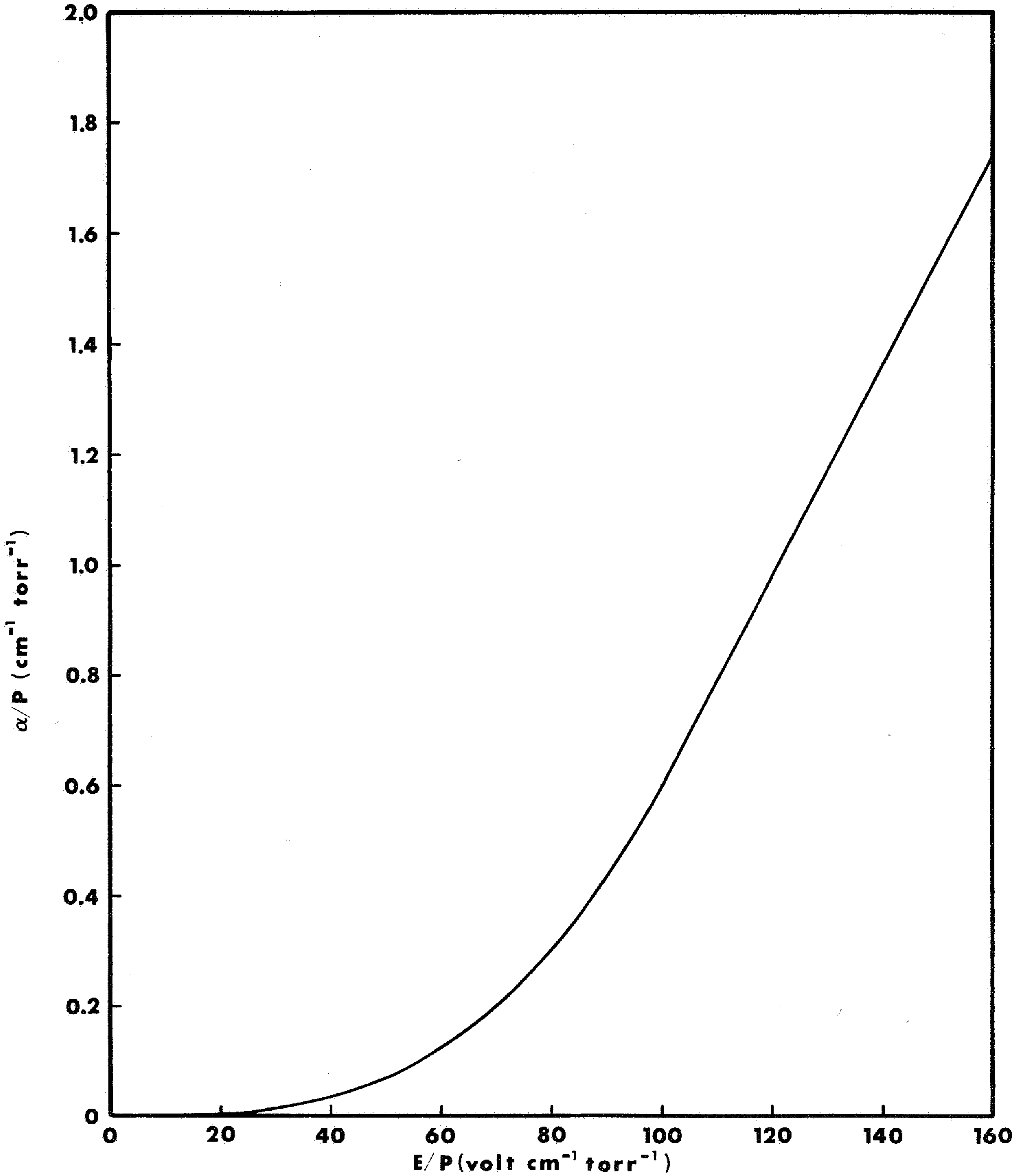


Figure 4. α/P VS E/P For Air (LOEB, P. 653)

An approximate equation can be written relating η to pressure and field intensity:

$$\eta = \frac{A}{E} P e^{-B P/E} \tag{10}$$

where A and B are constants for the gas in use.

The curves of Figure 3 can now be studied again in view of Equations (8), (9), (10). Equation (7) predicts that the attractive force will increase with the square of the applied voltage, but the curves of Figure 3 do not verify this. In fact, the force increases approximately linearly with applied voltage until the plateau is reached. However, Equation (7) was derived for a purely static case, neglecting any loss of charge by current flow. Equation (9) shows that the current should be increasing exponentially with the applied voltage. Therefore, the experimental result is not surprising and the plateau seems to arise simply because after the voltage has reached a certain point, further increases serve only to increase the current without increasing the charge on the plates, and therefore do not increase the attractive force. The curves of Figure 3 do show that the current increases with the voltage, but not as rapidly as Equation 9 would indicate. This result is not surprising either, since the geometry employed is not really parallel plates, down to a microscopic scale. As long as the plate separation is appreciable, the parallel plate approximation is a good one, but when the plates are in contact, since they are not highly polished, the approximation fails.

It can be noted in Figure 3 that in each case, the beginning of the plateau in the force curve occurs at approximately the same voltage as the upward break in the current curve. It was at first thought that this fact would be useful in predicting the force in various gases at different pressures, by computing the current curve. Taking the natural logarithm of both sides of Equation 10

$$\ln \eta = \ln \frac{AP}{E} - \frac{BP}{E} \tag{11}$$

In this case it can be assumed that P/E is small, since E is very large. If A and B are of comparable magnitude, then

$$\ln \eta \approx \ln \frac{AP}{E}$$

or

$$\eta \approx \frac{AP}{E} \tag{12}$$

Unfortunately, this relation does not coincide with the experimental results accurately enough to be useful in predicting current at still lower pressures. A number of extraneous factors enter in; for example, outgassing of the material quickly contaminates the microscopic air film with solvent vapors and other chemicals which completely change all of the constants involved, since these larger molecules become the principal carriers of the current.

Loeb does give some data from which qualitative conclusions about the performance of the electroadhesor in various gases can be drawn. At given values of E/P, the value of α/P for oxygen is slightly higher than that for air, and that of nitrogen is slightly lower than that for air. Using Equation 8, this implies that at a given pressure and voltage the current in oxygen would be slightly higher than in air, and the current in nitrogen would be slightly lower than in air. This, in turn, implies that the performance in oxygen would be slightly inferior to that in air, the performance in nitrogen would be slightly superior to that in air, and the performance in an oxygen-nitrogen mixture would be comparable to that in air. It has not yet been possible to obtain similar information for helium, so no conclusions can be reached about electroadhesor performance in helium or oxygen-helium mixtures.

Experimentation. The theoretical treatise presented in this report indicates that the key to successful development of optimized electroadhesor devices is the selection of the insulating material used between the electrodes to prevent voltage breakdown. For space applications, this material must not only possess the required dielectric properties, but must also possess the physical properties required to resist the rigors of the aerospace environment. The scope of investigation required to find the optimum material(s) can be appreciated by considering the wide range of base materials and compositions available.

Within the time limitation imposed by the Phase I schedule, laboratory experimentation was performed using randomly selected insulating materials selected on the basis of interest and availability. Materials selected for Phase I evaluation and testing encompassed three basic material forms; (1) coatings, (2) dry film or sheet stock, and (3) adhesive coated tape. Specific material types under each of these forms were:

Coatings (cured or dried state)	- Shellac Resin (Carboned) Enamel Ceramic Epoxy
Film/Sheet Stock	- Mylar Polyethylene Polyvinyl-chloride (PVC) Buna-N Rubber (three different formulations)

<u>Tape</u>	-	Silicone Rubber Paper
<u>Combination</u>	-	Polyvinyl-chloride film with liquid silicone resin coating

<u>Experimentation Plan</u>. - During the early part of Phase I testing, emphasis was placed on evaluation of a styrenated alkyd resin material which showed significant promise for producing electroadhesive forces without excessive current drainage of the power supply. However, experience in handling and processing the material to provide usable test specimens proved very time consuming and the extreme brittleness of the finished specimen material made it difficult to complete any given test without physical destruction of the insulation. For this reason, emphasis was placed on evaluation of a Buna-N rubber material which displayed comparable insulation characteristics to the resin material but which readily withstood physical handling and test processing. This material was accordingly selected as the material for experimentation in support of the Phase I theoretical analysis.

In line with the above, a test plan was devised to permit evaluation of this material covering the environmental and operational parameters in support of the Phase I analysis. Table I presents a master Test Matrix which defines the scope of testing performed on three formulations of the Buna-N rubber material. Each formulation was tested in two thicknesses, t (.075 in.) and 2t (.150 in.).

The Buna-N rubber material selected for this test program was a special formulation consisting of ingredients considered most appropriate for producing desirable electroadhesive performance. The materials were blended to produce an homogeneous composition and were "set" under a special curing cycle (time and temperature).

Material samples used for testing varied only in the condition of the ingredients at the time of manufacture and the normal variables associated with formulations processed at different times. Formulation "A" samples were manufactured during the summer of 1967 and Formulation "B" and "C" samples during November and December, 1967. Preliminary testing of both the "B" and "C" formulations indicated excessive electrical conductivity, and accordingly, these samples were subjected to a post-curing cycle at a slightly higher temperature and time than the initial manufacturing cycle. Test results presented herein for formulations "B" and "C" were established using post-cured material samples.

<u>Experimentation Equipment</u>. - Experimentation in support of the Phase I analysis involved use of two separate test fixture installations described as follows:

FORMULATION	"A"																				"B"											"C"						
THICKNESS	t																2t				t						2t					t			2t			
TEST NO.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38
INSULATION SURFACE																																						
SMOOTH	x	x	x	x	x	x			x	x			x		x	x	x	x	x		x	x		x	x	x	x	x	x		x	x	x	x	x	x	x	
ROUGH							x	x			x	x		x						x			x							x								x
ENVIRONMENTS																																						
AIR	x	x			x	x	x		x		x						x		x	x	x		x		x		x		x	x	x				x		x	x
PURE O_2													x	x												x								x				
O_2-N															x																							
O_2-HE																x																						
PRESSURE																																						
AMBIENT	x	x				x	x		x		x						x		x	x	x		x		x		x		x	x	x				x		x	x
CABIN													x	x	x	x										x								x				
PARTIAL VACUUM			x	x	x			x		x		x						x				x		x				x				x	x			x		
TEMPERATURE																																						
AMBIENT	x	x	x	x			x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		x	x	x	x	x	x	x	x		x	x	x	x	x
LOW					x																			x									x					
ELEVATED						x																																
POLARITY																																						
NEGATIVE	x		x		← Polarity to be determined based on results of tests No. 1 thru 4 →																																	
POSITIVE		x		x																																		
MEASUREMENTS																																						
FORCE VS VOLTAGE	x	x	x	x	x	x	x	x					x	x	x	x	x	x			x	x	x	x		x	x	x			x	x	x	x	x	x		
CURRENT VS VOLTAGE	x	x	x	x	x	x	x	x					x	x	x	x	x	x			x	x	x	x		x	x	x			x	x	x	x	x	x		
RESISTIVITY	x	x	x	x	x	x	x	x					x	x	x	x	x	x			x	x	x	x		x	x	x			x	x	x	x	x	x		
FORCE/VOLT/TIME DATA									x	x	x	x							x	x					x				x	x							x	x
SPARK/COMBUSTION DATA													x	x	x	x										x								x				

FORMULATION "A"
BUNA-N Rubber
1 Part Carbon Content
Chrysler Identification No. N45RS1

FORMULATION "B"
BUNA-N Rubber
0 Part Carbon Content
Chrysler Identification No. N45RS2

FORMULATION "C"
BUNA-N Rubber
2 Parts Carbon Content
Chrysler Identification No. N45RS3

CONSTANTS
Interface Material - Alum. Alloy Electrodes
Configuration - Flat, Parallel Plates
Loading - Tension Only

Table I - Test Matrix

Vacuum Facility: The vacuum test installation shown in Figure 5 was used for all testing except gaseous environment simulation. Equipment items are identified as follows:

Vacuum Equipment - Consolidated Vacuum Corporation Ionization Vacuum Gauge, Type GIC-110A.

Loading Frame - An angle-iron frame assembly, designed to fit within the confines of the bell jar, was used to support the specimen and loading apparatus. The frame incorporated a fixed base plate which served as the bottom electrode and a top plate assembly which acted as a guide for the loading apparatus. The loading apparatus was a simple pivot beam activated in an up and down motion by an hydraulic actuator mounted externally to the vacuum facility framework. A bellows-type expansion element was used to close the vacuum jar and to permit extension of the loading apparatus. Figure 6 is a close-up view of the test installation.

Test Specimens - Figure 7 is a close-up view of the top electrode specimen used for all testing of the Buna-N rubber material except gaseous environment simulation. The 1-5/8-inch dia. aluminum alloy specimen was machined to provide a flat, parallel plate interface with the bottom plate electrode. All other materials were tested using individual aluminum alloy channel specimens also shown in this figure.

Rough Surface Plate - A special bottom electrode plate was surface conditioned by scratching and gouging with a hacksaw blade. Figure 8 is a view of this plate.

Load Measurement - Applied loads were visually observed on a calibrated Dillon Force Gage (see Figure 6).

Elevated Temperature Apparatus - An electrical heating unit positioned on the bottom surface of the bottom electrode was used for elevated temperature testing. Thermocouples were positioned on the plate and recordings were observed on a temperature-sensing gage.

Low Temperature Apparatus - An open-loop liquid nitrogen (LN_2) system (see Figure 6) was used for low temperature testing. A dial-type thermometer mounted on the plate was used to monitor test temperatures.

Power Supply - Universal Voltronics Corporation Portable High Voltage Power Supply, 10 KV Direct Current.

Gaseous Environment Fixture: The gaseous environment test fixture installation is shown in Figure 9. Equipment items are identified as follows:

Chamber - A special machined steel chamber fixture was used for gaseous environment testing. The assembly incorporated plumbing elements for introduction of gas mixtures at simulated cabin pressure (5-7 psi),

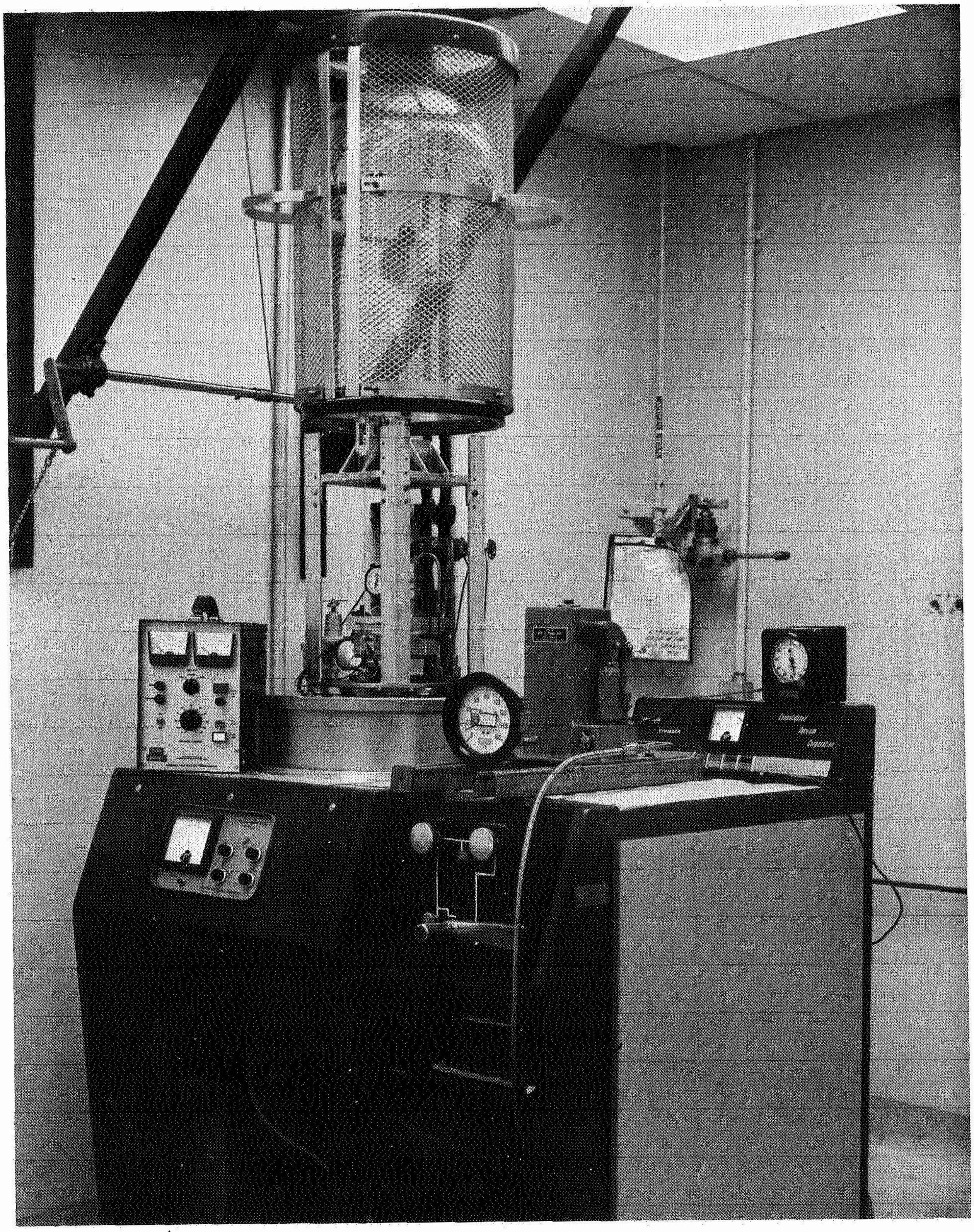


Figure 5 - Vacuum Test Facility

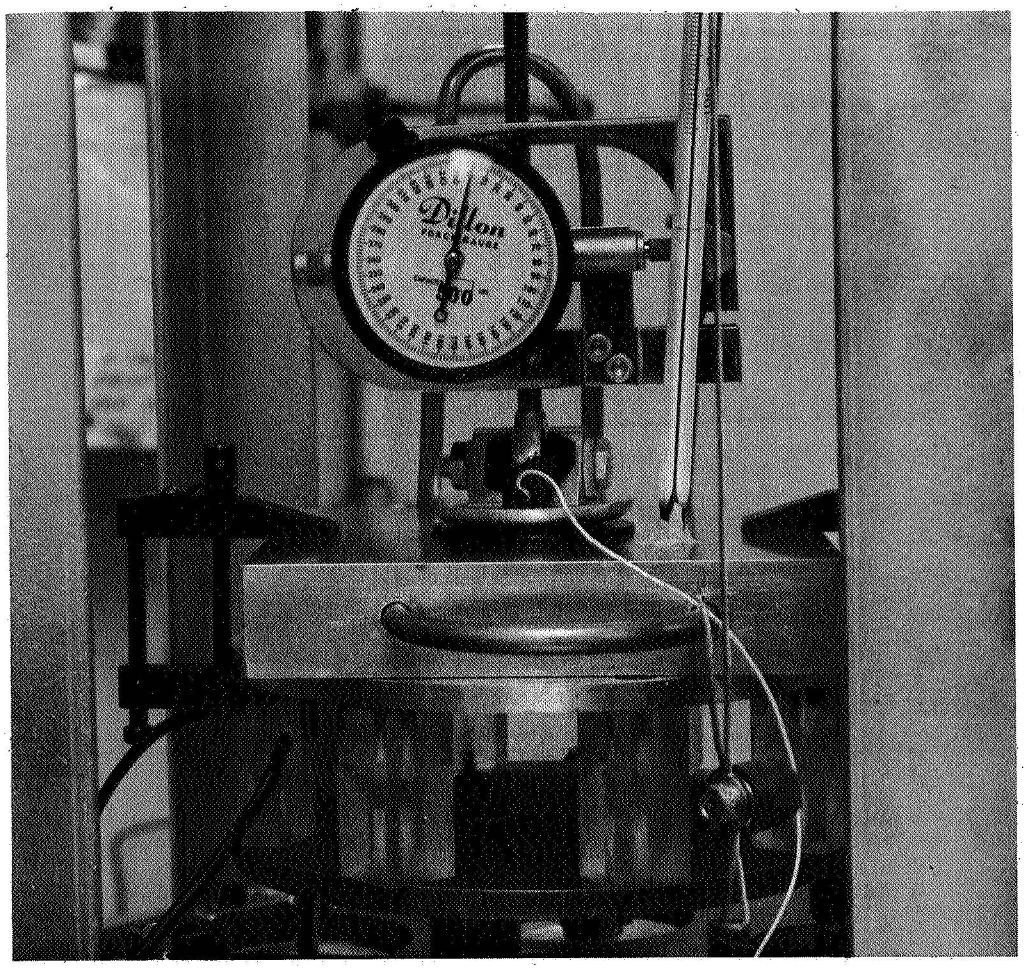


Figure 6 - Close-up View of Installation Used for Ambient Environment, Vacuum, and Low and Elevated Temperature Testing

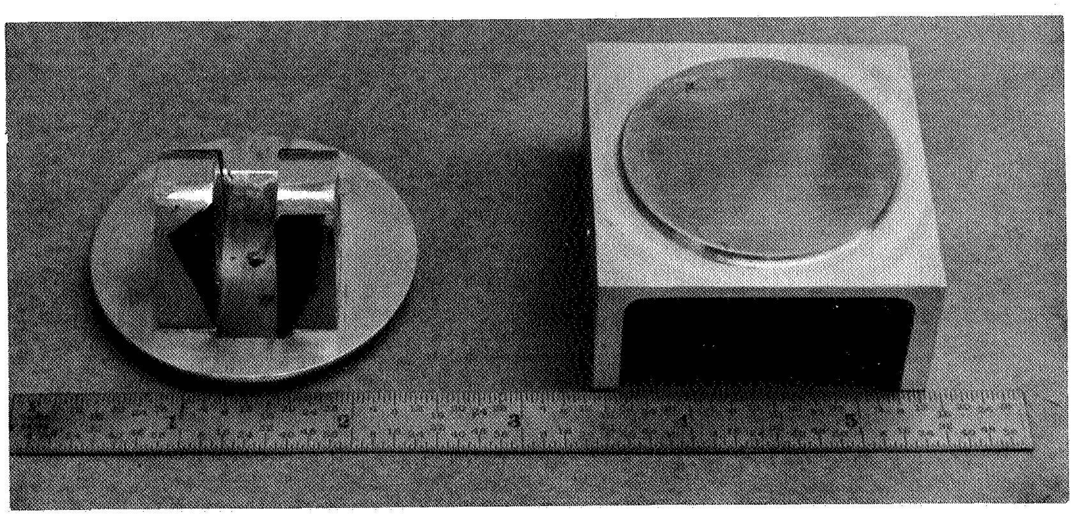


Figure 7 - Close-up view of Electrode Test Specimens

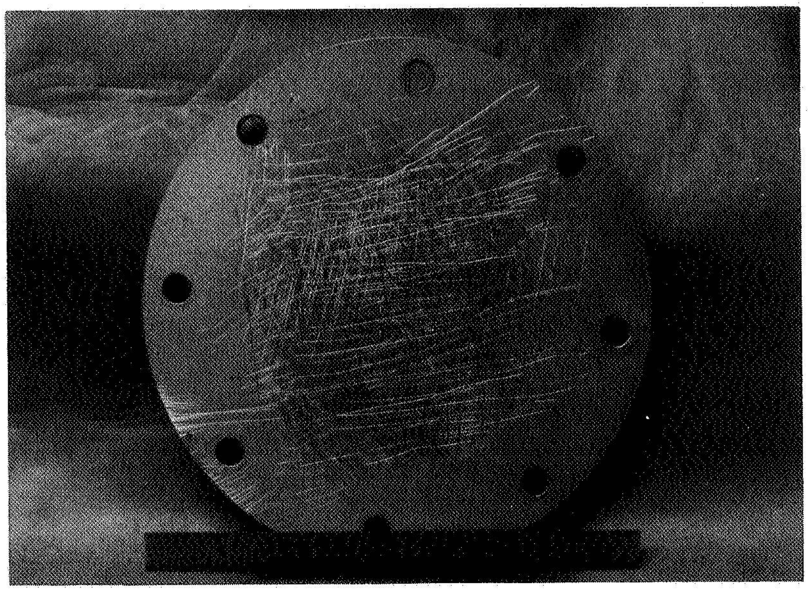


Figure 8 - Rough Surface Test Plate

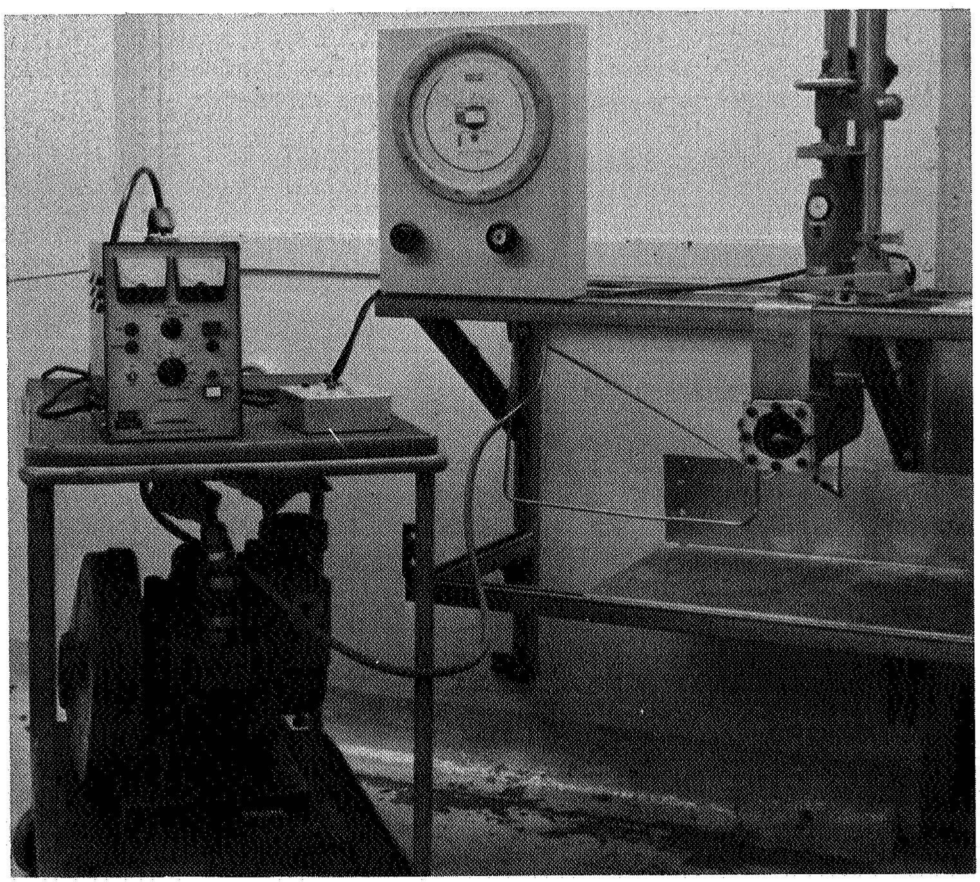


Figure 9 - Gaseous Environment Test Set-up

a test specimen assembly, and loading apparatus. A special plexiglas end plate permitted visual observation of any spark/combustion process within the chamber.

Test Specimen Assembly - Figure 10 is a photo of the 3/8-inch diameter test specimen disassembled to show the electrode and test material components.

Loading Apparatus - The loading apparatus for gaseous environment testing consisted of an electric motor friction drive assembly of the wheel and threaded stud type. A direct reading force gage was suspended from the end of the stud and linked to the moveable top electrode within the pressure chamber. A flexible disc type bellows was used to seal the pressure chamber and permitted slight vertical movement of the top electrode. Prior to testing, the force required to overcome the resistance of the bellows was determined with the electrodes in the uncharged condition. This force was subsequently subtracted from each test measurement to produce electroadhesive force data.

Pressure Reducer - A standard laboratory roughing pump was used to evacuate the test chamber prior to introduction of the gas mixture.

Gas Supply - Welders oxygen (99.6% pure), welders helium, and dry nitrogen gases were used. Gas mixtures were monitored by observation of chamber pressure on a standard laboratory barometer.

Power Supply - As previously described.

Experimentation Procedure. - The procedure for conduct of testing defined by the master test matrix is described as follows. The procedure for testing of other materials was essentially the same although data measurements were restricted to voltage/current/force relationships.

Voltage/Current/Force Relationship Tests: The test specimen was positioned between the top and bottom electrodes. The loading apparatus was adjusted to assure good contact between the electrodes and the test material with minimum compressive loading of the material. This condition was required since previous tests had indicated that compressed Buna-N rubber exhibited a certain affinity for "self-adhesion" in the uncharged state.

For each test, direct current voltage was applied in increments of 400 volts d.c. through 6000 volts d.c. Applied voltage was allowed to stabilize for approximately 30 seconds before read-out of current and application of loading. At each test increment, current drop was observed on a direct reading milliampere gage. Tensile force was applied at a rate of approximately one pound-per-second until separation of the electrode/specimen was observed. Separation load was visually observed on the force gage.

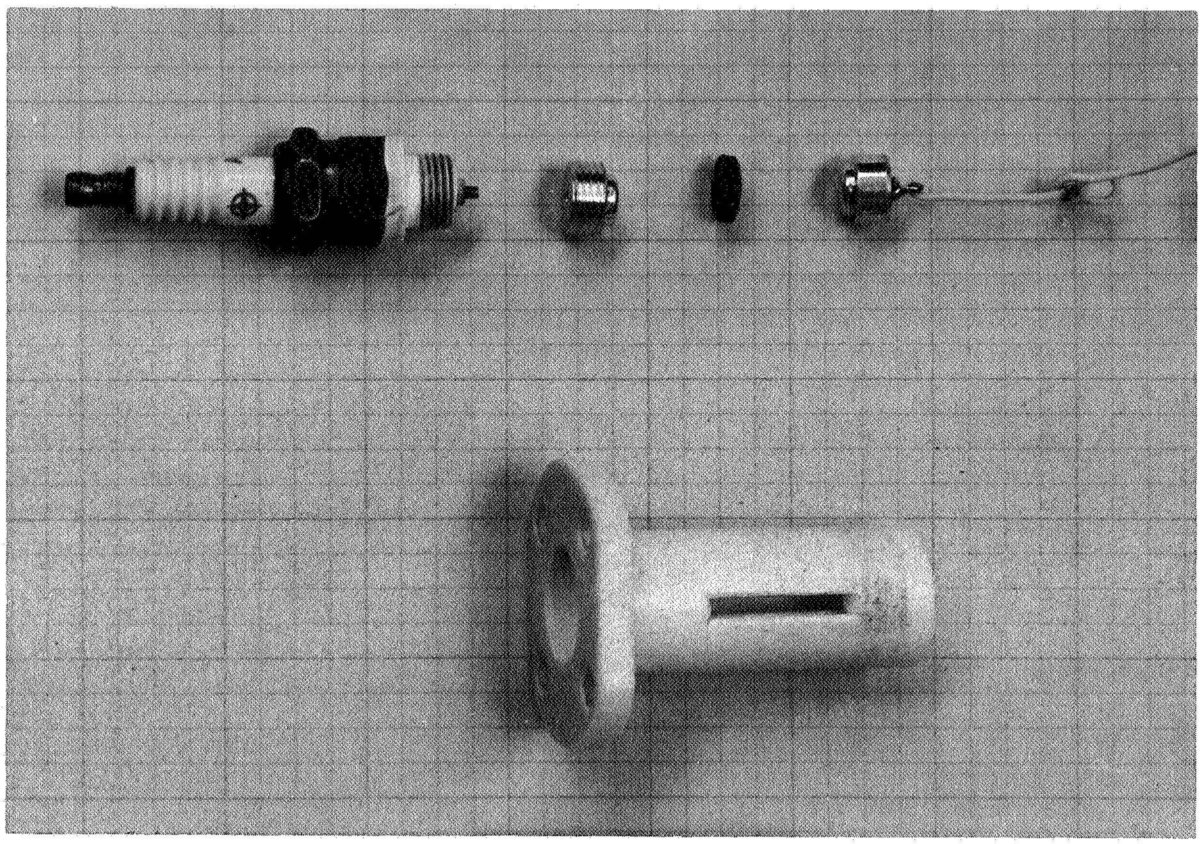


Figure 10 - Gaseous Test Specimen (Disassembled)

The effect of polarity (positive and negative) was evaluated during Matrix Test Numbers 1 through 4. All other tests were conducted using negative polarity of the applied charge.

Resistivity - Resistivity of the specimen material was calculated from established force/current/voltage test data. This was achieved by plotting the data as shown in graphs presented in this report (see Figures 11 thru 37). First, each curve of current versus applied voltage was examined to determine the set of data points which exhibited linearity or near linearity. A line drawn through these points was extended until it intersected with the applied voltage base line. The intersecting value of applied voltage thus determined was subtracted from an arbitrarily selected value of applied voltage within the linear portion of the voltage/current curve. The calculated voltage value, along with the corresponding current data value was used in the following mathematical relationship to determine the resistivity of the material.

$$\text{Resistivity (Ohm-Cm)} = \frac{\text{Resistance}\left(\frac{\text{Volts}}{\text{Amps}}\right) \text{ X Area } (\text{Cm}^2)}{\text{Thickness (Cm)}}$$

or:

$$R = \frac{\frac{E}{I} \text{ X } A}{t}$$

$$= \frac{EA}{It}$$

By converting test area and thickness to metric units, square inches to square centimeters and inches to centimeters using appropriate conversion factors, and the corresponding current value from milliamperes to amperes, the above formula reduces to:

$$R = \frac{(.00508)\ (E)}{(ma)\ (t)}$$

where E = calculated voltage value

ma = corresponding current value in milliampere

t = test thickness in inches.

Force/Voltage/Time Relationship Tests - For these tests, five incremental voltages were applied. At each increment, load was applied starting with a comparatively low value of the previously determined breaking force. The time required to produce breaking under each combination of voltage and load was measured. After five minutes of elapsed time the power supply was turned off and the time required for force decay was measured.

A second phase of testing was conducted to determine the effect of a constant applied load with decreasing voltage. For these tests, 5000 volts d.c. were first applied and the test assembly subjected to a tensile force slightly below that which was previously observed to cause separation of the electrodes. Under combined voltage and applied loading, the time required to produce electrode separation was measured. This procedure was then repeated for incrementally reduced voltages and applied loading.

Gaseous Environment Tests - Following installation of the test specimen and checkout of the loading apparatus, the test chamber was evacuated by operation of the roughing pump. The chamber was then purged several times using dry nitrogen gas. The gas mixture was then introduced into the chamber and stabilized at the test pressure. Voltage was applied across the test electrodes in the same increments used for previous testing and load was applied to produce a separation of the electrodes. At each increment of applied voltage and loading, visual observation was made to detect sparking or combustion within the chamber.

Tests were performed using the following gas or gas mixtures:

- Air (standard atmosphere)
- Oxygen-Nitrogen*
- Oxygen-Helium*
- Oxygen

Experimentation Results. - Figures 11 through 37 and Tables II through XII present experimentation data. Resistivity data is summarized in Table XIII. Results of testing performed on other than the Buna-N rubber are summarized as follows: Breaking forces for the specimens tested ranged from insignificant for certain material types (mylar, polyethylene, and others) to appreciable for other material types (polyvinyl-chloride, carboned lacquer, and the combined polyvinyl-chloride-silicone resin). Maximum tensile force capability was achieved with the polyvinyl-chloride-silicone resin combination (7-9 lbs/sq.in.). All other specimens developed less than 5 lbs/sq. in. breaking force.

*Gas mixtures proportioned equally by volume.

MATRIX TEST NO. 1

Material	BUNA-N RUBBER	Formulation	"A"
Thickness	t = .075 in.	Temperature	AMBIENT (78°F Norm)
Surface	SMOOTH	Pressure	AMBIENT (SEA LEVEL)
Environment	AIR	Polarity	NEGATIVE

Applied Voltage	Current Milliamperes	Force lbs/sq.in.	Applied Voltage	Current Milliamperes	Force lbs/sq.in.
400	.015	2.1	3600	.046	6.3
800	.020	2.8	4000	.053	7.1
1200	.025	3.0	4400	.059	7.9
1600	.028	3.4	4800	.063	8.5
2000	.030	4.1	5200	.068	8.8
2400	.032	4.8	5600	.073	9.0
2800	.036	5.3	6000	.081	9.1
3200	.040	5.8			

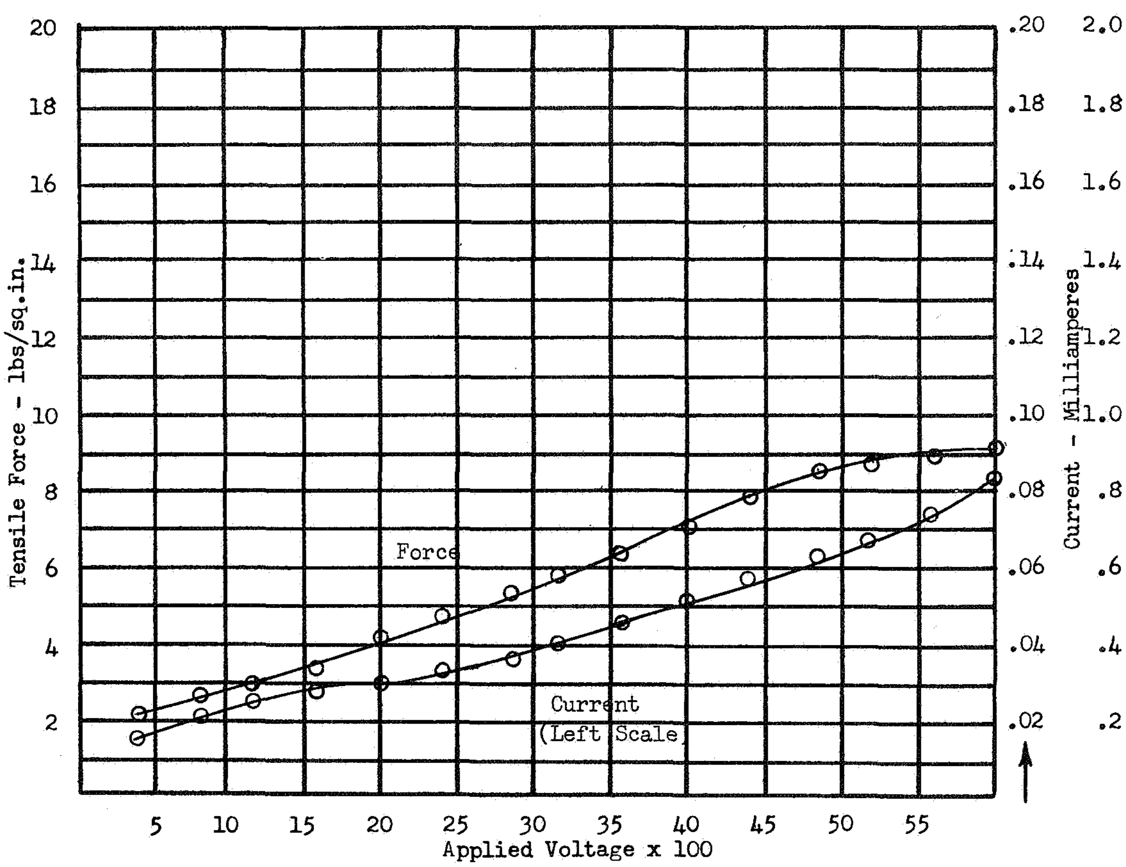


Figure 11 Electroadhesor Test Data
Force and Current at Applied Voltage

MATRIX TEST NO. 2

Material	BUNA-N RUBBER	Formulation	"A"
Thickness	t = .075 in.	Temperature	AMBIENT (78°F Norm.)
Surface	SMOOTH	Pressure	AMBIENT (SEA LEVEL)
Environment	AIR	Polarity	POSITIVE

Applied Voltage	Current Milliamperes	Force lbs/sq.in.	Applied Voltage	Current Milliamperes	Force lbs/sq.in.
400	.015	2.1	3600	.046	6.3
800	.020	2.8	4000	.053	7.1
1200	.025	3.0	4400	.059	7.9
1600	.028	3.4	4800	.063	8.5
2000	.030	4.1	5200	.068	8.8
2400	.032	4.8	5600	.073	9.0
2800	.036	5.3	6000	.081	9.1
3200	.040	5.8			

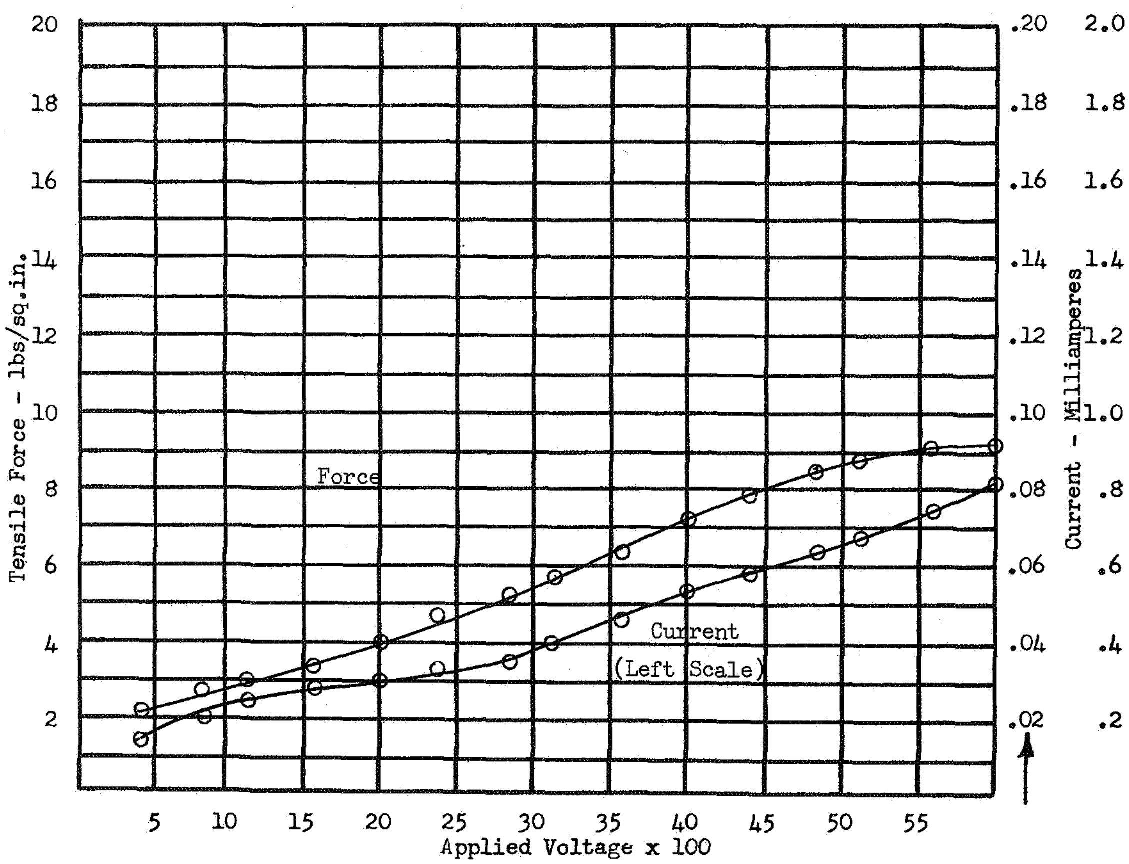


Figure 12 Electroadhesor Test Data
Force and Current at Applied Voltage

MATRIX TEST NO. 3

Material	BUNA-N RUBBER	Formulation	"A"
Thickness	t = .075 in.	Temperature	AMBIENT
Surface	SMOOTH	Pressure	1.0×10^{-5} mm Hg.
Environment	-	Polarity	NEGATIVE

Applied Voltage	Current Milliamperes	Force lbs/sq.in.	Applied Voltage	Current Milliamperes	Force lbs/sq.in.
400	.0112	2.8	3600	.032	8.5
800	.015	3.4	4000	.034	9.7
1200	.018	4.0	4400	.037	10.1
1600	.021	4.7	4800	.042	10.4
2000	.025	5.5	5200	.047	10.6
2400	.027	6.1	5600	.057	10.6
2800	.028	6.9	6000	.067	10.6
3200	.030	7.7			

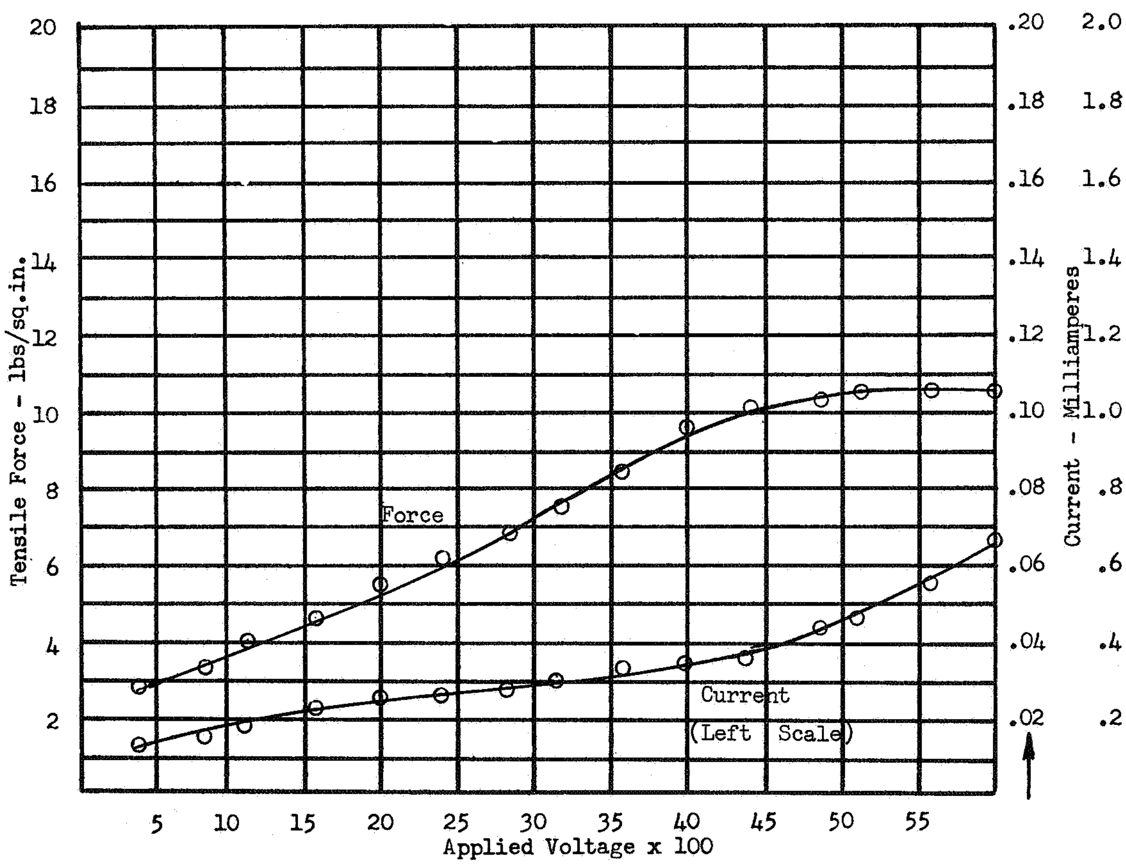


Figure 13 Electroadhesor Test Data
Force and Current at Applied Voltage

MATRIX TEST NO. 4

Material	BUNA-N RUBBER	Formulation	"A"
Thickness	t = .075 in.	Temperature	AMBIENT
Surface	SMOOTH	Pressure	1.0×10^{-5} mm Hg.
Environment	-	Polarity	POSITIVE

Applied Voltage	Current Milliamperes	Force lbs/sq.in.	Applied Voltage	Current Milliamperes	Force lbs/sq.in.
400	.011	2.8	3600	.032	8.5
800	.014	3.5	4000	.035	9.8
1200	.017	3.9	4400	.037	10.1
1600	.021	4.7	4800	.043	10.5
2000	.025	5.6	5200	.048	10.5
2400	.027	6.2	5600	.058	10.6
2800	.029	6.9	6000	.068	10.7
3200	.030	7.7			

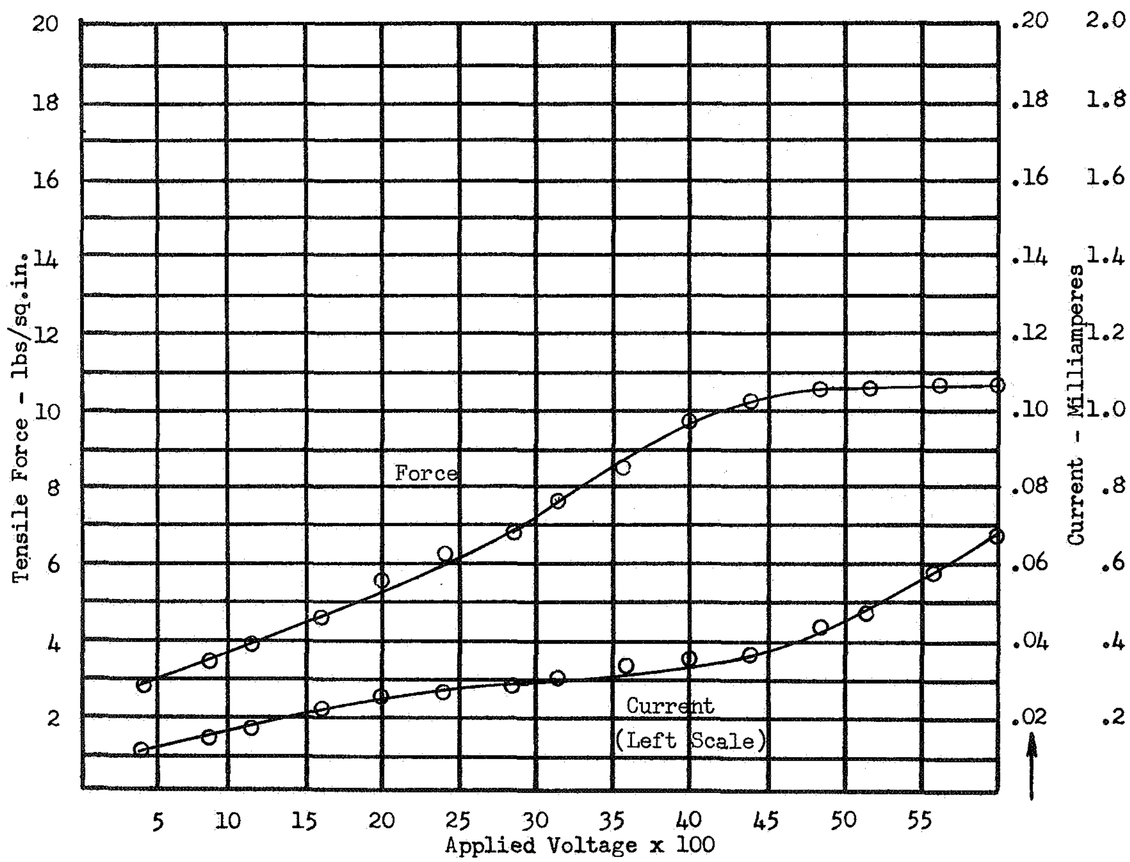


Figure 14 Electroadhesor Test Data
Force and Current at Applied Voltage

MATRIX TEST NO. 5

Material	BUNA-N RUBBER	Formulation	"A"
Thickness	t = .075 in.	Temperature	0°F
Surface	SMOOTH	Pressure	1.0×10^{-5} mm Hg.
Environment	-	Polarity	NEGATIVE

Applied Voltage	Current Milliamperes	Force lbs/sq.in.	Applied Voltage	Current Milliamperes	Force lbs/sq.in.
400	No data	No data	3600	.008	0.07
800	"	"	4000	.010	0.08
1200	"	"	4400	.010	1.00
1600	.002	"	4800	.010	1.00
2000	.002	"	5200	.010	1.40
2400	.004	"	5600	.012	1.80
2800	.006	0.02	6000	.012	1.80
3200	.008	0.05			

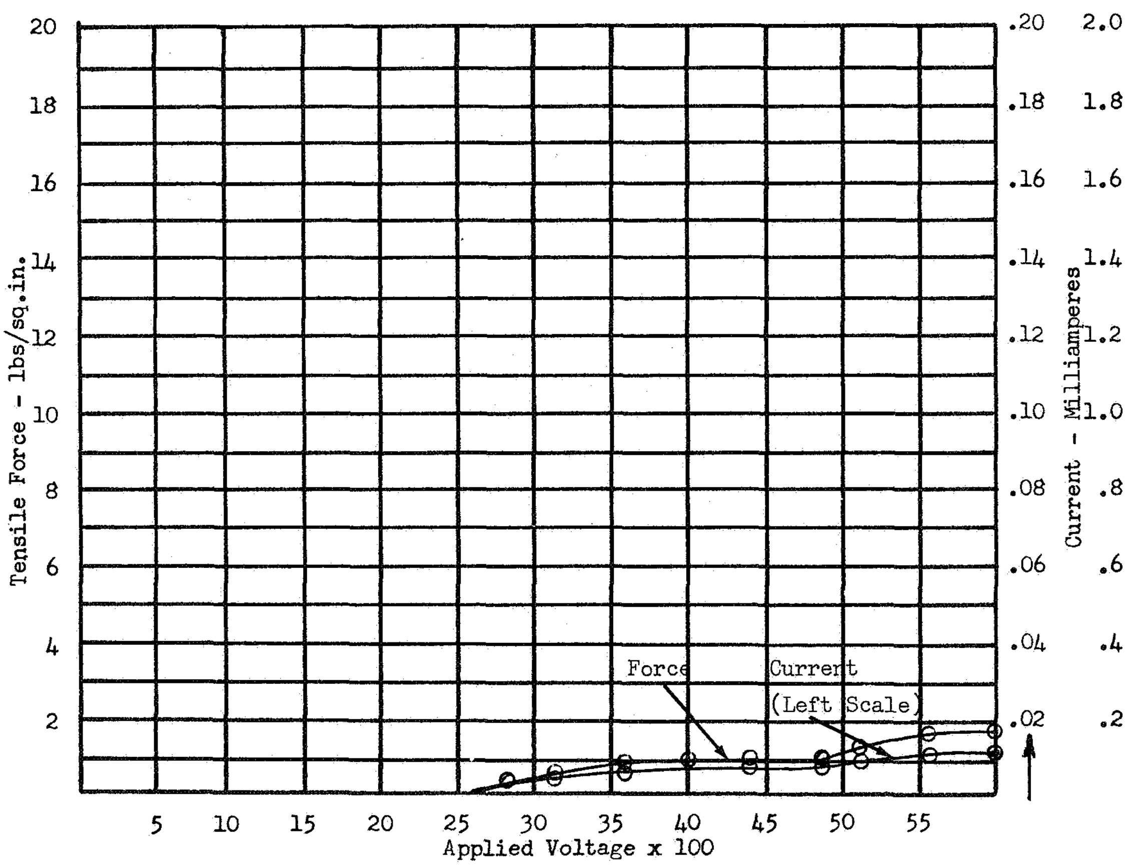


Figure 15 Electroadhesor Test Data
Force and Current at Applied Voltage

MATRIX TEST NO. 6

Material	BUNA-N RUBBER	Formulation	"A"
Thickness	t = .075 in.	Temperature	140°F
Surface	SMOOTH	Pressure	AMBIENT
Environment	AIR	Polarity	NEGATIVE

Applied Voltage	Current Milliamperes	Force lbs/sq.in.	Applied Voltage	Current Milliamperes	Force lbs/sq.in.
400	.12	No data	3600	No data	No data
800	.30	.07	4000	"	"
1200	.48	1.20	4400	"	"
1600	.69	1.60	4800	"	"
2000	.90	2.00	5200	"	"
2400	1.15	2.20	5600	"	"
2800	No data	No data	6000		
3200	"	"			

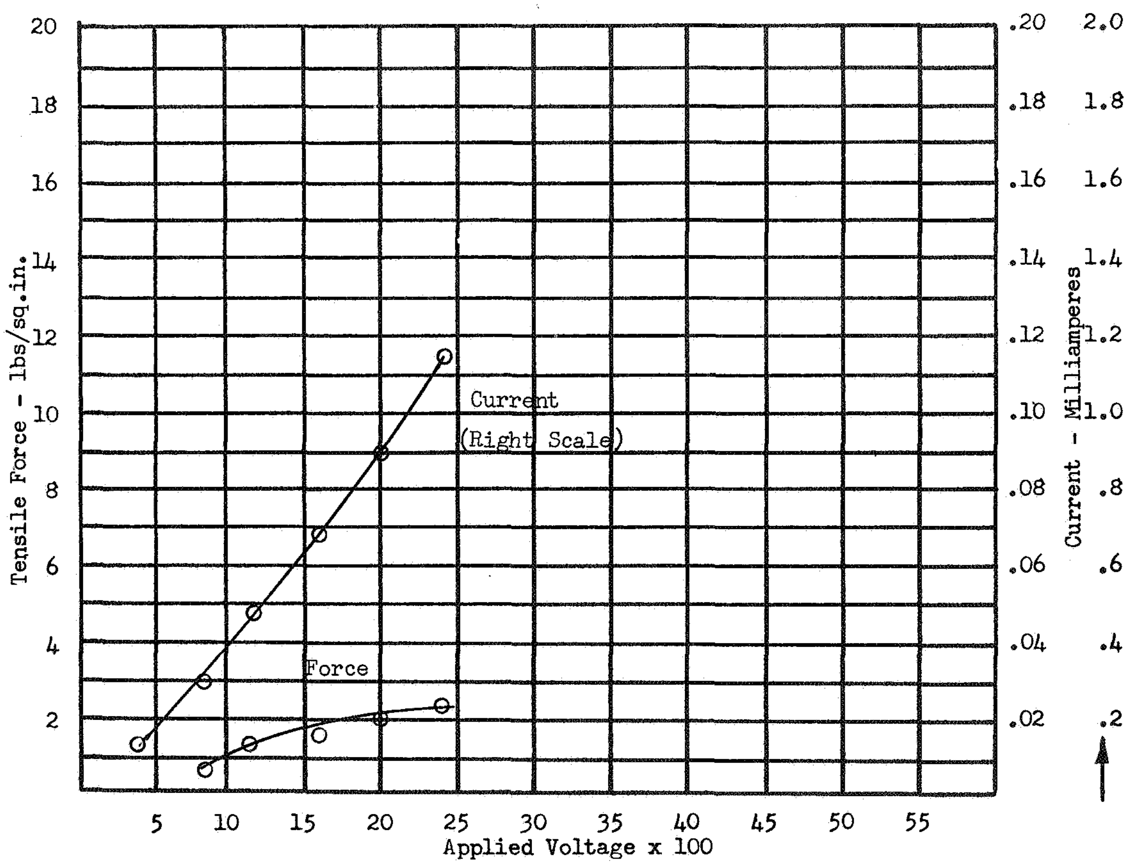


Figure 16 Electroadhesor Test Data
Force and Current at Applied Voltage

MATRIX TEST NO. 7

Material	BUNA-N RUBBER	Formulation	"A"
Thickness	t = .075 in.	Temperature	AMBIENT
Surface	ROUGH	Pressure	AMBIENT
Environment	AIR	Polarity	NEGATIVE

Applied Voltage	Current Milliamperes	Force lbs/sq.in.	Applied Voltage	Current Milliamperes	Force lbs/sq.in.
400	.015	.75	3600	.030	2.90
800	.016	1.20	4000	.032	3.00
1200	.018	1.60	4400	.037	3.50
1600	.022	2.10	4800	.050	4.30
2000	.027	2.20	5200	.058	4.80
2400	.028	2.50	5600	.068	5.00
2800	.029	2.80	6000	.079	5.00
3200	.029	2.80			

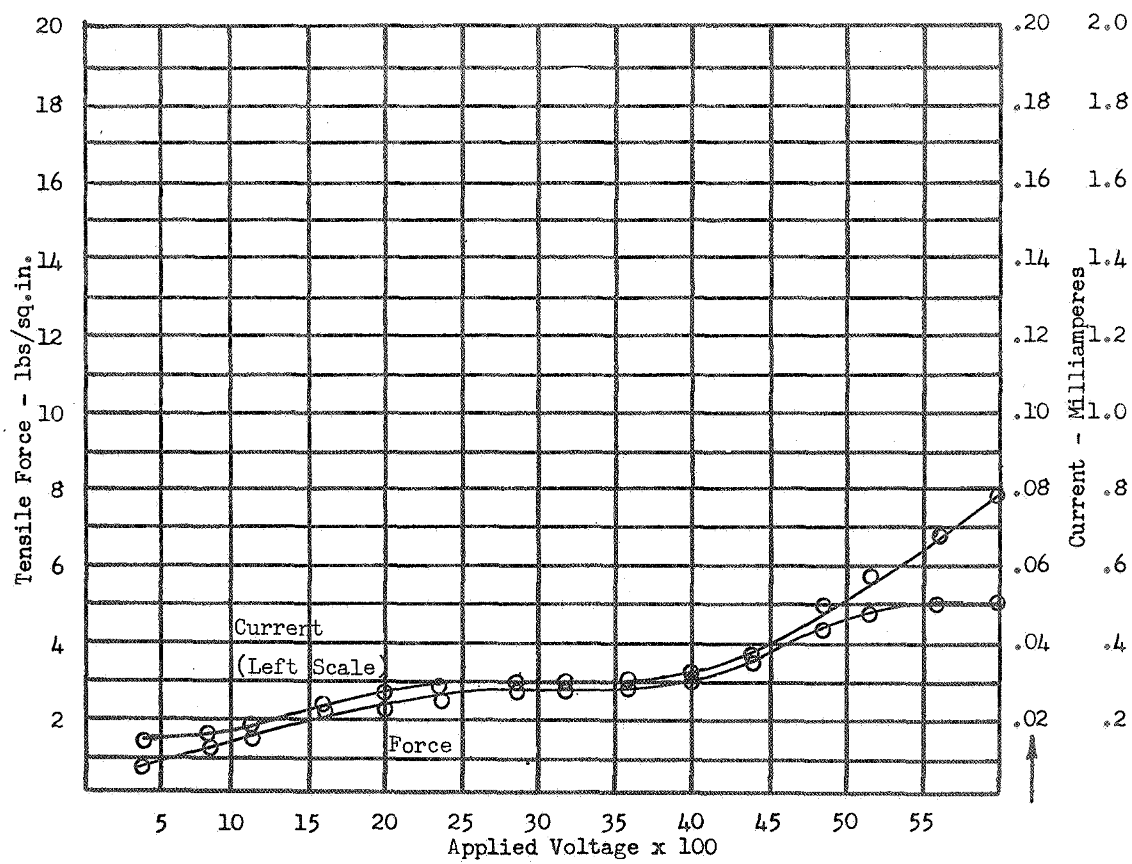


Figure 17 Electroadhesor Test Data
Force and Current at Applied Voltage

MATRIX TEST NO. 8

Material	BUNA-N RUBBER	Formulation	"A"
Thickness	t = .075 in.	Temperature	AMBIENT
Surface	ROUGH	Pressure	1.5 x 10^{-5} mm Hg.
Environment	-	Polarity	NEGATIVE

Applied Voltage	Current Milliamperes	Force lbs/sq.in.	Applied Voltage	Current Milliamperes	Force lbs/sq.in.
400	No data	No data	3600	.034	6.0
800	No data	No data	4000	.038	6.5
1200	.022	4.0	4400	.042	6.8
1600	.028	4.1	4800	.047	7.0
2000	.029	4.2	5200	.050	7.1
2400	.030	4.5	5600	.055	7.1
2800	.031	5.2	6000	.061	7.1
3200	.032	5.5			

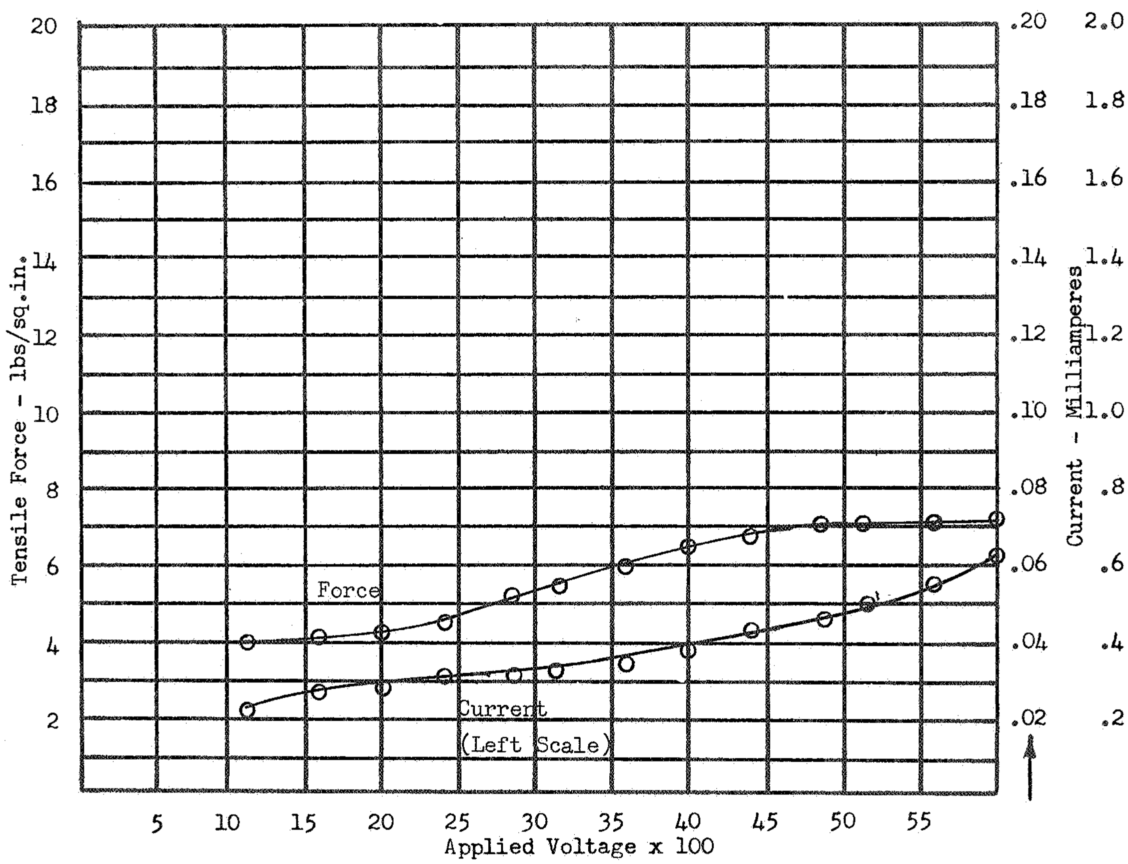


Figure 18 Electroadhesor Test Data
Force and Current at Applied Voltage

MATRIX TEST NO. 13

Material	BUNA-N RUBBER	Formulation	"A"
Thickness	t = .075 in.	Temperature	AMBIENT
Surface	SMOOTH	Pressure	5 - 7 PSIA
Environment	OXYGEN (O_2)	Polarity	NEGATIVE

Applied Voltage	Current Milliamperes	Force lbs/sq.in.	Applied Voltage	Current Milliamperes	Force lbs/sq.in.
400	.002	0	3600	.008	3.0
800	.004	0.5	4000	Current Arc - Over	
1200	.005	1.0	4400		
1600	.006	1.5	4800		
2000	.007	2.0	5200		
2400	.008	2.2	5600		
2800	.007	3.0	6000		
3200	.008	3.0			

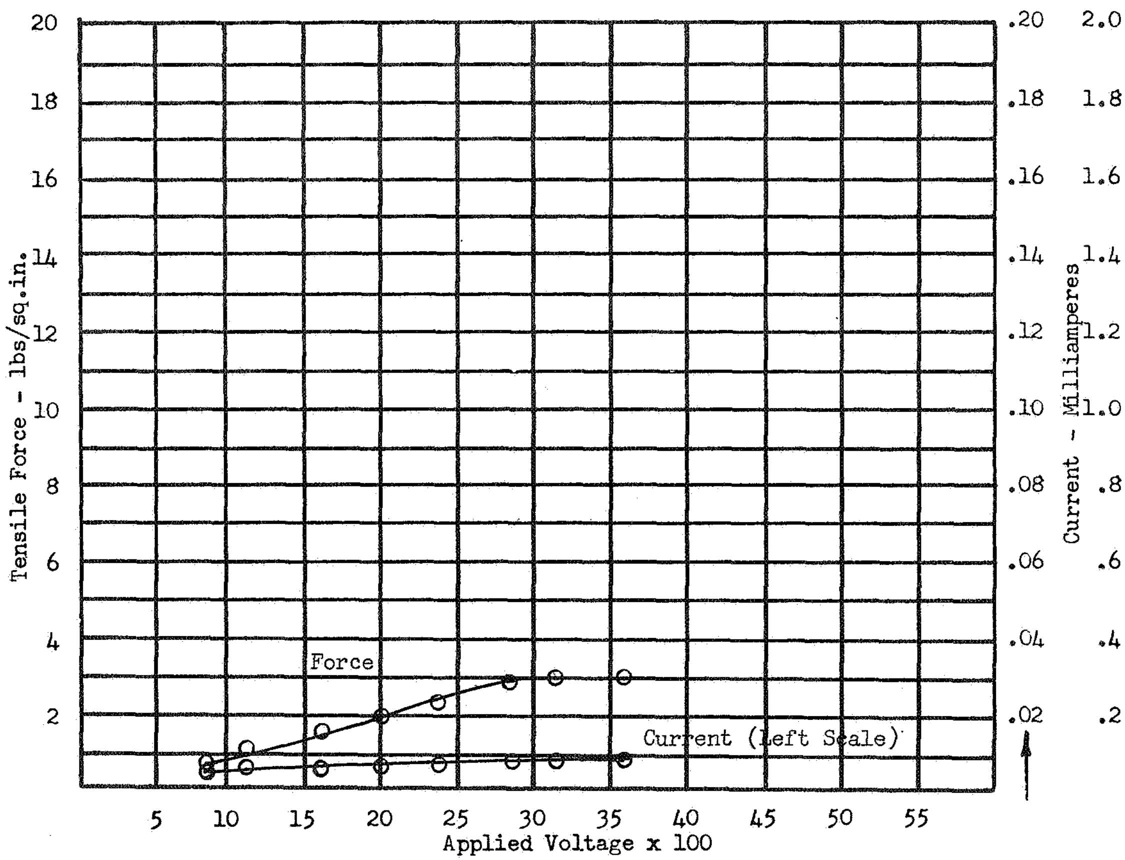


Figure 19 Electroadhesor Test Data
Force and Current at Applied Voltage

MATRIX TEST NO. 14

Material	BUNA-N RUBBER	Formulation	"A"
Thickness	t = .075 in.	Temperature	AMBIENT
Surface	ROUGH	Pressure	5 - 7 PSIA
Environment	OXYGEN GAS	Polarity	NEGATIVE

Applied Voltage	Current Milliamperes	Force lbs/sq.in.	Applied Voltage	Current Milliamperes	Force lbs/sq.in.
400	.002	0	3600	.006	.25
800	.002	0	4000	.006	.25
1200	.003	0	4400	Current Arc-Over	
1600	.004	.25	4800		
2000	.005	.25	5200		
2400	.006	.25	5600		
2800	.006	.25	6000		
3200	.006	.25			

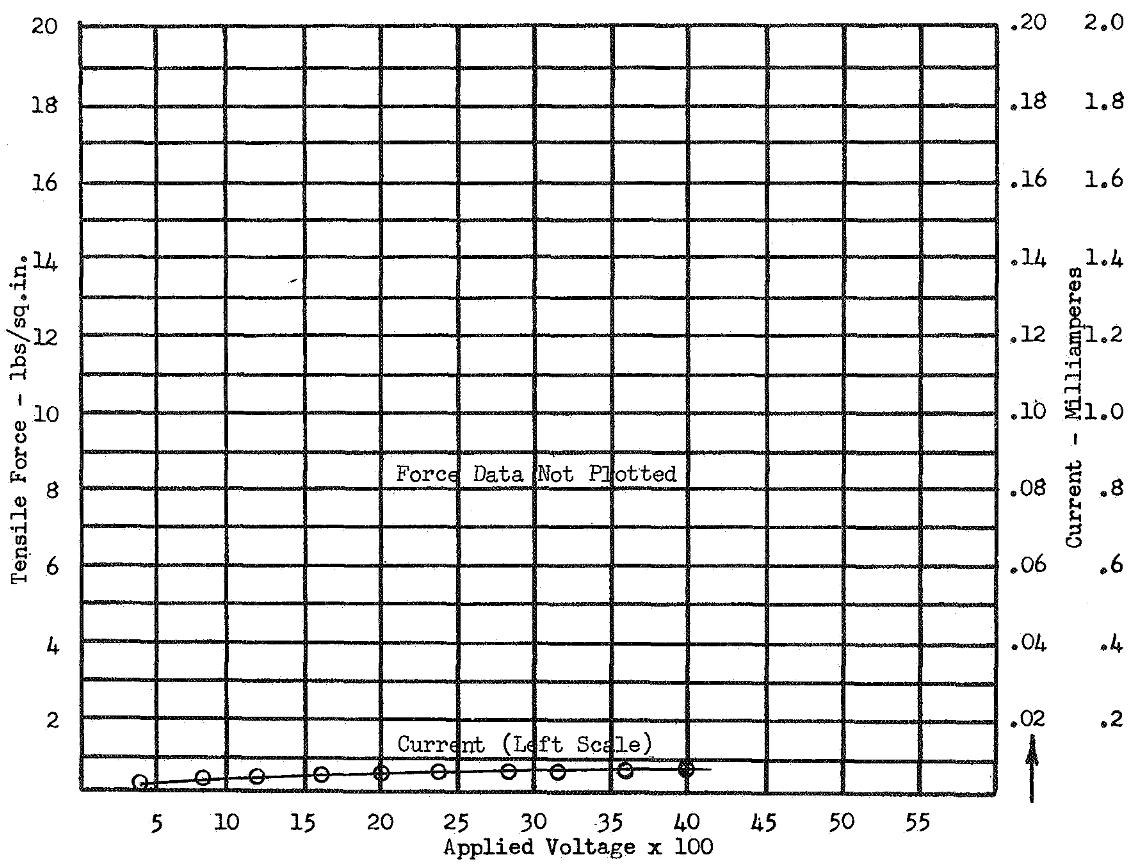


Figure 20 Electroadhesor Test Data
Force and Current at Applied Voltage

MATRIX TEST NO. 15

Material	BUNA-N RUBBER	Formulation	"A"
Thickness	t = .075 in.	Temperature	AMBIENT
Surface	SMOOTH	Pressure	5 - 7 PSIA
Environment	OXYGEN-NITROGEN GAS	Polarity	NEGATIVE

Applied Voltage	Current Milliamperes	Force lbs/sq.in.	Applied Voltage	Current Milliamperes	Force lbs/sq.in.
400	.001	0.5	3600	.008	5.1
800	.001	1.0	4000	Current Arc-Over	
1200	.002	1.1	4400		
1600	.003	1.1	4800		
2000	.004	1.8	5200		
2400	.004	3.0	5600		
2800	.005	5.0	6000		
3200	.007	5.0			

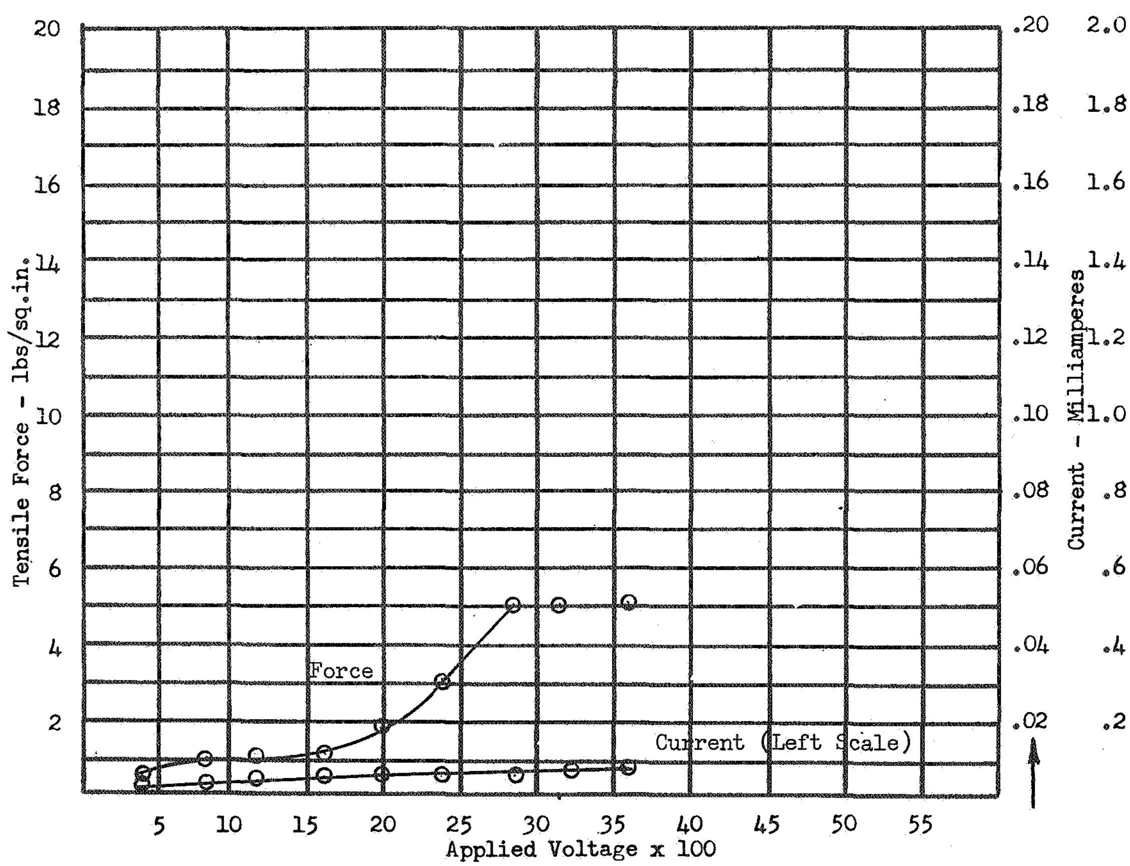


Figure 21 Electroadhesor Test Data
Force and Current at Applied Voltage

MATRIX TEST NO. 16

Material	BUNA-N RUBBER	Formulation	"A"
Thickness	t = .075 in.	Temperature	AMBIENT
Surface	SMOOTH	Pressure	5 - 7 PSIA
Environment	OXYGEN-HELIUM GAS	Polarity	NEGATIVE

Applied Voltage	Current Milliamperes	Force lbs/sq.in.	Applied Voltage	Current Milliamperes	Force lbs/sq.in.
400	.002	0.5	3600	.008	5.0
800	.003	1.0	4000	Current Arc-Over	
1200	.004	1.5	4400		
1600	.005	3.0	4800		
2000	.005	4.0	5200		
2400	.006	4.5	5600		
2800	.007	5.0	6000		
3200	.007	5.0			

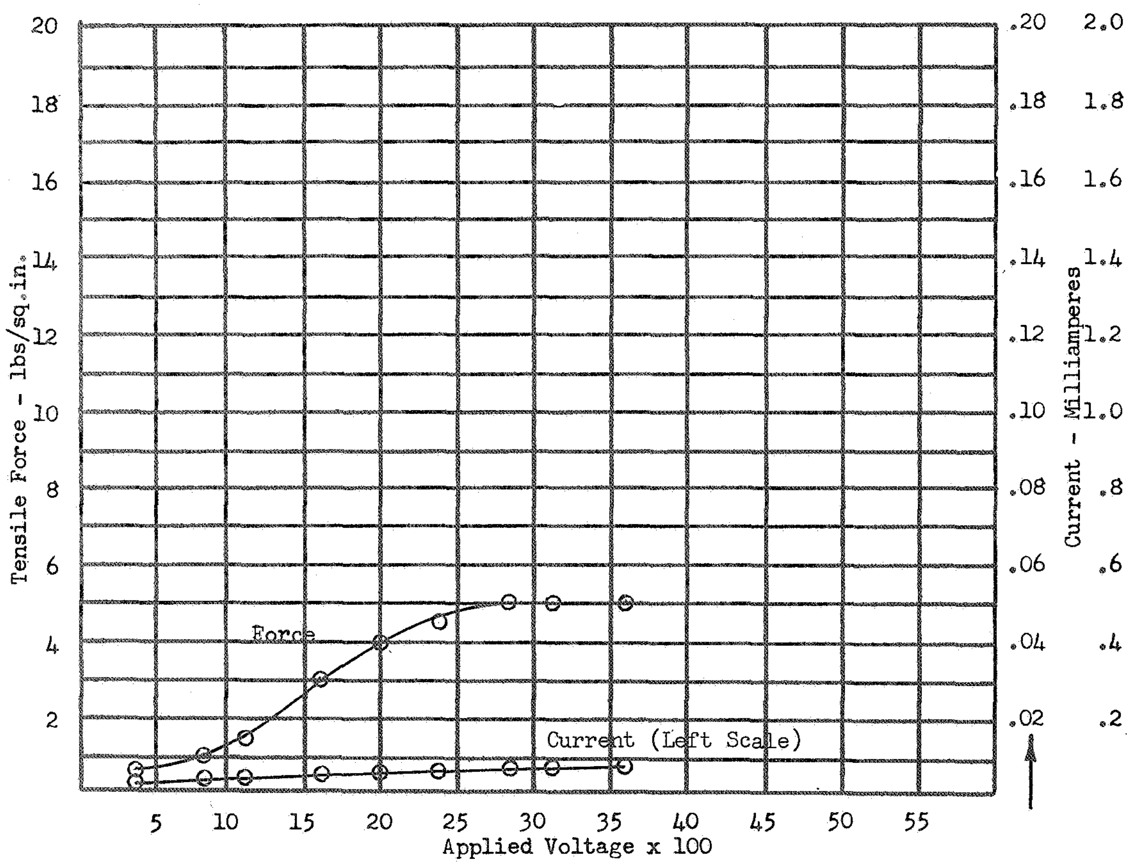


Figure 22 Electroadhesor Test Data
Force and Current at Applied Voltage

MATRIX TEST NO. 17

Material	BUNA-N RUBBER	Formulation	"A"
Thickness	2t = .150 in.	Temperature	AMBIENT
Surface	SMOOTH	Pressure	AMBIENT
Environment	AIR	Polarity	NEGATIVE

Applied Voltage	Current Milliamperes	Force lbs/sq.in.	Applied Voltage	Current Milliamperes	Force lbs/sq.in.
400	.011	2.6	3600	.031	8.2
800	.014	3.0	4000	.033	9.5
1200	.018	3.8	4400	.037	10.0
1600	.020	4.5	4800	.041	10.5
2000	.024	5.3	5200	.047	10.5
2400	.027	6.0	5600	.058	10.5
2800	.028	6.7	6000	.066	10.5
3200	.029	7.5			

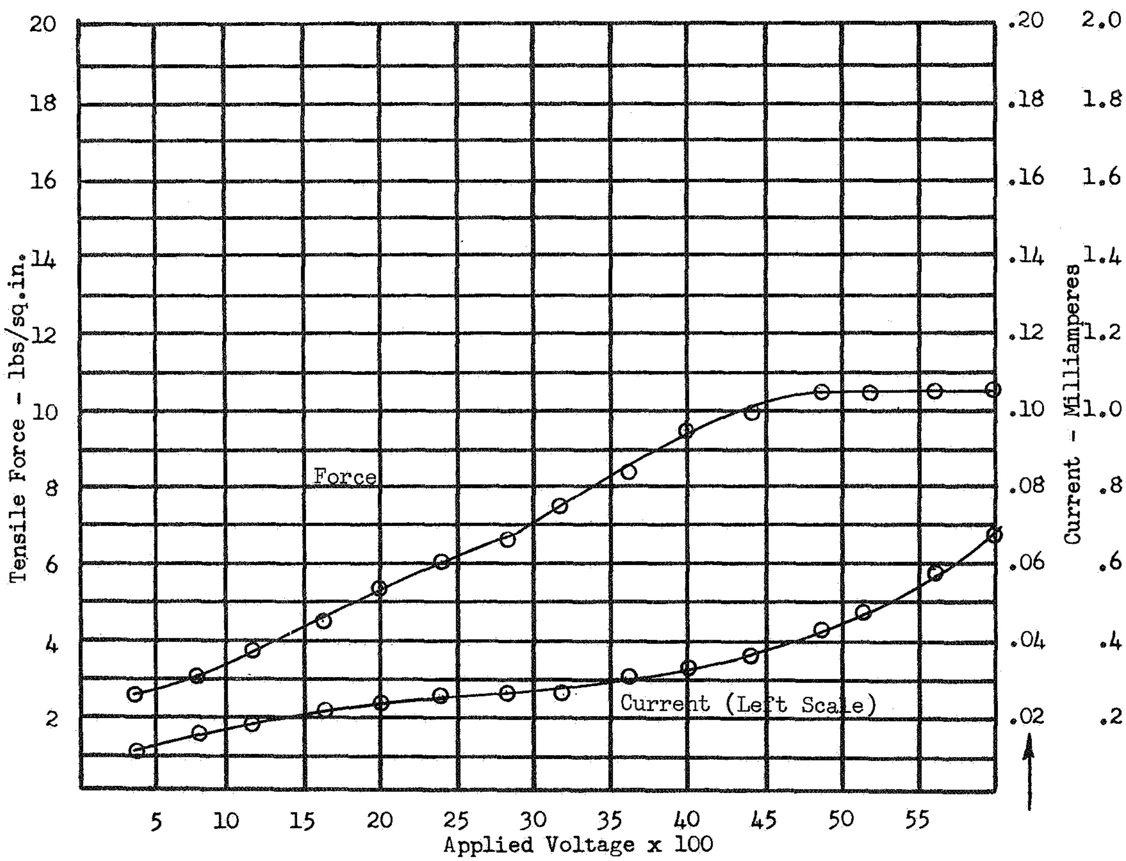


Figure 23 Electroadhesor Test Data
Force and Current at Applied Voltage

MATRIX TEST NO. 18

Material	BUNA-N RUBBER	Formulation	"A"
Thickness	2t = .150 in.	Temperature	AMBIENT
Surface	SMOOTH	Pressure	1.0 X 10^{-5} mm Hg
Environment	-	Polarity	NEGATIVE

Applied Voltage	Current Milliamperes	Force lbs/sq.in.	Applied Voltage	Current Milliamperes	Force lbs/sq.in.
400	.018	2.8	3600	.031	11.5
800	.020	4.8	4000	.032	12.0
1200	.025	6.8	4400	.035	12.5
1600	.028	8.0	4800	.038	12.8
2000	.029	9.0	5200	.042	13.0
2400	.030	9.7	5600	.048	13.2
2800	.031	10.4	6000	.054	13.2
3200	.031	11.0			

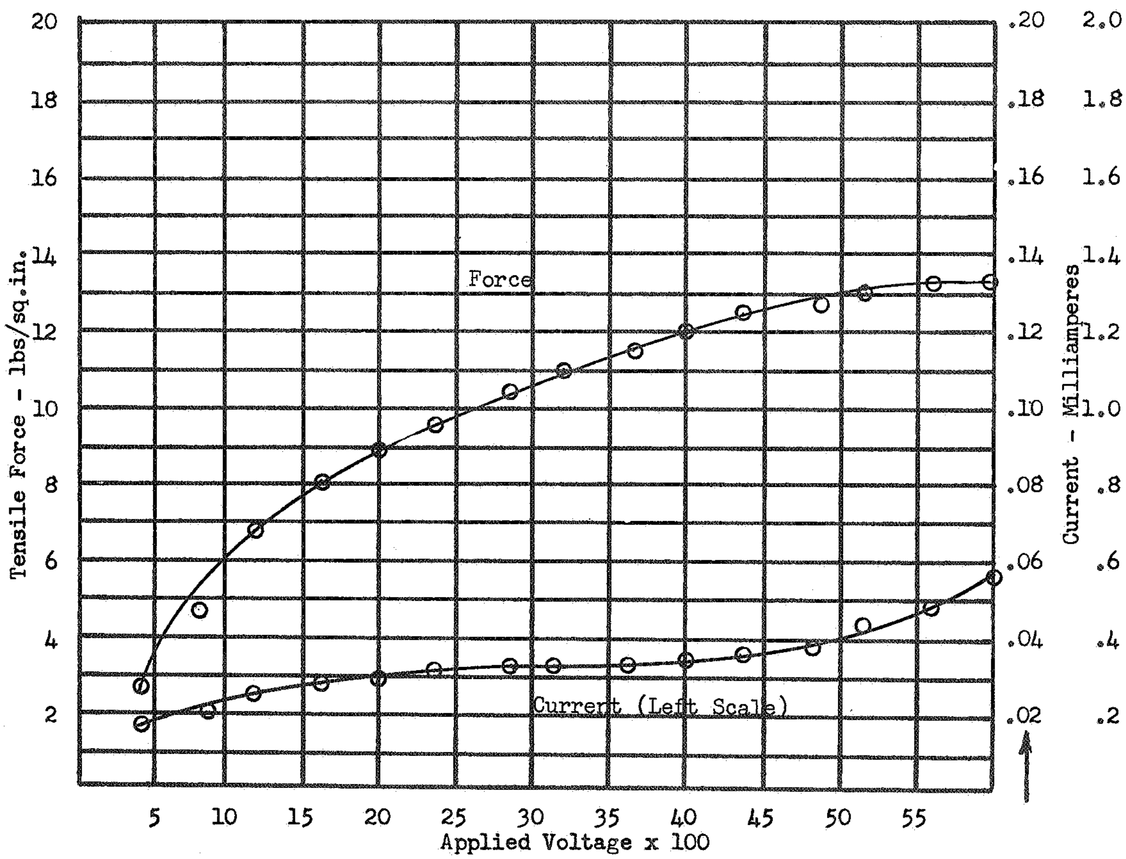


Figure 24 Electroadhesor Test Data
Force and Current at Applied Voltage

MATRIX TEST NO. 21

Material	BUNA-N RUBBER	Formulation	"B"
Thickness	t = .075 in.	Temperature	AMBIENT
Surface	SMOOTH	Pressure	AMBIENT
Environment	AIR	Polarity	NEGATIVE

Applied Voltage	Current Milliamperes	Force lbs/sq.in.	Applied Voltage	Current Milliamperes	Force lbs/sq.in.
400	.002	1.5	3600	.022	4.4
800	.004	1.8	4000	.025	5.1
1200	.007	2.1	4400	.029	5.7
1600	.009	2.1	4800	.031	6.5
2000	.011	2.4	5200	.035	7.1
2400	.015	2.6	5600	.040	7.1
2800	.017	3.0	6000	.048	7.1
3200	.020	3.7			

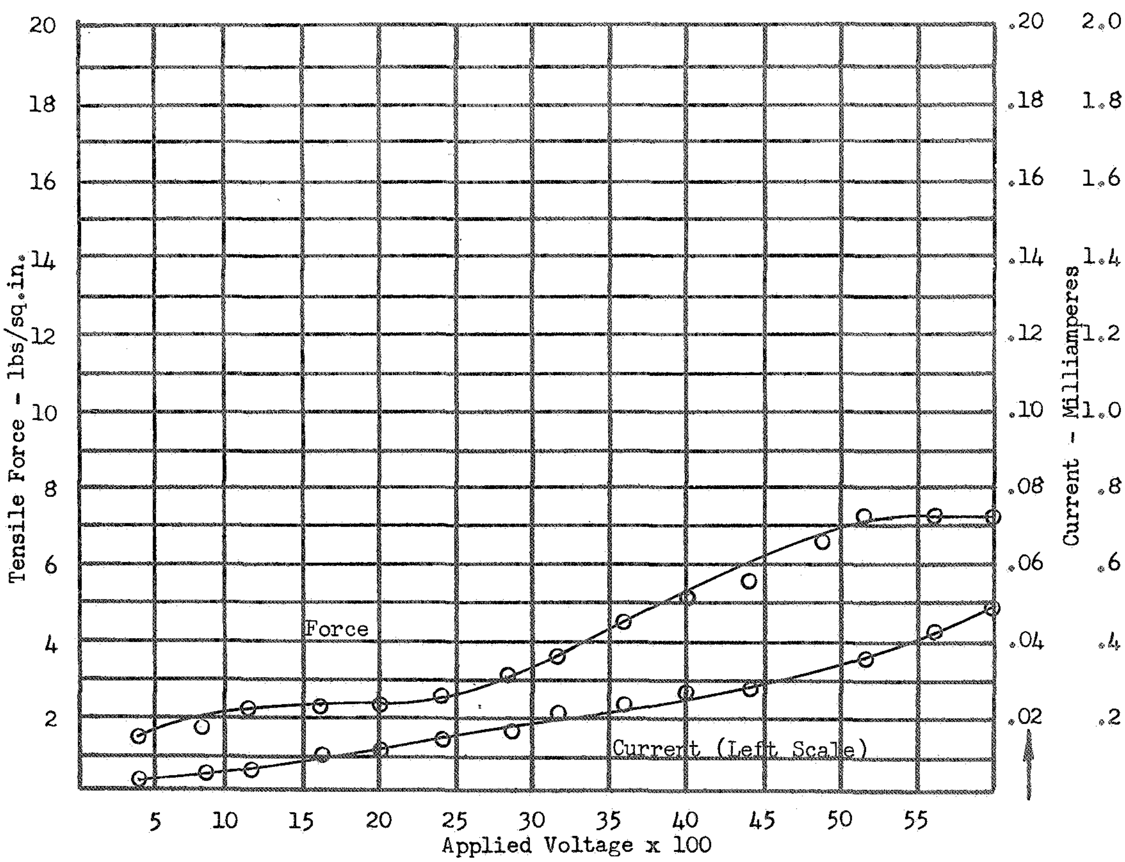


Figure 25 Electroadhesor Test Data
Force and Current at Applied Voltage

MATRIX TEST NO. 22

Material	BUNA-N RUBBER	Formulation	"B"
Thickness	t = .075 in.	Temperature	AMBIENT
Surface	SMOOTH	Pressure	1.0 X 10^{-5} mm Hg
Environment	-	Polarity	NEGATIVE

Applied Voltage	Current Milliamperes	Force lbs/sq.in.	Applied Voltage	Current Milliamperes	Force lbs/sq.in.
400	.001	2.0	3600	.016	7.9
800	.002	2.7	4000	.019	8.8
1200	.005	3.3	4400	.022	9.5
1600	.007	4.0	4800	.025	10.0
2000	.009	4.5	5200	.030	10.2
2400	.011	4.9	5600	.038	10.2
2800	.012	5.8	6000	.046	10.2
3200	.014	6.8			

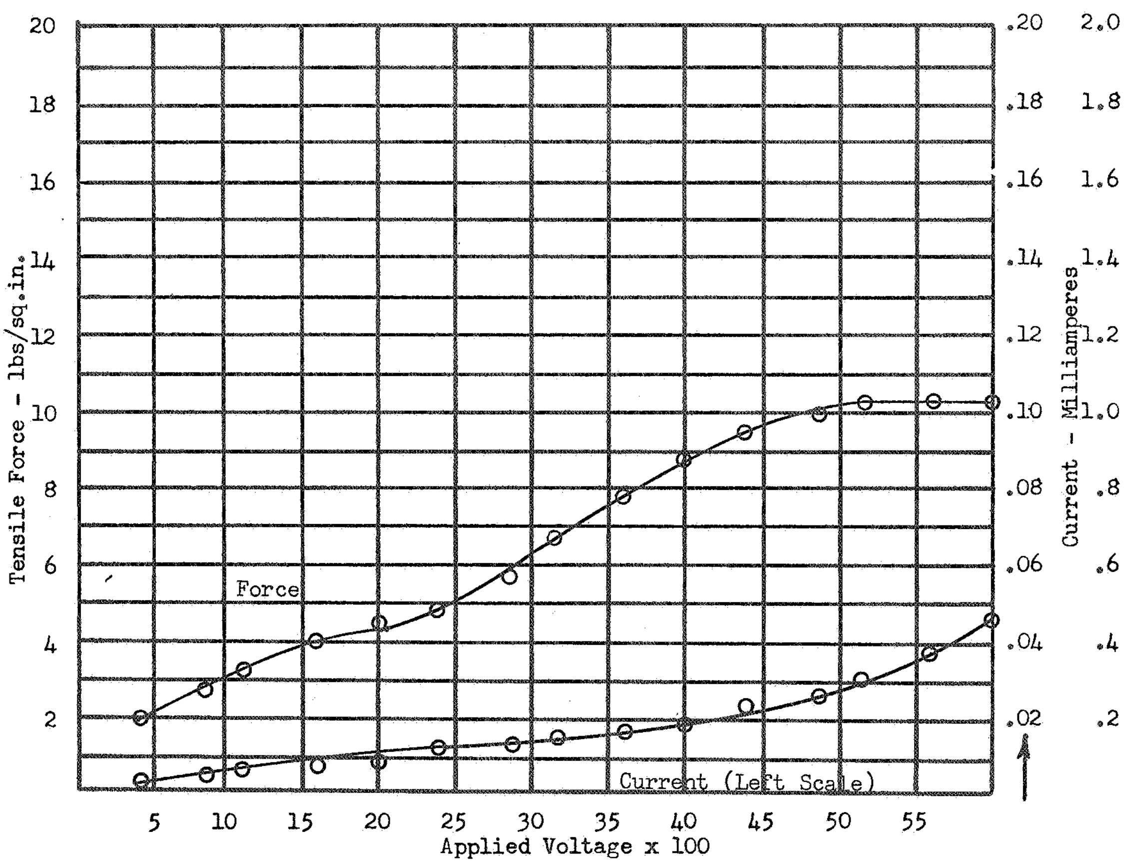


Figure 26 Electroadhesor Test Data
Force and Current at Applied Voltage

MATRIX TEST NO. 23

Material	BUNA-N RUBBER	Formulation	"B"
Thickness	t = .075 in.	Temperature	AMBIENT
Surface	ROUGH	Pressure	AMBIENT
Environment	AIR	Polarity	NEGATIVE

Applied Voltage	Current Milliamperes	Force lbs/sq.in.	Applied Voltage	Current Milliamperes	Force lbs/sq.in.
400	.007	No Data	3600	.060	2.4
800	.010	No Data	4000	.067	2.8
1200	.017	0.80	4400	.075	3.0
1600	.022	0.90	4800	.082	3.2
2000	.030	1.40	5200	.095	3.2
2400	.034	1.70	5600	.105	3.2
2800	.045	1.90	6000	.120	3.2
3200	.052	2.10			

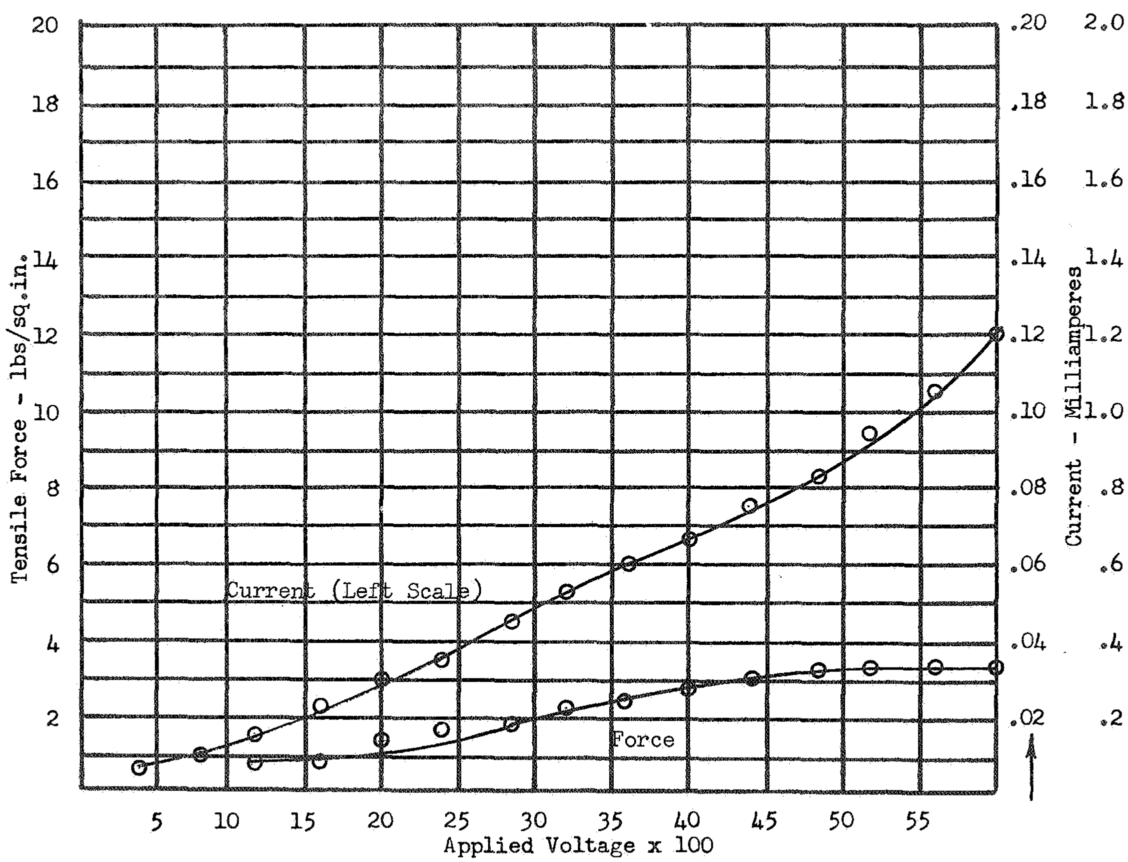


Figure 27 Electroadhesor Test Data
Force and Current at Applied Voltage

MATRIX TEST NO. 24

Material	BUNA-N RUBBER	Formulation	"B"
Thickness	t = .075 in.	Temperature	0°F
Surface	SMOOTH	Pressure	1.0 X 10^{-5} mm Hg
Environment	-	Polarity	NEGATIVE

Applied Voltage	Current Milliamperes	Force lbs/sq.in.	Applied Voltage	Current Milliamperes	Force lbs/sq.in.
400	No Data	No Data	3600	.008	0.08
800	No Data	No Data	4000	.010	1.00
1200	.001	No Data	4400	.011	1.10
1600	.002	No Data	4800	.011	1.20
2000	.003	No Data	5200	.012	1.40
2400	.004	0.02	5600	.014	2.00
2800	.006	0.04	6000	.014	2.00
3200	.007	0.06			

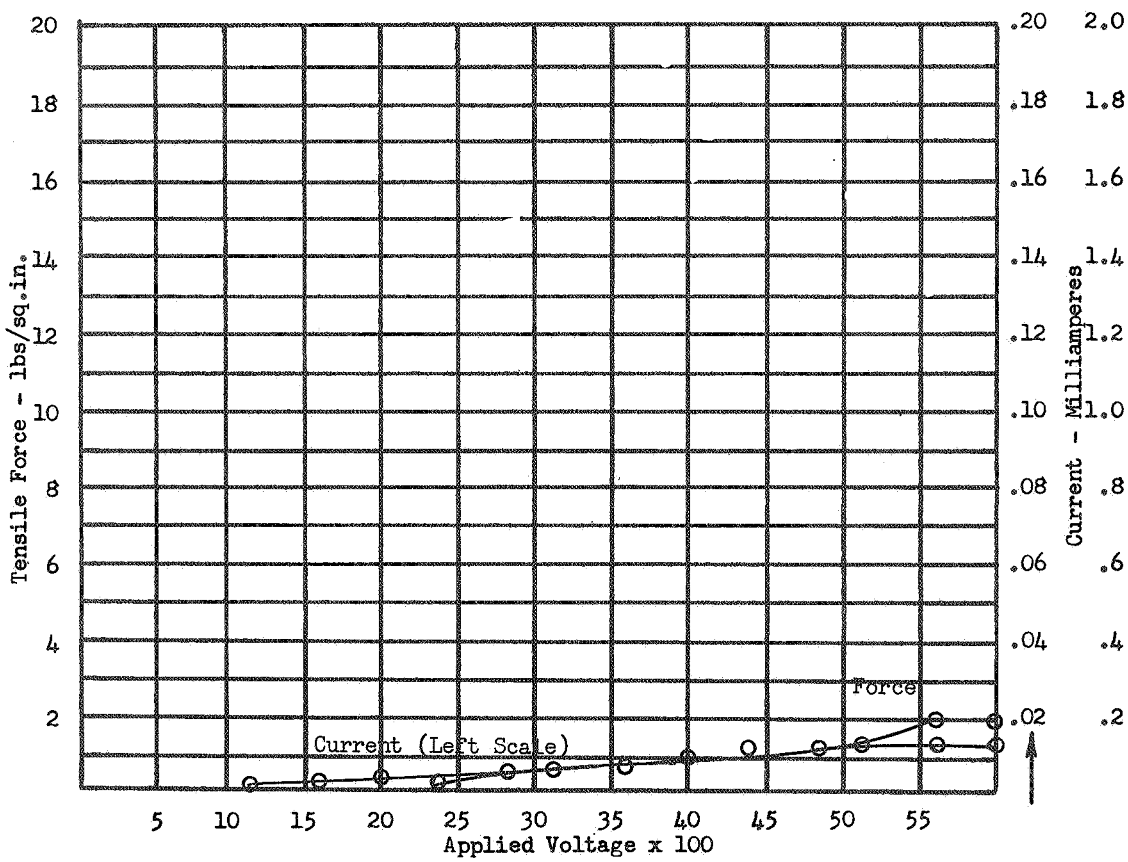


Figure 28 Electroadhesor Test Data
Force and Current at Applied Voltage

MATRIX TEST NO. 26

Material	BUNA-N RUBBER	Formulation	"B"
Thickness	t = .075 in.	Temperature	AMBIENT
Surface	SMOOTH	Pressure	5 - 7 PSIA
Environment	OXYGEN GAS	Polarity	NEGATIVE

Applied Voltage	Current Milliamperes	Force lbs/sq.in.	Applied Voltage	Current Milliamperes	Force lbs/sq.in.
400	.003	0.5	3600	,008	7.5
800	.004	1.0	4000	Current Arc-Over	
1200	.004	2.0	4400		
1600	.005	3.0	4800		
2000	.006	3.5	5200		
2400	.007	4.0	5600		
2800	.007	5.0	6000		
3200	.008	5.8			

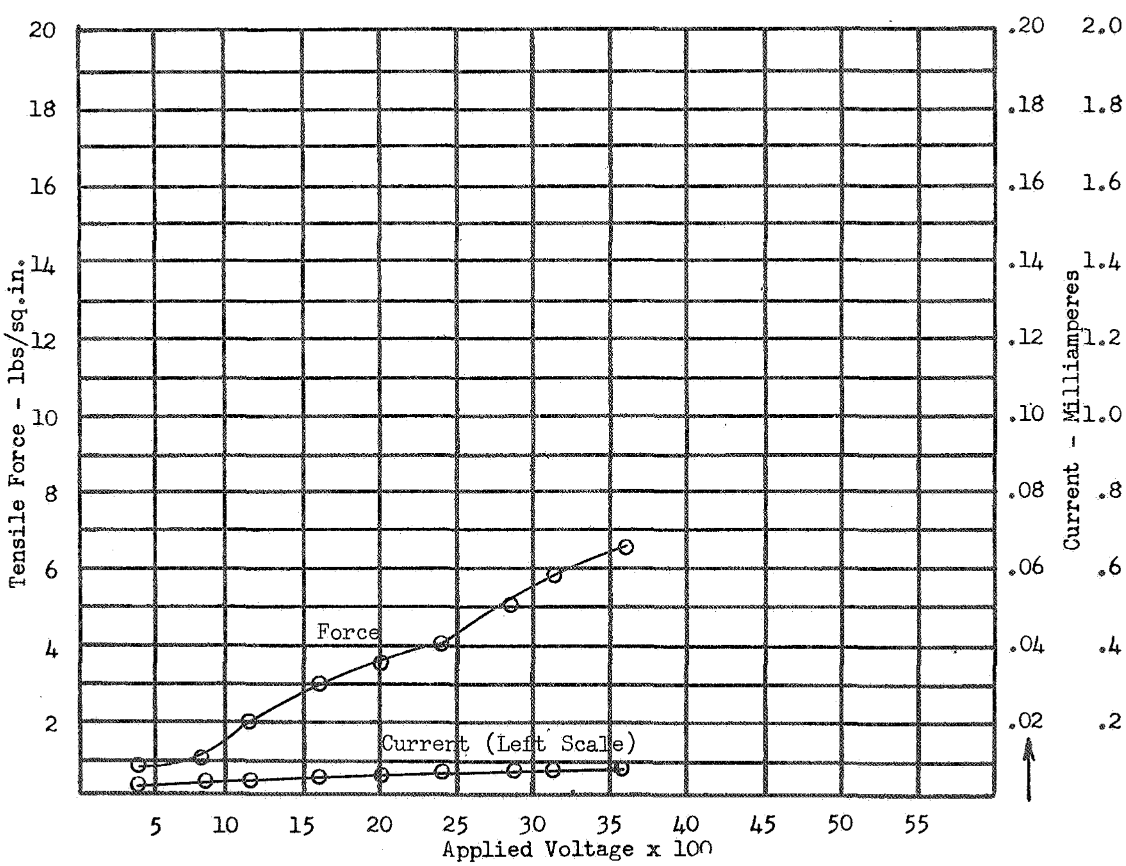


Figure 29 Electroadhesor Test Data
Force and Current at Applied Voltage

MATRIX TEST NO. 27

Material	BUNA-N RUBBER	Formulation	"B"
Thickness	2t = .150 in.	Temperature	AMBIENT
Surface	SMOOTH	Pressure	AMBIENT
Environment	AIR	Polarity	NEGATIVE

Applied Voltage	Current Milliamperes	Force lbs/sq.in.	Applied Voltage	Current Milliamperes	Force lbs/sq.in.
400	.002	1.7	3600	.010	6.8
800	.002	1.9	4000	.012	7.4
1200	.003	2.0	4400	.014	8.0
1600	.005	2.5	4800	.015	8.6
2000	.006	3.1	5200	.017	8.6
2400	.007	4.0	5600	.018	8.6
2800	.008	5.0	6000	.019	8.6
3200	.009	5.4			

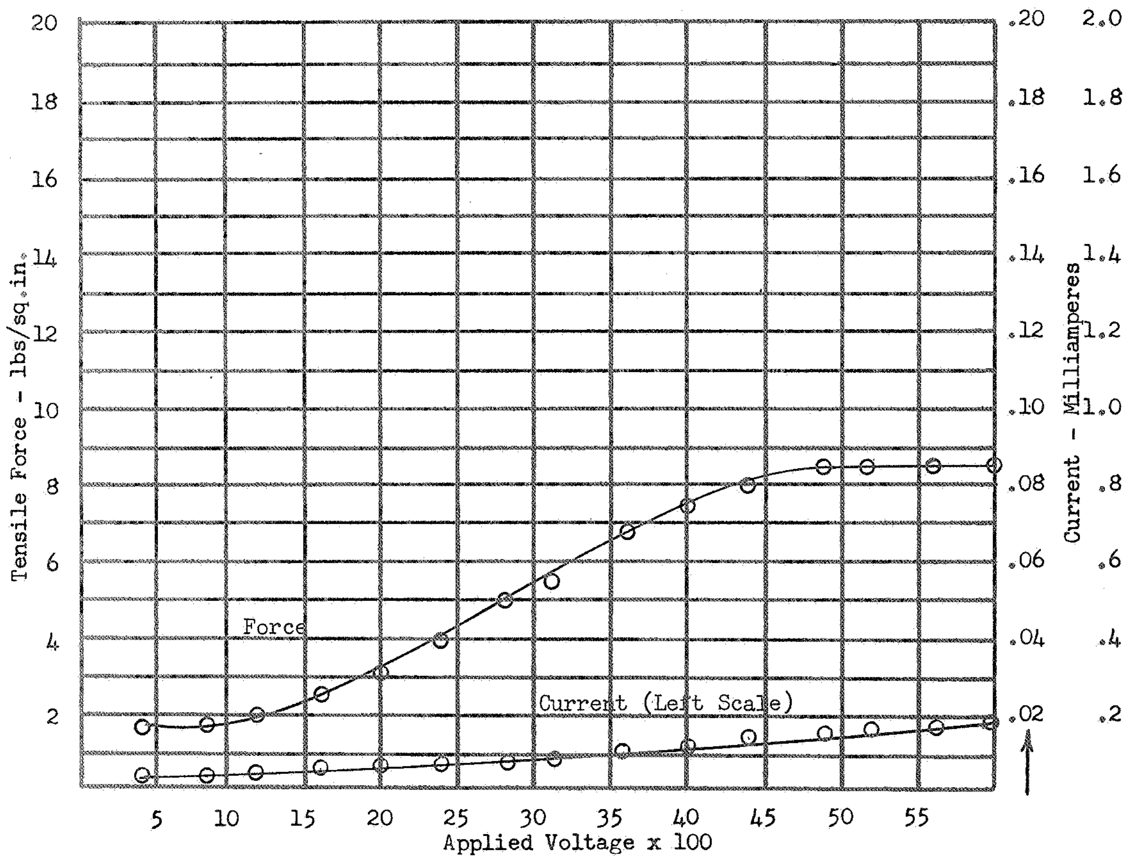


Figure 30 Electroadhesor Test Data
Force and Current at Applied Voltage

MATRIX TEST NO. 28

Material	BUNA-N RUBBER	Formulation	"B"
Thickness	2t = .150 in.	Temperature	AMBIENT
Surface	SMOOTH	Pressure	1.0×10^{-5} mm Hg
Environment	-	Polarity	NEGATIVE

Applied Voltage	Current Milliamperes	Force lbs/sq.in.	Applied Voltage	Current Milliamperes	Force lbs/sq.in.
400	No Data	2.1	3600	.009	9.0
800	.001	2.5	4000	.010	9.9
1200	.002	3.0	4400	.011	10.7
1600	.002	3.7	4800	.014	10.9
2000	.005	4.3	5200	.016	11.0
2400	.006	5.3	5600	.019	11.0
2800	.007	6.5	6000	.022	11.0
3200	.008	7.2			

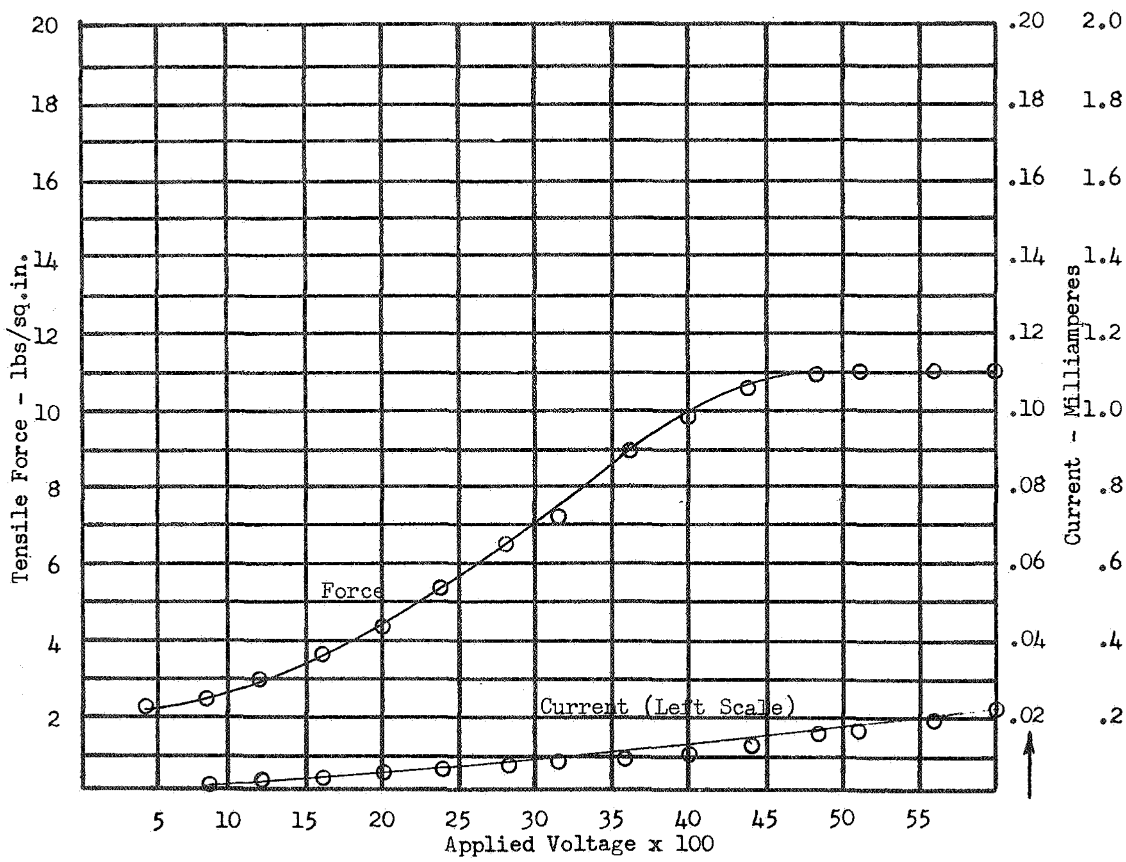


Figure 31 Electroadhesor Test Data
Force and Current at Applied Voltage

MATRIX TEST NO. 31

Material	BUNA-N RUBBER	Formulation	"C"
Thickness	t = .075 in.	Temperature	AMBIENT
Surface	SMOOTH	Pressure	AMBIENT
Environment	AIR	Polarity	NEGATIVE

Applied Voltage	Current Milliamperes	Force lbs/sq.in.	Applied Voltage	Current Milliamperes	Force lbs/sq.in.
400	.007	1.2	3600	.045	5.9
800	.010	1.6	4000	.049	7.1
1200	.012	1.8	4400	.055	8.0
1600	.016	2.0	4800	.060	8.8
2000	.019	2.8	5200	.065	9.1
2400	.027	3.3	5600	.070	9.2
2800	.035	4.2	6000	.075	9.2
3200	.040	5.0			

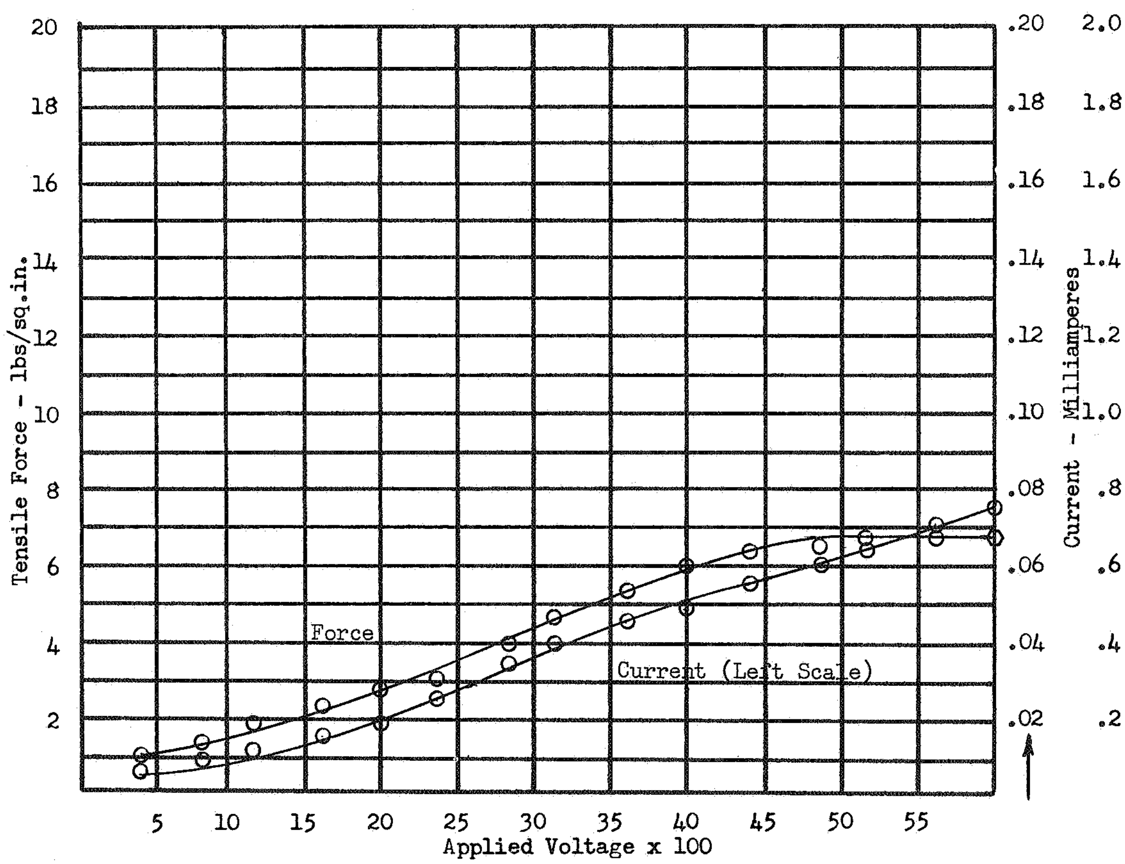


Figure 32 Electroadhesor Test Data
Force and Current at Applied Voltage

MATRIX TEST NO. 32

Material	BUNA-N RUBBER	Formulation	"C"
Thickness	t = .075 in.	Temperature	AMBIENT
Surface	SMOOTH	Pressure	1.0 X 10^{-5} mm Hg
Environment	-	Polarity	NEGATIVE

Applied Voltage	Current Milliamperes	Force lbs/sq.in.	Applied Voltage	Current Milliamperes	Force lbs/sq.in.
400	.003	2.0	3600	.027	7.0
800	.005	2.8	4000	.029	7.8
1200	.008	3.2	4400	.033	8.2
1600	.011	3.7	4800	.038	9.0
2000	.015	4.0	5200	.043	9.6
2400	.018	4.4	5600	.048	9.6
2800	.021	5.1	6000	.054	9.6
3200	.024	5.5			

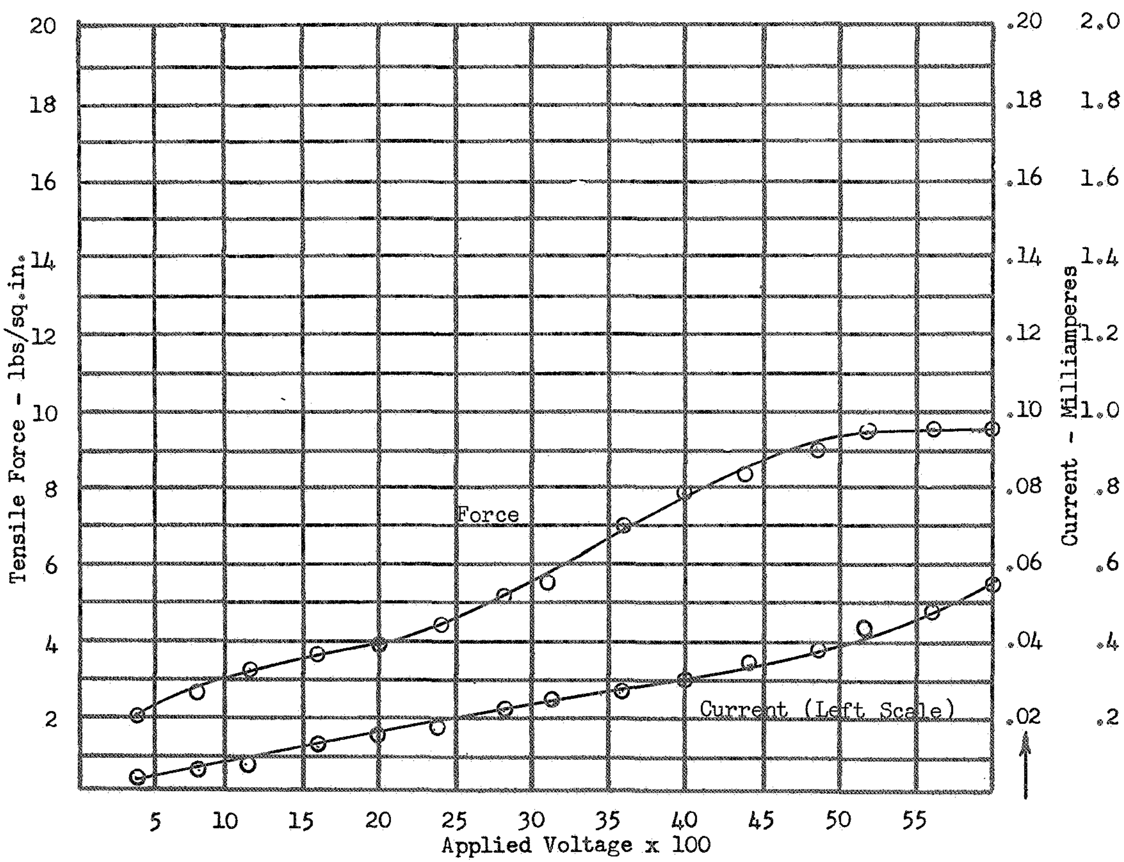


Figure33 Electroadhesor Test Data
Force and Current at Applied Voltage

MATRIX TEST NO. 33

Material	BUNA-N RUBBER	Formulation	"C"
Thickness	t = .075 in.	Temperature	0°F
Surface	SMOOTH	Pressure	1.0 X 10^{-5} mm Hg
Environment	-	Polarity	NEGATIVE

Applied Voltage	Current Milliamperes	Force lbs/sq.in.	Applied Voltage	Current Milliamperes	Force lbs/sq.in.
400	0	0	3600	.002	0.02
800	0	0	4000	.003	0.04
1200	0	0	4400	.005	0.07
1600	0	0	4800	.006	0.10
2000	0	0	5200	.007	0.10
2400	0	0	5600	.009	0.10
2800	0	0	6000	.009	0.10
3200	.001	0			

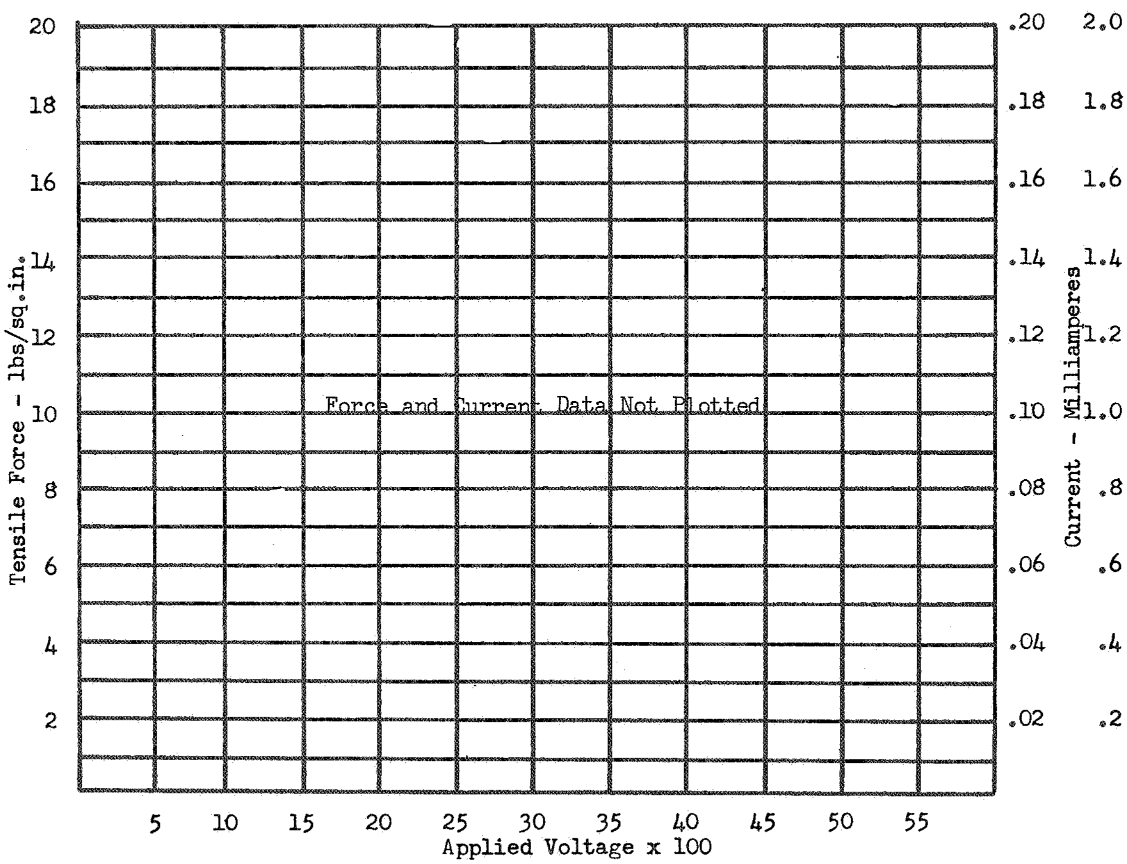


Figure 34 Electroadhesor Test Data
Force and Current at Applied Voltage

MATRIX TEST NO. 34

Material	BUNA-N RUBBER	Formulation	"C"
Thickness	t = .075 in.	Temperature	AMBIENT
Surface	SMOOTH	Pressure	5 - 7 PSIA
Environment	OXYGEN GAS	Polarity	NEGATIVE

Applied Voltage	Current Milliamperes	Force lbs/sq.in.	Applied Voltage	Current Milliamperes	Force lbs/sq.in.
400	.002	1.0	3600	.007	3.0
800	.002	2.0	4000	Current Arc-Over	
1200	.003	2.5	4400		
1600	.004	2.7	4800		
2000	.005	3.0	5200		
2400	.005	3.0	5600		
2800	.006	3.0	6000		
3200	.006	3.0			

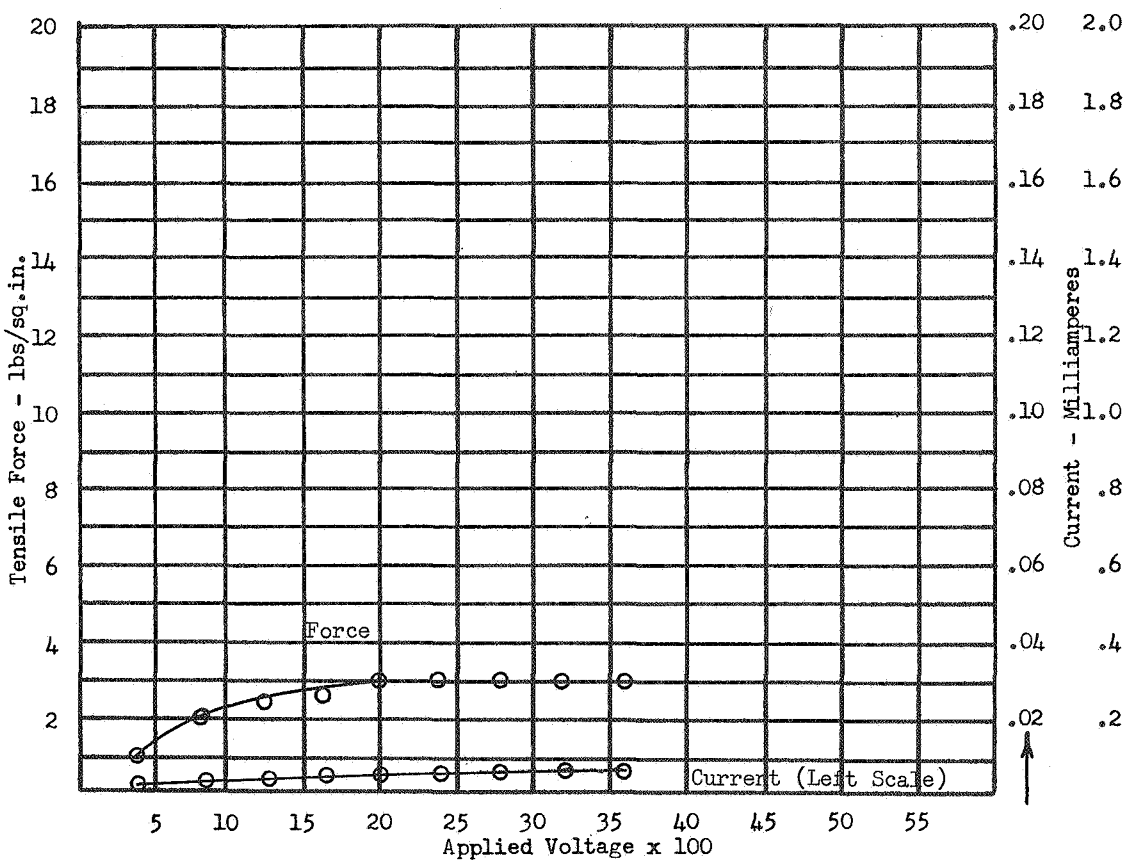


Figure 35 Electroadhesor Test Data
Force and Current at Applied Voltage

MATRIX TEST NO. 35

Material	BUNA-N RUBBER	Formulation	"C"
Thickness	2t = .150 in.	Temperature	AMBIENT
Surface	SMOOTH	Pressure	AMBIENT
Environment	AIR	Polarity	NEGATIVE

Applied Voltage	Current Milliamperes	Force lbs/sq.in.	Applied Voltage	Current Milliamperes	Force lbs/sq.in.
400	.005	2.3	3600	.026	5.8
800	.007	2.7	4000	.028	6.3
1200	.010	3.1	4400	.030	6.9
1600	.012	3.6	4800	.033	7.3
2000	.015	3.9	5200	.038	7.6
2400	.017	4.2	5600	.041	7.8
2800	.019	4.6	6000	.045	7.8
3200	.023	5.2			

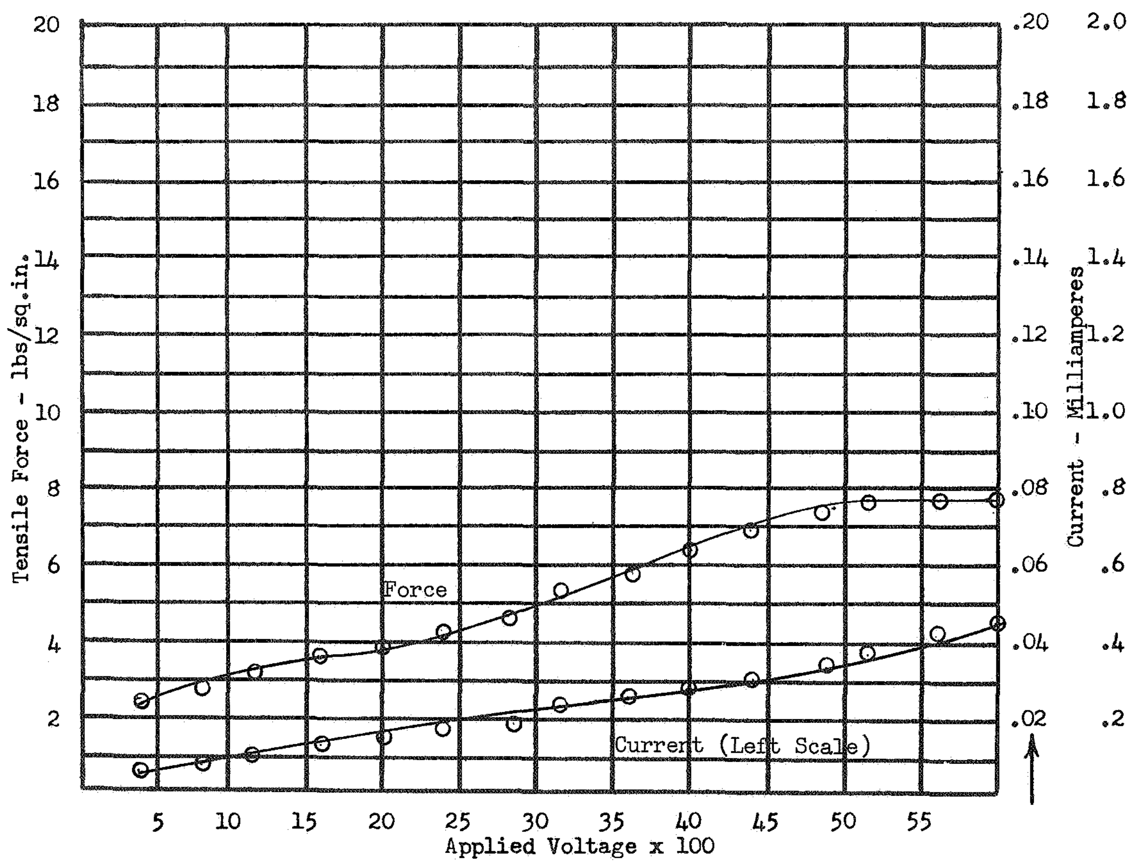


Figure36 Electroadhesor Test Data
Force and Current at Applied Voltage

MATRIX TEST NO. 36

Material	BUNA-N RUBBER	Formulation	"C"
Thickness	2t = .150 in.	Temperature	AMBIENT
Surface	SMOOTH	Pressure	1.0×10^{-5} mm Hg
Environment		Polarity	

Applied Voltage	Current Milliamperes	Force lbs/sq.in.	Applied Voltage	Current Milliamperes	Force lbs/sq.in.
400	.005	3.0	3600	.022	8.2
800	.006	3.6	4000	.025	9.0
1200	.008	4.1	4400	.027	9.7
1600	.009	4.6	4800	.030	9.9
2000	.011	4.9	5200	.033	10.0
2400	.015	5.2	5600	.041	10.0
2800	.017	6.4	6000	.049	10.0
3200	.019	7.1			

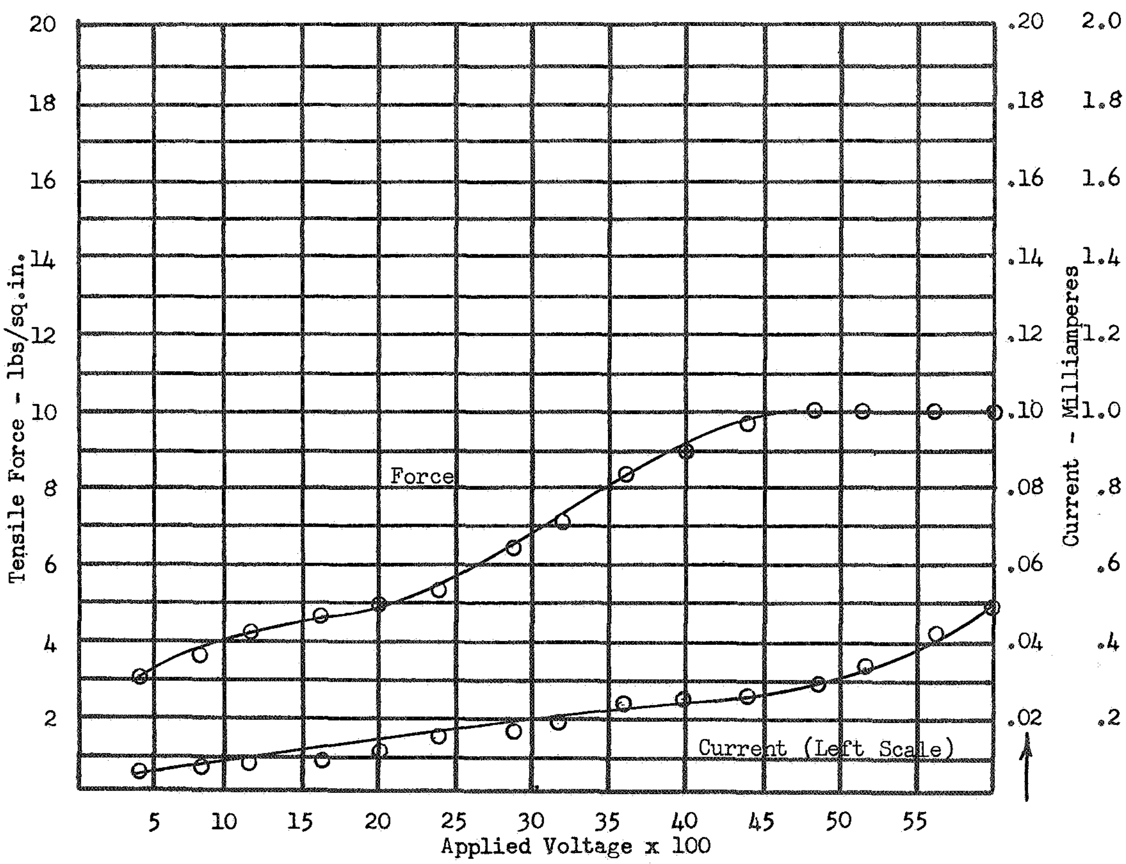


Figure 37 Electroadhesor Test Data
Force and Current at Applied Voltage

MATRIX TEST NO. 9

Material	BUNA-N RUBBER	Formulation	"A"
Thickness	t = .075 in.	Temperature	AMBIENT
Surface	SMOOTH	Pressure	AMBIENT
Environment	AIR	Polarity	NEGATIVE

VOLTAGE HELD CONSTANT AT	FORCE VARIED IN SEQUENCE	POWER-ON TIME AND RESULTS	POWER-OFF TIME TO FORCE DECAY
400	2.5 lbs/sq.in.	Released after 5 sec.	-
1200	2.5	No release after 5 min.	30 sec.
	4.5	Released after 30 sec.	-
	5.0	Released immediately	-
	6.0	Released immediately	-
2400	2.5	No release after 5 min.	1 min. 30 sec.
	4.5	No release after 5 min.	30 sec.
	5.0	Released after 2 min.	-
	6.0	Released immediately	
3800	2.5	No release after 5 min.	2 min. 30 sec.
	4.5	No release after 5 min.	2 min.
	5.0	Released after 2 min.	-
	6.0	Released immediately	-
5000	2.5	No release after 5 min.	2 min. 30 sec.
	4.5	No release after 5 min.	2 min.
	5.0	Released after 2 min.	-
	6.0	Released immediately	-

LOAD HELD CONSTANT AT	VOLTAGE VARIED IN SEQUENCE	POWER-ON TIME AND RESULTS
5 lb./sq. in.	5000	Released after 1 min. 15 sec.
	3800	Released after 20 sec.
	3400	Released after 10 sec.
	2800	Released immediately

Table II Electroadhesor Test Data
Force-Voltage-Time Relationship

MATRIX TEST NO. 10

Material	BUNA-N RUBBER	Formulation	"A"
Thickness	t = .075 in.	Temperature	AMBIENT
Surface	SMOOTH	Pressure	1.0 X 10^{-5} mm Hg
Environment	-	Polarity	NEGATIVE

VOLTAGE HELD CONSTANT AT	FORCE VARIED IN SEQUENCE	POWER-ON TIME AND RESULTS	POWER-OFF TIME TO FORCE DECAY
400	2.5 lbs/sq.in.	Released after 10 sec.	-
1200	2.5	No release after 5 min.	1 min.
	4.5	Released after 1 min.	-
	5.0	Released after 10 sec.	-
	6.0	Released immediately	-
2400	2.5	No release after 5 min.	1 min. 45 sec.
	4.5	No release after 5 min.	50 sec.
	5.0	Released after 3 min. 15	-
	6.0	Released after 15 sec.	-
3800	2.5	No release after 5 min.	3 min.
	4.5	No release after 5 min.	2 min. 40 sec.
	5.0	Released after 4 min. 10	-
	6.0	Released after 1 min.	-
5000	2.5	No release after 5 min.	2 min. 30 sec.
	4.5	No release after 5 min.	1 min. 45 sec.
	5.0	No release after 5 min.	30 sec.
	6.0	Released after 50 sec.	-

LOAD HELD CONSTANT AT	VOLTAGE VARIED IN SEQUENCE	POWER-ON TIME AND RESULTS
5 lb./sq. in.	5000	Released after 2 minutes
	3800	Released after 1 minute 10 seconds
	3400	Released after 35 seconds.
	2800	Released after 20 seconds
	2000	Released immediately

Table III Electroadhesor Test Data
Force-Voltage-Time Relationship

MATRIX TEST NO. 11

Material	BUNA-N RUBBER	Formulation	"A"
Thickness	t = .075 in.	Temperature	AMBIENT
Surface	ROUGH	Pressure	AMBIENT
Environment	AIR	Polarity	NEGATIVE

VOLTAGE HELD CONSTANT AT	FORCE VARIED IN SEQUENCE	POWER-ON TIME AND RESULTS	POWER-OFF TIME TO FORCE DECAY
400	2.5 lbs/sq.in.	Released immediately	-
1200	2.5	Released immediately	-
	4.5	Released immediately	-
	5.0	Released immediately	-
	6.0	Released immediately	-
2400	2.5	Released immediately	-
	4.5	Released immediately	-
	5.0	Released immediately	-
	6.0	Released immediately	-
3800	2.5	Released after 10 sec.	-
	4.5	Released immediately	-
	5.0	Released immediately	-
	6.0	Released immediately	-
5000	2.5	No release after 5 min.	90 sec.
	4.5	Released after 5 sec.	-
	5.0	Released immediately	-
	6.0	Released immediately	-

LOAD HELD CONSTANT AT	VOLTAGE VARIED IN SEQUENCE	POWER-ON TIME AND RESULTS
3.0 lb./sq. in.	5000	No release after 5 min.
	3800	No release after 5 min.
	3400	Released after 30 sec.
4.0 lb./sq. in.	5000	Released after 10 sec.
	3800	Released immediately

Table IV Electroadhesor Test Data
Force-Voltage-Time Relationship

MATRIX TEST NO. 12

Material	BUNA-N RUBBER	Formulation	"A"
Thickness	t = .075 in.	Temperature	AMBIENT
Surface	ROUGH	Pressure	1.0×10^{-5} mm Hg.
Environment	-	Polarity	NEGATIVE

VOLTAGE HELD CONSTANT AT	FORCE VARIED IN SEQUENCE	POWER-ON TIME AND RESULTS	POWER-OFF TIME TO FORCE DECAY
400	2.5 lbs/sq.in.	Released immediately	-
1200	2.5	Released immediately	-
	4.5	Released immediately	-
	5.0	Released immediately	-
	6.0	Released immediately	-
2400	2.5	No release after 5 min.	15 sec.
	4.5	Released immediately	-
	5.0	Released immediately	-
	6.0	Released immediately	-
3800	2.5	No release after 5 min.	10 sec.
	4.5	No release after 5 min.	5 sec.
	5.0	Released immediately	-
	6.0	Released immediately	-
5000	2.5	No release after 5 min.	8 sec.
	4.5	No release after 5 min.	3 sec.
	5.0	No release after 5 min.	1 sec.
	6.0	Released immediately	-

LOAD HELD CONSTANT AT	VOLTAGE VARIED IN SEQUENCE	POWER-ON TIME AND RESULTS
5.0 lb./sq.in.	5000	No release after 5 min.
	4600	No release after 5 min.
	4200	Released immediately
	3800	Released immediately

Table V Electroadhesor Test Data
Force-Voltage-Time Relationship

MATRIX TEST NO. 19

Material	BUNA-N RUBBER	Formulation	"A"
Thickness	2 t = .150 in.	Temperature	AMBIENT
Surface	SMOOTH	Pressure	AMBIENT
Environment	AIR	Polarity	NEGATIVE

VOLTAGE HELD CONSTANT AT	FORCE VARIED IN SEQUENCE	POWER-ON TIME AND RESULTS	POWER-OFF TIME TO FORCE DECAY
400	2.5 lbs/sq.in.	No release after 5 min.	1 min.
1200	2.5	No release after 5 min.	45 sec.
	4.5	No release after 5 min.	30 sec.
	5.0	Released after 3 min.	-
	6.0	Released after 30 sec.	-
2400	2.5	No release after 5 min.	2 min.
	4.5	No release after 5 min.	1 min.
	5.0	No release after 5 min.	30 sec.
	6.0	Released after 30 sec.	-
3800	2.5	No release after 5 min.	3 min. 30 sec.
	4.5	No release after 5 min.	2 min. 15 sec.
	5.0	No release after 5 min.	2 min.
	6.0	Released after 30 sec.	-
5000	2.5	No release after 5 min.	2 min.
	4.5	No release after 5 min.	1 min. 30 sec.
	5.0	No release after 5 min.	1 min.
	6.0	Released after 15 sec.	-

LOAD HELD CONSTANT AT	VOLTAGE VARIED IN SEQUENCE	POWER-ON TIME AND RESULTS
5.0 lb./sq. in.	5000	No release after 5 min.
	3800	No release after 5 min.
	3400	No release after 5 min.
	2800	Released after 1 min.
	2600	Released after 30 sec.

Table VI Electroadhesor Test Data
Force-Voltage-Time Relationship

MATRIX TEST NO. 20

Material	BUNA-N RUBBER	**Formulation**	"A"
Thickness	2t = .150 in.	**Temperature**	AMBIENT
Surface	ROUGH	**Pressure**	AMBIENT
Environment	AIR	**Polarity**	NEGATIVE

VOLTAGE HELD CONSTANT AT	FORCE VARIED IN SEQUENCE	POWER-ON TIME AND RESULTS	POWER-OFF TIME TO FORCE DECAY
400	2.5 lbs/sq.in.	Released after 30 sec.	-
1200	2.5	Released after 5 sec.	-
	4.5	Released immediately	-
	5.0	Released immediately	-
	6.0	Released immediately	-
2400	2.5	Released after 30 sec.	-
	4.5	Released immediately	
	5.0	Released immediately	-
	6.0	Released immediately	-
3800	2.5	Released after 50 sec.	-
	4.5	Released after 20 sec.	-
	5.0	Released immediately	-
	6.0	Released immediately	-
5000	2.5	Released after 50 sec.	-
	4.5	Released after 10 sec.	-
	5.0	Released after 5 sec.	-
	6.0	Released immediately	-

LOAD HELD CONSTANT AT	VOLTAGE VARIED IN SEQUENCE	POWER-ON TIME AND RESULTS
5.0 lb./sq.in.	5000	Released after 10 seconds
	3800	Released immediately
	3400	Released immediately
	2800	Released immediately

Table VII Electroadhesor Test Data
Force-Voltage-Time Relationship

MATRIX TEST NO. 25

Material	BUNA-N RUBBER	Formulation	"B"
Thickness	t = .075 in.	Temperature	AMBIENT
Surface	SMOOTH	Pressure	AMBIENT
Environment	AIR	Polarity	NEGATIVE

VOLTAGE HELD CONSTANT AT	FORCE VARIED IN SEQUENCE	POWER-ON TIME AND RESULTS	POWER-OFF TIME TO FORCE DECAY
400	2.5 lbs/sq.in.	No release after 5 min.	1 min. 10 sec.
1200	2.5	No release after 5 min.	1 min.
	4.5	No release after 5 min.	40 sec.
	5.0	Released after 4 min. 30	-
	6.0	Released after 2 min.	-
2400	2.5	No release after 5 min.	2 min. 30 sec.
	4.5	No release after 5 min.	2 min.
	5.0	No release after 5 min.	1 min. 15 sec.
	6.0	Released after 1 min. 30	-
3800	2.5	No release after 5 min.	No rel. after 5 min.
	4.5	No release after 5 min.	3 min.
	5.0	No release after 5 min.	2 min. 20 sec.
	6.0	Released after 1 min. 10	-
5000	2.5	No release after 5 min.	No rel. after 5 min.
	4.5	No release after 5 min.	2 min. 50 sec.
	5.0	No release after 5 min.	3 min. 15 sec.
	6.0	Released after 1 min. 20	-

LOAD HELD CONSTANT AT	VOLTAGE VARIED IN SEQUENCE	POWER-ON TIME AND RESULTS
5.0 lb./sq.in.	5000	No release after 5 minutes
	3800	No release after 5 minutes
	3400	No release after 5 minutes
	2800	No release after 5 minutes
	2600	Released after 2 minutes 15 seconds
	2000	Released immediately

Table VIII Electroadhesor Test Data
Force-Voltage-Time Relationship

MATRIX TEST NO. 29

Material	BUNA-N RUBBER	Formulation	"B"
Thickness	2t = .150 in.	Temperature	AMBIENT
Surface	SMOOTH	Pressure	AMBIENT
Environment	AIR	Polarity	NEGATIVE

VOLTAGE HELD CONSTANT AT	FORCE VARIED IN SEQUENCE	POWER-ON TIME AND RESULTS	POWER-OFF TIME TO FORCE DECAY
400	2.5 lbs/sq.in.	Released after 2 min. 20 sec.	-
1200	2.5	Released after 10 sec.	-
	4.5	Released immediately	-
	5.0	Released immediately	-
	6.0	Released immediately	-
2400	2.5	Released after 10 sec.	-
	4.5	Released immediately	-
	5.0	Released immediately	-
	6.0	Released immediately	-
3800	2.5	Released after 6 sec.	-
	4.5	Released immediately	-
	5.0	Released immediately	-
	6.0	Released immediately	-
5000	2.5	Released after 25 sec.	-
	4.5	Released after 1 min.	-
	5.0	Released immediately	-
	6.0	Released immediately	-

LOAD HELD CONSTANT AT	VOLTAGE VARIED IN SEQUENCE	POWER-ON TIME AND RESULTS
5.0 lb./sq.in.	5000	Released after 20 sec.
	3800	Released immediately
	3400	Released immediately
	2800	Released immediately

Table IX Electroadhesor Test Data
Force-Voltage-Time Relationship

MATRIX TEST NO. 30

Material	BUNA-N RUBBER	Formulation	"B"
Thickness	2t = .150 in.	Temperature	AMBIENT
Surface	ROUGH	Pressure	AMBIENT
Environment	AIR	Polarity	NEGATIVE

VOLTAGE HELD CONSTANT AT	FORCE VARIED IN SEQUENCE	POWER-ON TIME AND RESULTS	POWER-OFF TIME TO FORCE DECAY
400	2.5 lbs/sq.in.	Released immediately	-
1200	2.5	Released immediately	-
	4.5	Released immediately	-
	5.0	Released immediately	-
	6.0	Released immediately	-
2400	2.5	Released immediately	-
	4.5	Released immediately	-
	5.0	Released immediately	-
	6.0	Released immediately	-
3800	2.5	Released immediately	-
	4.5	Released immediately	-
	5.0	Released immediately	-
	6.0	Released immediately	-
5000	2.5	Released immediately	-
	4.5	Released immediately	-
	5.0	Released immediately	-
	6.0	Released immediately	-

LOAD HELD CONSTANT AT	VOLTAGE VARIED IN SEQUENCE	POWER-ON TIME AND RESULTS
5.0 lb./sq.in.	5000	Released immediately
	3800	Released immediately
	3400	Released immediately
	2800	Released immediately

Table X Electroadhesor Test Data
Force-Voltage-Time Relationship

MATRIX TEST NO. 37

Material	BUNA-N RUBBER	**Formulation**	"C"
Thickness	2t = .150 in.	**Temperature**	AMBIENT
Surface	SMOOTH	**Pressure**	AMBIENT
Environment	AIR	**Polarity**	NEGATIVE

VOLTAGE HELD CONSTANT AT	FORCE VARIED IN SEQUENCE	POWER-ON TIME AND RESULTS	POWER-OFF TIME TO FORCE DECAY
400	2.5 lbs/sq.in.	Released after 20 sec.	-
1200	2.5	Released after 15 sec.	-
	4.5	Released immediately	-
	5.0	Released immediately	-
	6.0	Released immediately	-
2400	2.5	Released after 30 sec.	-
	4.5	Released after 15 sec.	-
	5.0	Released after 10 sec.	-
	6.0	Released immediately	-
3800	2.5	No release after 5 min.	1 min.
	4.5	Rel. after 1 min. 50 sec.	-
	5.0	Rel. after 1 min. 10 sec.	-
	6.0	Released immediately	-
5000	2.5	No release after 5 min.	1 min. 15 sec.
	4.5	No release after 5 min.	30 sec.
	5.0	Released immediately	-
	6.0	Released immediately	-

LOAD HELD CONSTANT AT	VOLTAGE VARIED IN SEQUENCE	POWER-ON TIME AND RESULTS
4.5 lb./sq.in.	5000	Released after 5 sec.
	3800	Released after 5 sec.
	2400	Released after 3 sec.
	1200	Released immediately
5.0 lb./sq.in.	5000	Released after 2 sec.
	3800	Released after 1 sec.
	2400	Released immediately

Table XI Electroadhesor Test Data
Force-Voltage-Time Relationship

MATRIX TEST NO. 38

Material	BUNA-N RUBBER	Formulation	"C"
Thickness	2t = .150 in.	Temperature	AMBIENT
Surface	ROUGH	Pressure	AMBIENT
Environment	AIR	Polarity	NEGATIVE

VOLTAGE HELD CONSTANT AT	FORCE VARIED IN SEQUENCE	POWER-ON TIME AND RESULTS	POWER-OFF TIME TO FORCE DECAY
400	2.5 lbs/sq.in.	Released after 10 sec.	-
1200	2.5	Released after 20 sec.	-
	4.5	Released immediately	-
	5.0	Released immediately	-
	6.0	Released immediately	-
2400	2.5	Released after 20 sec.	-
	4.5	Released immediately	-
	5.0	Released immediately	-
	6.0	Released immediately	-
3800	2.5	Released after 30 sec.	-
	4.5	Released immediately	-
	5.0	Released immediately	-
	6.0	Released immediately	-
5000	2.5	Released after 35 sec.	-
	4.5	Released after 5 sec.	-
	5.0	Released immediately	-
	6.0	Released immediately	-

LOAD HELD CONSTANT AT	VOLTAGE VARIED IN SEQUENCE	POWER-ON TIME AND RESULTS
5.0 lb./sq.in.	5000	Released after 15 sec.
	3800	Released after 2 sec.
	3400	Released immediately

Table XII Electroadhesor Test Data
Force-Voltage-Time Relationship

MATRIX TEST NO. (REF)	FIGURE NO. (REF)	MATERIAL FORMULATION	THICKNESS IN.	RESISTIVITY* OHM-CM
1	11	"A"	.075 in.	5.30×10^3
2	12	"	"	5.10×10^3
3	13	"	"	7.60×10^3
4	14	"	"	7.60×10^3
5	15	"	"	Indeterminate
6	16	"	"	1.50×10^2
7	17	"	"	Indeterminate
8	18	"	"	7.15×10^3
13	19	"	"	Indeterminate
14	20	"	"	Indeterminate
15	21	"	"	Indeterminate
16	22	"	"	Indeterminate
17	23	"	.150 in.	7.85×10^3
18	24	"	"	8.50×10^3
21	25	"B"	.075 in.	1.10×10^4
22	26	"	"	1.52×10^4
23	27	"	"	4.10×10^3
24	28	"	"	Indeterminate
26	29	"	"	Indeterminate
27	30	"	.150 in.	2.40×10^4
28	31	"	"	2.70×10^4
31	32	"C"	.075 in.	7.15×10^3
32	33	"	"	9.05×10^3
33	34	"	"	Indeterminate
34	35	"	"	Indeterminate
35	36	"	.150 in.	4.68×10^3
36	37	"	"	6.02×10^3

* See figure references for test conditions.
Resistivity determined from test data for which a minimum 3-point linearity on plotted curves could be readily established.

Table XIII - Resistivity Data, Buna-N Rubber

Discussion of Experimentation Results. - Based on test results presented herein, parameters or conditions which promote electroadhesion are:

- Semi-conductive insulation interface
- Smooth, clean contact surface finish
- Ambient temperature
- Low pressure atmosphere
- Pure tensile or shear load alignment

Conversely, parameters or conditions which have a deleterious effect on electroadhesion are:

- Extremely conductive or highly insulated interface
- Rough, dirty contact surface finish
- Low or elevated temperatures
- High pressure atmosphere
- Peel forces

A comparison between Phase I theoretical analysis and experimentation results is presented as follows:

1. Resistivity of the electroadhesive coating.

Theory - This appears to be one of the key factors in determining electroadhesive properties. If the resistivity is too high, movement of charge will be too restricted, and if the resistivity is too low, too much current will be drawn.

Experimentation - Results of testing indicate that electroadhesion is dependent on both the resistivity and chemical properties of the insulation material. The role each of these properties contribute under specific conditions was not clearly established by test.

2. Thickness of coating.

Theory - The thickness, together with the resistivity, determines the current. Since some time is required for the charge to accumulate on the surface of the coating, and until that time has elapsed the charge is on the surface of the conductor and in the body of the coating. The coating should be thin to minimize voltage requirements, but not so thin that mechanical tolerances are difficult to hold.

Experimentation - Test results do not substantiate theoretical considerations with the Buna-N rubber material. Force output was somewhat higher using the thicker specimen of test material. Additional testing is required to establish whether or not this trend continues with even thicker, or thinner specimens.

3. Current density of the adhering interface.

Theory - The current density is, of course, not an independent variable, but, rather, a dependent one. It will be determined by the nature of the coating, the applied voltage, and the parameters of the ambient gas. It is important because a study of the manner in which it varies with applied voltage and ambient gas pressure provides an insight into the principles involved in the phenomenon of electroadhesion.

Experimentation - This parameter was not measured during testing, but observations indicate that the electroadhesive phenomenon is dependent on the magnitude of applied voltage (until a plateau is reached), and the rate at which the interface charge is dissipated. Best results were obtained when the adhering object was allowed to stabilize under applied voltage over a long period of time.

4. Effects of surface condition.

Theory - The condition of the surfaces (especially the surface smoothness) of the electroadhesor materials is an important consideration. If the surfaces are not smooth, intimate contact cannot be achieved. The effective electrode spacing is thereby increased and the force reduced.

Experimentation - Results of Matrix Tests No. 7, 8, 11, 12, 14, 20, 23, 30, and 38 indicate that electroadhesion is greatly reduced with roughened surfaces and emphasizes the need for providing intimacy of the contacting surfaces.

5. Polarity of applied voltage.

Theory - There is no known reason for the polarity of the applied voltage to have any effect, since the device is symmetrical. Furthermore, experiment has borne this out, within the limits of measurement accuracy.

Experimentation - Results of Matrix Tests No. 1, 2, 3, and 4 verify that the polarity of the applied charge can be either positive or negative without significant affect on the electroadhesive force.

6. Environment.

Theory - The gaseous environment in which the electroadhesor is placed plays a very important part in its performance. This effect occurs because the gas which is present between the electrodes has the capability of carrying a current, which serves to drain away the charge on the plates, reducing the force. Experience has shown that the presence of air at sea level pressure can reduce the force by a factor of five from that under vacuum conditions. Indications are that reducing the air pressure to 5.5 psi, a typical value for a spacecraft cabin, may increase the force by a factor of two.

The nature of the gas also plays a part in electroadhesor performance, since the current passed by a gas at a given applied voltage and pressure depends on the characteristics of the gas. It is thought that performance in pure oxygen at 5.5 psi will be slightly inferior to that in air at the same pressure. It is also thought that performance in an oxygen-nitrogen mixture would be about the same as in air at the same pressure. At the present time, no conclusions can be drawn about the performance in oxygen-helium mixtures.

Experimentation - Results of Matrix Tests No. 13, 19, 15, 16, 26, and 34 generally substantiate the theoretical analysis.

7. Temperature.

Theory - Temperature has an effect on electroadhesor performance because it affects the resistivity of the coating material. The temperature may also have an effect on the conductivity of the ambient gas.

Experimentation - Results of Matrix Tests No. 5, 6, 24, and 33 indicate that electroadhesion is greatly reduced in the presence of both low and elevated temperatures. Elevated temperatures accelerate particle movement within the insulator material and increase the electrical conductivity, and conversely, low temperatures appear to immobilize the particles and reduce the effect of the applied voltage.

8. Time (Build-up and die-out of forces).

Theory - As has already been mentioned, some non-zero time is required for the electrostatic charge to concentrate itself on the surface of the coating material. The amount of time involved depends on the dielectric constant and the resistivity of the material. Therefore, the time required for the force to build-up depends on these same parameters.

The decay of charge, and, hence, the decay of force depends on the resistivity and dielectric strength of the material. Of course, in the absence of a shorting switch, the leakage in the power supply rectifiers and filter capacitors plays a part.

Experimentation - Results for Matrix Tests No. 9, 10, 11, 12, 14, 20, 25, 29, 30, 37, and 38 indicate that the time a given electroadhesive force can be maintained is dependent on the magnitude of the force, its direction relative to normal and the magnitude of voltage applied. Some evidence is indicated that a cyclic voltage application, with alternate change in polarity, may extend the time a given force can be maintained. Test results also indicate that electroadhesion performance can be improved by allowing a significant time period under applied voltage before load is applied.

9. Dependence on chemical identity.

Theory - As far as is known, the phenomenon of electroadhesion does not depend on the chemical properties of the materials - only their physical properties.

Experimentation - This parameter was not specifically evaluated by test, but observation of the overall tests performed indicate that the chemical properties of the insulator materials may be a significant factor in producing electroadhesion. Results of preliminary experiments performed outside the scope of this contract, where individual elements of a multi-element material were tested individually for electroadhesion, indicate that only one or two of the elements was responsible for producing the electroadhesive force. This area of interest needs further investigation.

PHASE II

STUDY OF TECHNIQUES FOR APPLICATION OF THE ELECTROADHESIVE PRINCIPLE

Phase II, Study of Techniques for Application of the Electroadhesive Principle, consisted of an investigation of approaches to the design of devices operating on the electroadhesion principle. This work was performed to determine what can be accomplished with the application of the electroadhesion principle and the ultimate use of devices operating on this principle. The following elements were studied under this phase.

1. Mounting of the Electroadhesor.

   a. Rigid electroadhesive material on a rigid mounting
   b. Flexible material on a semi-flexible mounting
   c. Rigid metal electroadhesor with coated hull
   d. Flexible leaf design, coated and uncoated, for conforming to a curved hull surface
   e. Mosaic design, coated and uncoated with many small elements capable of tolerating rivet heads, etc.

2. Power Supply.

   a. High efficiency converter
   b. High voltage battery stack

3. Lock and Release Technique.

   a. High voltage switch
   b. Reverse pulse releasing

Results of the Phase II study are presented as follows for each of the above listed study items.

1. Mounting of the Electroadhesor.

Rigid electroadhesive material on a rigid mounting - Early proof of principle prototype models featured the use of rigid insulation coatings on rigid electrodes. This type of device presents no real design problem other than the need to provide very flat, parallel surfaces at the adhering interface.

Experience has shown that the highest performance devices are those in which complete intimacy of contact surfaces is provided and load is applied either normal or parallel to the adhering surface. A round electrode surface configuration has been demonstrated to perform better than sharp cornered electrodes. Best results are attained with electrically conductive electrode materials which are highly polished and free of internal discontinuities. The insulation material should be of an intermediate electrical resistivity, free of internal and surface discontinuities, and impervious to moisture absorption.

Investigative work using single-pole and two-pole electrode system indicates that somewhat improved electroadhesion can be attained using the single-pole electrode with the adhering object used as a ground connection to the power supply. Phase I experimentation data was established using this system.

For aerospace application development, it would appear that the single-pole system should be used for coated electrodes against bare metal surfaces, and conversely, two-pole systems should be developed for use of bare electrodes against suitable coated adhering surfaces. In either case, the intimacy of adhering surfaces must be assured.

Flexible material on a semi-flexible mounting - This arrangement promises to be the best for design of a device capable of being mounted to flat, convex, or concave surfaces. Figure 38 and figure 39 are photos showing "proof of principle" prototypes developed for this capability. Design problems do not appear untenable although this arrangement has shown some characteristic "peel" delamination at relative low loading.

Rigid metal electroadhesor with coated hull - Experimentation has shown that electroadhesion occurs whether the proper insulation material is mounted to the electrode or the adhering surface.

Flexible leaf (or radial petal) design, coated and uncoated for conforming to a curved hull surface - Comments of above apply.

Mosaic design, coated and uncoated with many small elements capable of tolerating rivet heads, etc. - Comments of above apply, although none of the materials tried to date have been sufficiently flexible to tolerate all expected surface conditions. This approach holds promise of being one of the most fruitful areas for future research.

2. Power Supply

The electroadhesor power supply presents unusual problems due to the high voltage, low current requirements. Approximately 4000 volts* d. c. at a current of approximately one microampere is desirable for vacuum operation of the device. The supply should carry its own self-contained battery power source. Battery life should be as long as possible, and 50 hours was chosen as a design goal. The supply, including batteries, should be mounted in the handle of the device (or remotely operated) and should conform to the form and size of this handle. The power supply should be small and lightweight.

* The 1850 volt d. c. power supply incorporated in the deliverable prototypes was developed under a previous contract. Time did not permit redesign of the power supply to reflect voltage requirements established under this contract.

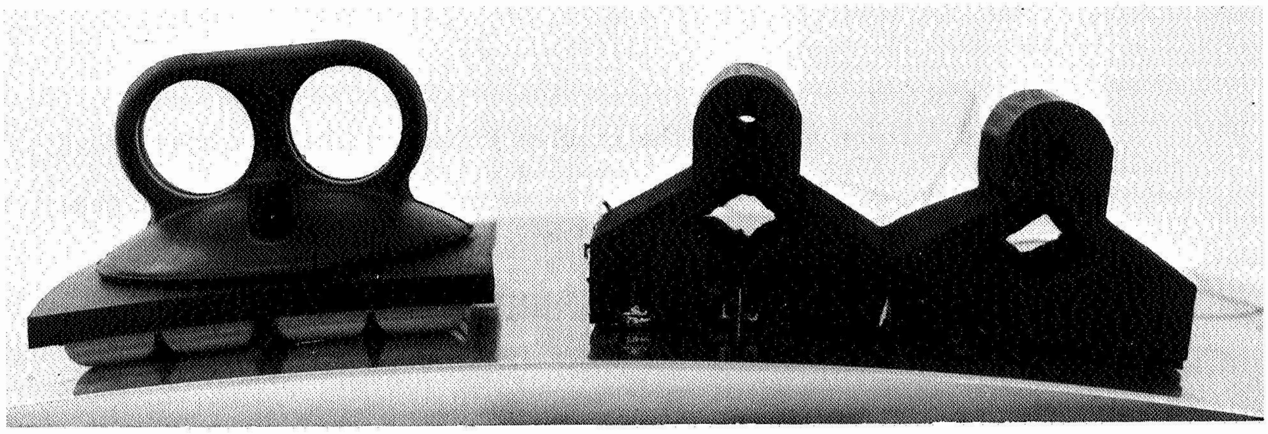


Figure 38 - Flexible "Proof of Principle" Type Electroadhesor

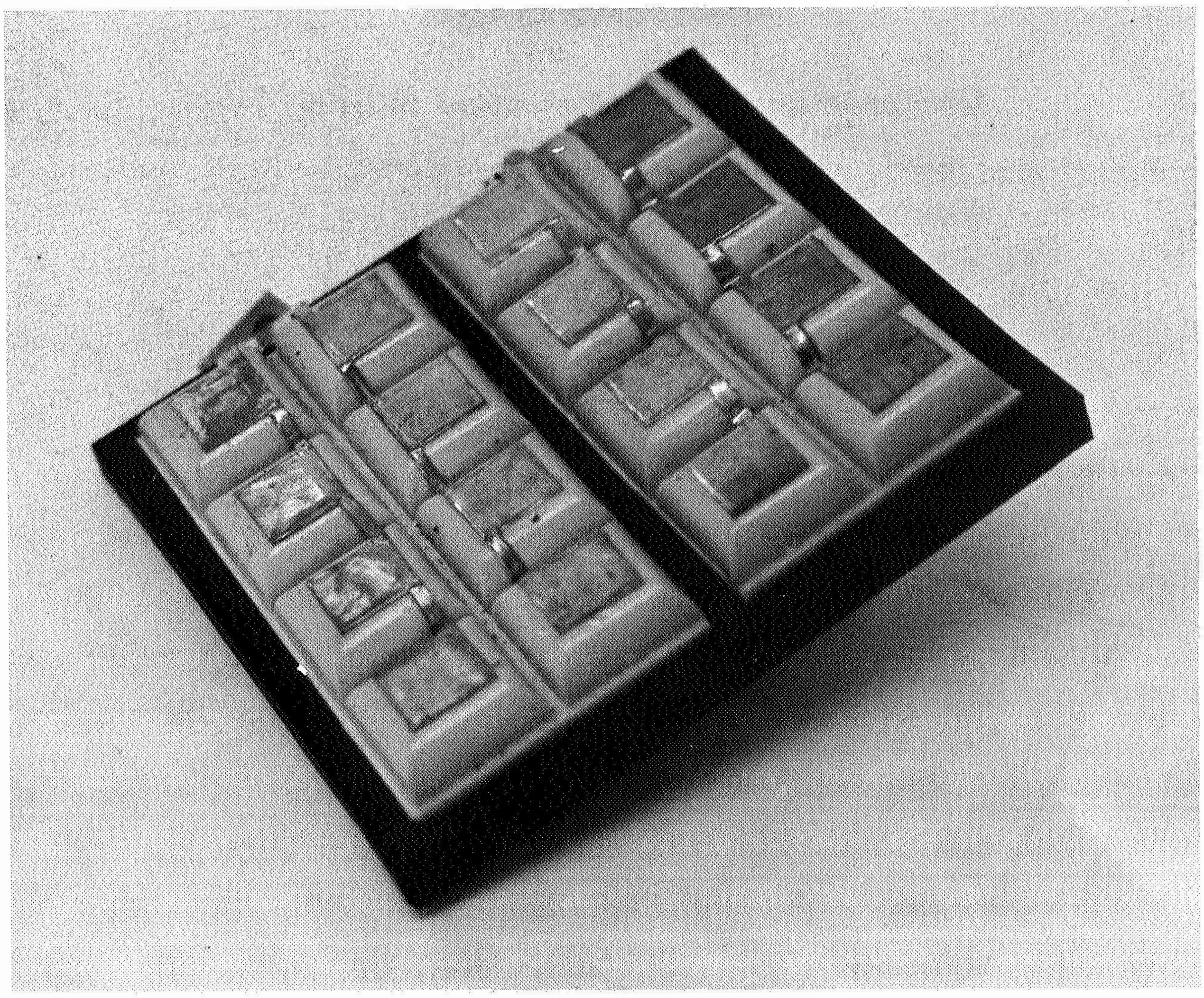


Figure 39 - Flexible "Proof of Principle" Type Electroadhesor (Bottom View)

A preliminary study of the problem indicated that two approaches could be used. The first would be to employ a low voltage battery and a solid state d.c. to d.c. converter and the second to employ a high voltage battery directly. A comparison of these two types was conducted.

High efficiency converter - The d.c. to d.c. converter problem was considered first. An initial survey of commercially available converters was made and the following information obtained:

<u>Specimen A</u>

Specifications:	Output:	500 to 3000 v.d.c. @ 100 μ a
	Input:	3 to 12 v.d.c.
Line Regulation:		Proportional to input
Ripple:		0.1% peak to peak
Stability:		0.01%/°C
Operating Temp.:		-55°C to 71°C
Size:		1" dia. x $2\frac{1}{4}$" long
Weight:		Less than 3 oz.

<u>Specimen B</u>

Specifications:	Output:	2000 v.d.c. @ 500 μ a (full load)
	Input:	25 - 31 v.d.c.
Line Regulation:		($\frac{1}{2}$ to full load) 3%
Ripple:		0.6% peak to peak
Operating Temp.:		-55°C to 100°C
Size:		1.6 in^3 (1.25" x 2.5" x 0.5")
Weight:		2.4 oz.
Efficiency:		(at full load) 50%

The two noted supplies are typical of the many commercially available units. It is to be noted that the full load efficiency of the Specimen B unit is greater than 50% which is typical of d.c. to d.c. converters of this type which can be designed with efficiencies as high as 80%. However, the no-load current is of the order of 20 ma which is also typical of converters with 1 watt output capacity.

If this particular unit were used to power the electroadhesor, assumed to require 2 mw, the input current would be about 20 ma at 25 volts making the input power 500 mw. Thus the efficiency would be only 0.4% under these conditions. A typical mercury battery delivers 24.3 v and has 1000 mah capacity. If used with the Specimen B supply would have a useful life of 50 hours. This battery is 2-1/16" in diameter and 2-5/16" long and weighs 8 oz. The combined weight of the converter and battery would be 10.4 oz. and the total volume would be 9.3 cu. in.

In view of the very low efficiency of the comercially available d.c. to d.c. converters, an analysis to determine the feasibility of designing a more efficient converter was undertaken. A typical circuit of a d.c. to d.c. converter is shown in Figure 40.

The voltage doubler circuit was first analyzed as follows:

Specifications:

Output: 2000 v.d.c., 10^{-6} amp

Ripple: 1% peak to peak

Ripple calculations: (Refer to Figure 40)

Rectifier Stacks - CR_1, CR_2

2000 v peak inverse voltage

Back current (typical stack) - 25 X 10^{-6} amp

Front to back ratio: 10^{-5}

E_{21} = 2000 V peak to peak, 10 kc square wave
(See waveforms, Figure 41)

$$\Delta E = \frac{TE_o}{RC_1} \tag{13}$$

where ΔE is the peak-to-peak ripple voltage, T is the "on" time of the square wave input (one-half period, or 0.5 X 10^{-4} sec), and R is the effective resistance seen by the output voltage.

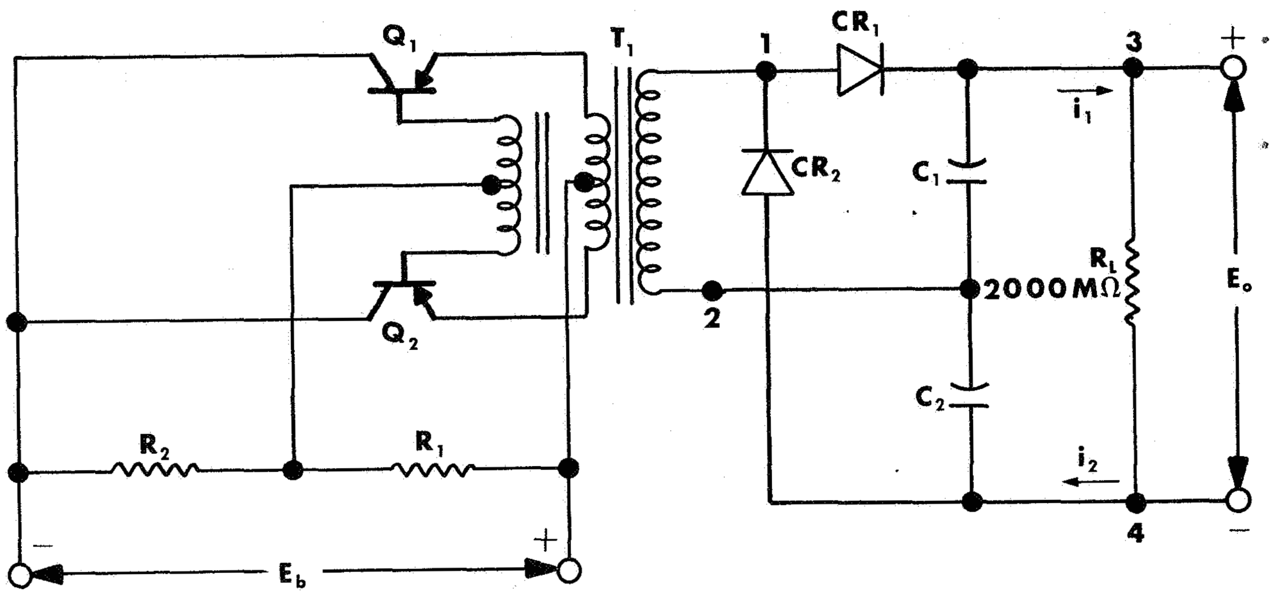


Figure 40 - d.c. to d.c. Converter Circuit

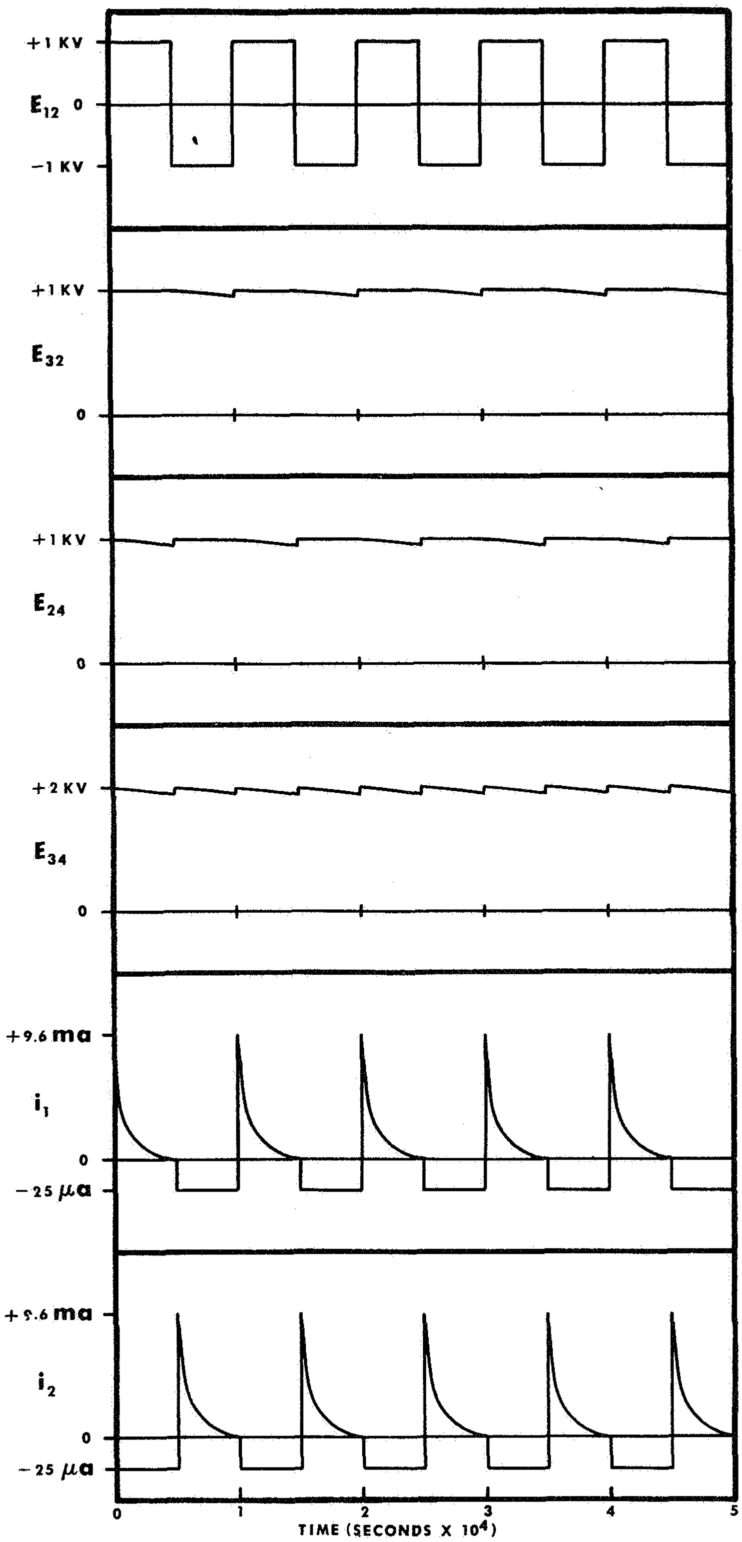


Figure 41 - Waveforms in d.c. to d.c.
Converter of Figure 5

Since $E_o = 2000$ V,

$$\frac{E_o}{R} = 10^{-6} + 25 \times 10^{-6} = 26 \times 10^{-6} \text{ amp}$$

C_1 may now be computed from Equation 13 to be 65 $\mu\mu$ f. Choosing the closest RMA value of 68 $\mu\mu$ f, the actual ripple can be re-computed to be 19.1 V.

The efficiency may now be computed. The power delivered to the load (P_{load}) is 2 mw, and the power loss (P_{loss}) is 2000 X 25 X 10^{-6} = 50 mw.

$$\% \text{ Efficiency} = \frac{P_{load}}{P_{load} + P_{loss}} \times 100 = \frac{2}{52} \times 100 = 3.84\%$$

It is evident from these calculations that the low efficiency of the overall d.c. to d.c. converter is due to the low efficiency of the final a.c. to d.c. conversion. An increase of nearly two orders of magnitude in the back resistance of the solid state rectifiers will be required in order to raise this above 50%. Thus with currently available rectifier units and a d.c. to a.c. conversion efficiency of 50% the overall d.c. to d.c. conversion efficiency would amount to only 1.92%.

Several other schemes such as a magnetically biased transformer were considered, but preliminary inspection showed that no improvement could be expected using these schemes.

To provide a check on the theory developed above, a small power supply was constructed. The schematic diagram of this power supply is given in Figure 42. Its performance very closely checked with predictions. Its output voltage was adjustable around a value of 2000 volts. If this output was set at 2000 volts, with only the meter attached, the input current was about 18 ma. The voltmeter used in these measurements was the most sensitive one available, but it still drew a current of about 5 μ amp. Thus, it was not possible to check the input current under true no-load conditions (If the meter had been removed, the output voltage would have risen an unknown amount).

This supply was powered by a small Mercury battery (Mallory TR-126T2), which had a 600 mah capacity. Thus, with this present supply, battery life could be expected to exceed 30 hours. The entire power supply and battery package can be housed in a cylindrical tube approximately 1-inch in diameter and 4 inches long.

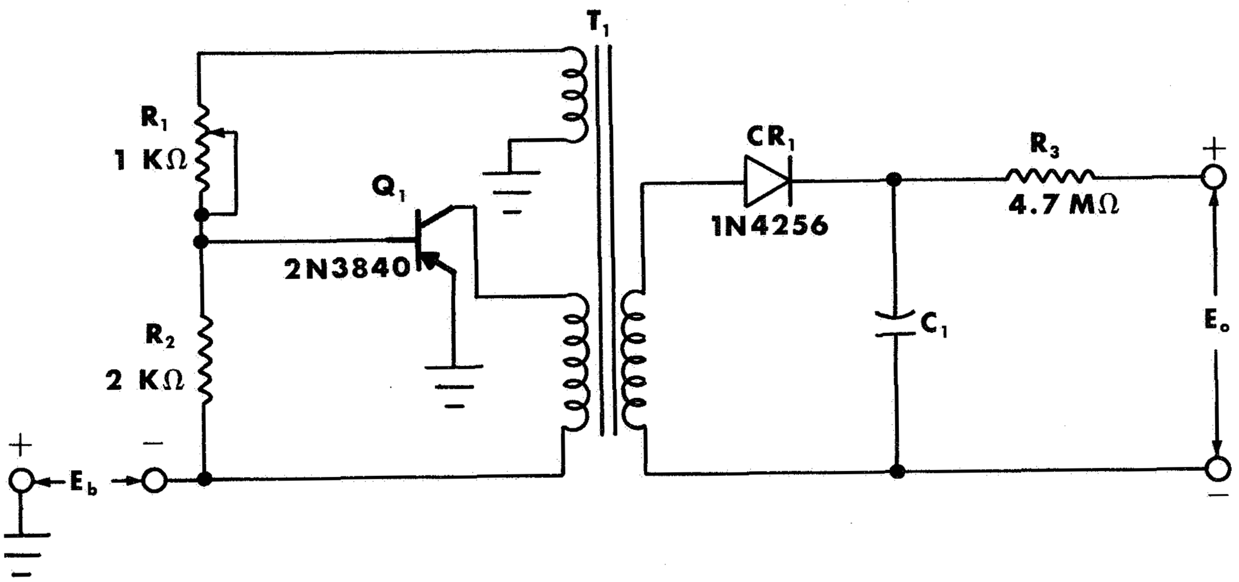


Figure 42 - d.c. to d.c. Converter Constructed for Test

High voltage battery stack - High voltage batteries were also considered. A search of the literature indicated that such batteries in small sizes were available. One of these is a solid electrolyte battery. The 100-volt unit with a current capacity of one microampere measures $1\frac{1}{4}$ inches long by 3/8 inches diameter and weighs less than $\frac{1}{2}$ ounce. Twenty of these batteries in series will be required to produce the required 2000 V. Thus the total solid electrolyte battery package will weigh less than 10 ounces and occupy about 2.8 cubic inches plus a factor for packaging. If the batteries were considered square in cross section the total volume would increase to 3.5 cubic inches. This is to be compared with the 9.3 cubic inches for the d.c. to d.c. converter plus low voltage battery described previously.

The obvious conclusion based on size and weight is that the high voltage solid electrolyte battery is the better choice for the electroadhesor power supply. However, these batteries also have disadvantages. One problem associated with the high voltage batteries is that of designing an enclosure with the necessary switching without the presence of excessive leakage of current. The useful life of the batteries would be drastically shortened by a very small leakage of current. A second disadvantage is that of cost. Buying in small quantities, a 2000 volt stack of these batteries would cost about $1000. Considering these facts, it might be preferable to sacrifice some size and weight and use a d.c. to d.c. converter.

Lock and release techniques - Lock and release techniques were investigated to determine the requirements for instantaneous control over the electroadhesive phenomenon. High voltage switch and reverse pulse releasing techniques were studied. The following discusses results of these studies.

High voltage switch - The use of a high quality switch in the power supply circuit should reduce or eliminate undesirable current leakage across the adhering electrodes and would have the added benefit of increasing battery longevity.

Reverse pulse releasing - This does not appear to be a valid method for controlling the electroadhesor operation. A slight peeling force applied to the electroadhesor interface should produce the desired delamination.

PHASE III - TEST AND EVALUATION

Phase III, Test and Evaluation, involved design, fabrication, and test of three (3) prototype electroadhesive devices. The prototype devices represented the best design(s) developed under Phase II and were fitted with mountings such that the underlined applications from the following list of applications could be evaluated.

1. <u>Hand holds</u>
2. Foot attachments
3. Knee pads
4. Back and seat pads
5. <u>Implement holder</u>
6. Safety belt holder
7. Spacecraft grappling unit

The quality, appearance, packaging and other physical characteristics of the prototype electroadhesors are such as to be suitable for further testing under simulated zero-gravity conditions but are not intended to be finished products suitable for extended human use or for space qualification. The following parametric tests were performed under normal gravity conditions.

1. Static pull force
2. Skid force
3. Battery longevity

The three (3) electroadhesor prototype devices delivered under this contract represent "state-of-the-art" devices and were conceived during Phase I and Phase II experimentations and studies. As such, they do not necessarily represent the "optimum" in configuration, materials, power supplies, or performance capabilities.

Two of these deliverable items were designed as rigid "hand hold" devices suitable for adhering to flat surfaces only. These devices differed in design in switching components and in the use of two-pole and single-pole electrodes. Figure 43 is a photo showing the single-pole electrode device. In each of these devices the battery and power supply elements were incorporated in the housing body.

The third prototype device was designed as a flexible prototype intended for use in adhering to single (or double) radius surfaces. The device was designed as either a hand-hold or implement holder with remote power supply and control. Figure 44 is a photo showing this device in operation.

The power supply for each of the delivered prototypes is shown schematically in Figure 45. The power supply voltage specifications are as follows:

Figure 43 - Hand-Model Electroadhesor Prototype (Single-Pole Type Shown)

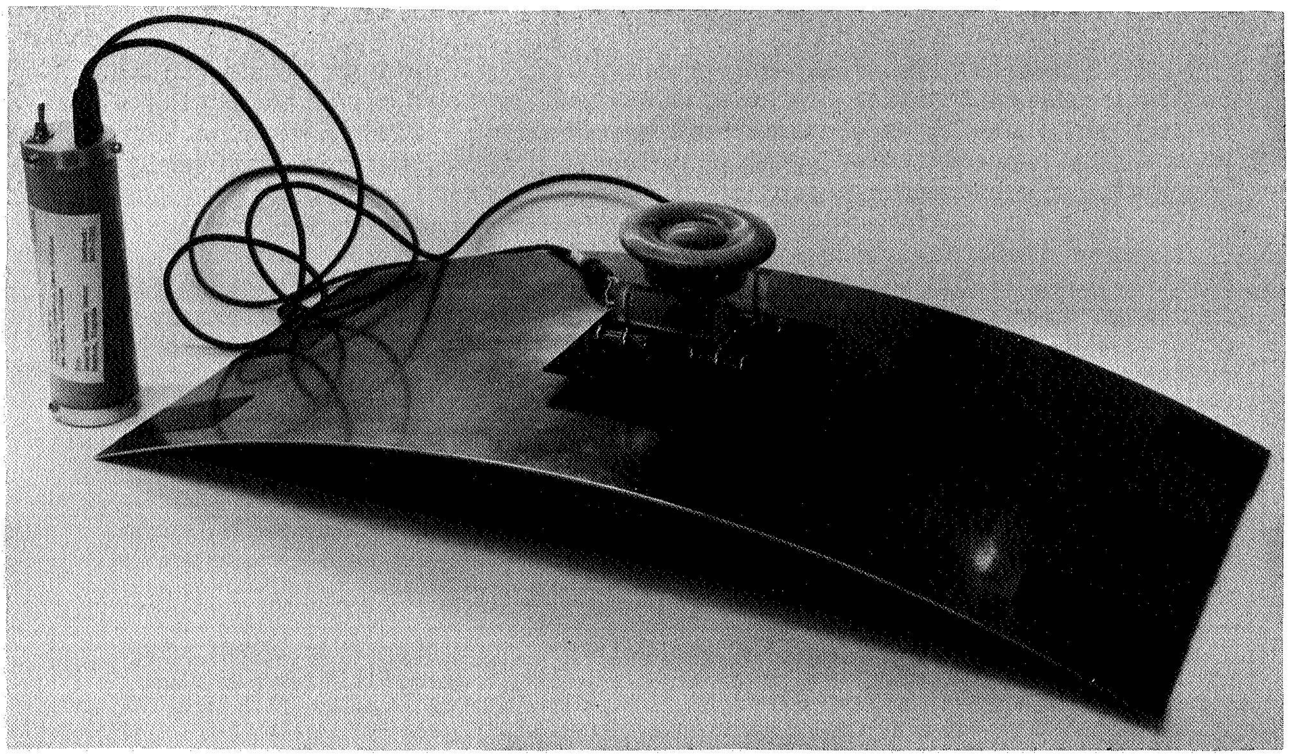
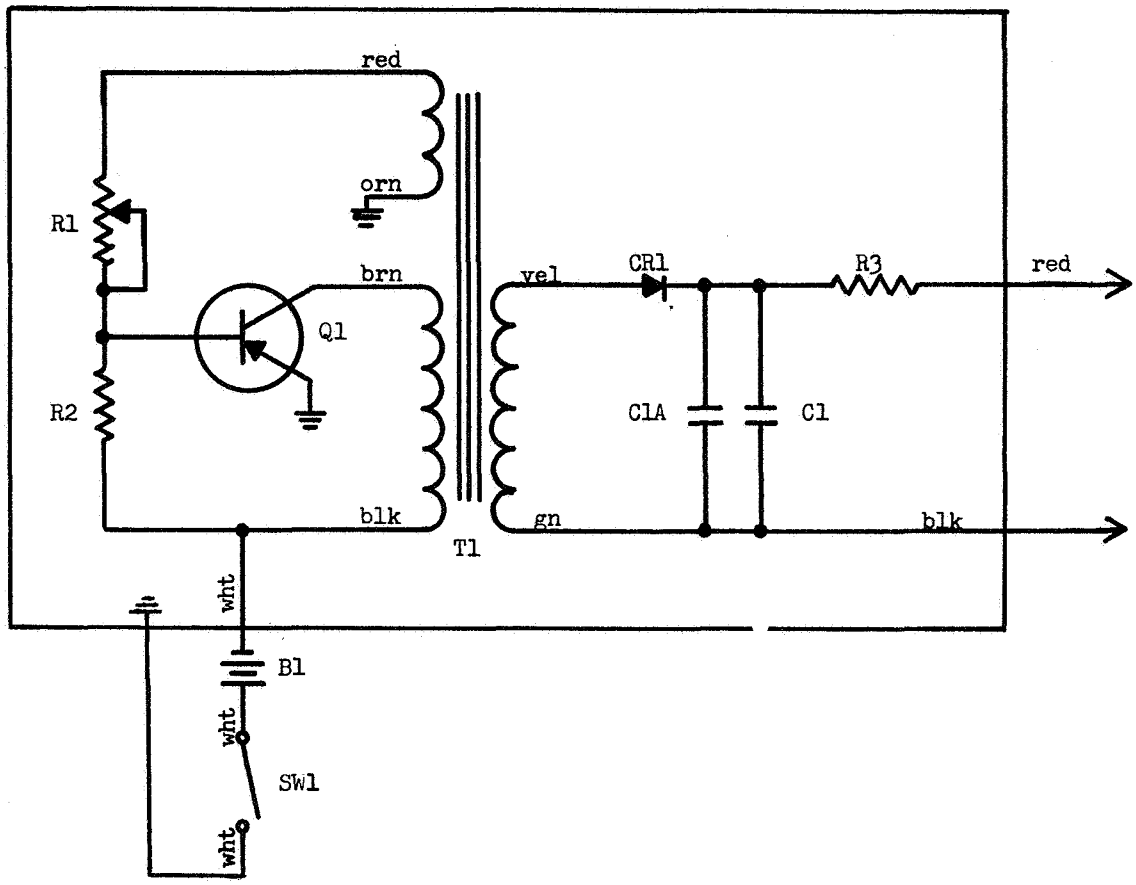


Figure 44 - Flexible Prototype Electroadhesor



Item	Qty	Description	MFG Name or Mil Spec	MFG Part No. or Mil Type
SW1	1	Switch		
B1	1	Battery 8.4 V	Mallory	TR-126T2
T1	1	Transformer	Microtran	M 8050
R1	1	Potentiometer 1K	Bourns	3280W-66-100
R2	1	Resistor 2K 1/4W 5%	Mil-R-11	RC07GF202J
R3	1	Resistor 4.7M 1/4W 5%	Mil-R-11	RC07GF475J
C1,1A	2	Capacitor .005MFD 3000V	Sprague	306A-D50
CR1	1	Rectifier	Semtech Corp.	1N4256
Q1	1	Transistor		2N3840

Figure 45 -Electrical Schematic-Prototype Electroadhesor Power Supply

Input voltage - 8.4 volts d.c.
Output voltage - 1850 volts d.c.
Current drawn (at max. output voltage)-30 μ amp.
Battery longevity - 30-40 hours

Simple operating instructions for use of the prototype devices are presented as follows:

1. Clean all interface surfaces (electrodes, insulation material, and adhering surface) with alcohol or other suitable cleaning agent. Wipe dry. (Important note: All interface surfaces should be free of burrs, scratches, voids, and contaminents.)

2. Place prototype on adhering object and push gently to assure intimacy of contacting surfaces. Visually check to assure that insulating material separates the electrode elements. Do not ground electrodes by touching or by any electrically conductive material.

3. Actuate power supply by turning switch to "on" position. Allow a few seconds time (or longer) for charge buildup.

4. Apply a steady-state pull in a direction either normal or parallel to the interface. Avoid bending or peeling forces.

5. For deactivation, turn switch to "off" position, wait at least 10 seconds for charge decay, and then apply a slight bending or peeling force to the body or mounting.

(Note: Protect interface surfaces at all times when device is not in use. Store in dry, ventilated area. Desiccants may be used for storage purposes.)

Results of tests performed to determine the operating performance of the three delivered prototype devices are presented as follows.

Hand Model Prototype (Two-Pole):

Static pull force - 3 pounds tensile at 1850 volts
Skid force - 18 pounds shear at 1850 volts
Battery longevity - 27 hours

Hand Model Prototype (Single-Pole):

Static pull force - 6 pounds tensile at 1850 volts
Skid force - 40 pounds shear at 1850 volts
Battery longevity - 42 hours

Flexible Prototype (Single-Pole):

Static pull force - 2 pounds at 1850 volts
Skid force - 1 pound (with loading wiffletree extended normal length at 1850 volts)
Battery longevity - 40 hours

CONCLUSIONS

Based on information and data contained in this report, the following general conclusions regarding the electroadhesive phenomenon can be made.

The theoretically derived expression governing the phenomenon of electroadhesion can be expressed mathematically as follows:

$$\frac{F}{A} = \frac{\epsilon V^2}{2 d^2}$$

where F is the strength of the electroadhesive bond between two charged electrodes separated by a suitable insulator material

ϵ is the dielectric constant of the insulator material

V is the magnitude of applied voltage

d is the linear measurement of electrode separation

A is the effective area of contact

Data contained in this report is useful in assessing the effect of operational and environmental parameters on electroadhesive performance. Conclusions based on experimentation performed in support of the designated Phase I parameters are presented earlier in this report (ref. Discussion of Test Results, page 63) and summarized below. It should be noted that these conclusions are based on results obtained using specific test materials and procedures and may not apply for other materials tested under other conditions or environment parameters.

a. Resistivity of the electroadhesive coating - Experimental results indicate that the electrical resistivity as well as the chemical identity of the coating material are key factors in determining electroadhesive properties. The role each of these properties contributes under specific conditions was not clearly established by test.

b. Thickness of coating - Test results indicate that coating thickness is a key factor in producing desirable electroadhesive properties. Optimum thickness is dependent on both the electrical resistivity and chemical nature of the coating. The control of uniformity also appears to be an important parameter. Force vs thickness trends identified by these tests are not in agreement with predictions made by theoretical means.

c. Current density at the adhering interface - Based on test observations, the current density and the rate at which the current changes with applied voltage, controls an electroadhesive performance. Test results demonstrate that electroadhesive force increases under progressively increasing applied voltage until a plateau is reached, after which further applied voltage serves only to increase the current consumption.

d. Effects of surface condition - Test results demonstrate that best results are obtained where an optimum condition of electrode interface, in regard to smoothness, flatness, and cleanliness, is provided. Rough, unclean surfaces greatly reduce electroadhesive performance.

e. Polarity of applied voltage - Test results verify theoretical considerations in that either negative or positive polarity of applied voltage produces similar electroadhesive performance.

f. Environment - The nature of the operating environment, regarding composition and pressure, affects electroadhesion. Test results demonstrate that electroadhesive performance is improved in a low pressure gaseous environment of a composition which reduces the possibility of electrical discharge under applied voltage. Electroadhesion performance, for instance, is superior in a low pressure nitrogen gas atmosphere than in air or pure oxygen. These results are qualitatively in agreement with theory.

g. Temperature - Test results demonstrate that electroadhesive performance is reduced under both low and elevated temperatures. The change in current consumption, i.e., increased under elevated temperature and decreased under low temperature, suggests that the temperature phenomenon experienced with Buna-N rubber is caused by a definite physical change in the materials. These results may not be indicative of electroadhesive performance for other materials tested under similar temperature conditions.

h. Time (build-up and die-out of forces) - Test observations indicate that the time required for force build-up and die-out is dependent on the chemical and physical properties of the coating material. Test observations of Buna-N rubber indicates that this material demonstrates a significant "sticking" force after power is turned off.

i. Dependence on chemical identity - IR&D program test observations indicate that the chemical nature of the coating material is a key factor in electroadhesion performance. This conclusion is based on the demonstrated ability of certain elements of a multi-element material to respond to electroadhesion while other elements either responded poorly or not at all.

In practice, electroadhesion was found to occur when any suitable insulator material was placed between two electrodes charged in a manner to allow a small current to pass from one to the other. The intimacy of the contacting surfaces (minimal plate separation) was found the most difficult condition to establish and maintain. Under controlled laboratory conditions, electroadhesive forces measured in this series of tests on the order of 13 pounds-per-square-inch were obtained. (Higher forces up to 42 psi have been obtained during experiments performed prior to this contract. The objective of this contract was not large forces but the evaluation of the effect of specified operational and environmental parameters.)

Based on results of Phase II and Phase III work, the design of both rigid and flexible type electroadhesor devices is feasible. The design of such devices for aerospace applications regarding materials, power supply elements, and configuration requires further advancement in technology and understanding of the phenomenon.

Evaluation of overall project results indicates that further research and development activity is necessary and desirable to establish electroadhesion as a means for producing positive and reliable bonds. These activities should be concentrated on detail investigations of the phenomenon, the mechanism(s) which control its behavior, and the solution of problems attendant with the operational or environmental parameters which degrade its performance.

RECOMMENDATIONS

On the basis of information established as a result of work performed under this contract, the following recommendations are presented for consideration in planning of future electroadhesor research and development activities. The recommendations emphasize the need for continued investigation of the fundamental principles of electroadhesion, material analysis and experimentation, test and evaluation, and design development.

1. Materials Analysis and Experimentation. - The physical and chemical properties of several classes and types of insulator materials should be analyzed at the molecular level to establish the reasons for their affinity to, or rejection of, electroadhesive performance. Both isotropic and orthotropic materials should be investigated. Laboratory experimentation in support of material analyses should continue. Emphasis should be placed on determining the nature and distribution of body and surface particles in the uncharged state and how these particles are redistributed to produce electroadhesion under applied voltage. The relationship between both constant and pulsed direct-current voltage, current, and time should be established. Operational and environmental parameters having either a beneficial or detrimental affect on electroadhesion should be investigated in depth.

2. Design Development. - Concurrent with the above noted activities, electroadhesor design and development should continue. Prototype models reflecting state-of-the-art improvements in materials, power supply elements, and configuration should be manufactured and tested in the aerospace environment. Design criteria for space qualified devices should be established during the prototype development.

3. Fundamentals of Electroadhesion. - Inasmuch as contract work emphasized operational and environmental testing and prototype development, essentially no effort was given to analysis or experimentation in support of the fundamental principles of electroadhesion. In order to establish a secure basis for such activities, it is strongly recommended that a concerted effort be initiated to perform those studies and experiments directly related to fundamentals. Specifically, studies should be made concerning the basic principles of electrical conduction, processes of gaseous electronics, solid state physics, and related technologies as applicable to electroadhesion. These studies should be supported by experimentation to the extent necessary to unlock the "secrets" of electroadhesion, its causes, and how it can be developed for practical aerospace application.

Chrysler Corporation Space Division
New Orleans, Louisiana
March 8, 1968

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