STATIC ELECTRIFICATION OF FILAMENTS: EFFECT OF FILAMENT DIAMETER IN A NYLON-TANTALUM SYSTEM

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ABSTRACT

STATIC ELECTRIFICATION OF FILAMENTS:
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A systematic study was made of the effect of filament diameter on the charge transferred between filaments rubbed together under controlled ambient and mechanical conditions. Nylon monofilaments of various diameters (9.2-32-mils) specially prepared from the same batch of polymer were rubbed against tantalum wires of various diameters (7-62-mils) at different normal forces between filaments. The charge transferred was found to be more or less proportional to the square root of the normal force between the filaments, in agreement with earlier findings. The charge transferred followed no simple law with respect to filament diameter, however. At constant diameter of tantalum, the charge was nearly independent of nylon filament diameter. At constant diameter of nylon filament, the charge increased with increasing diameter of tantalum wire for small diameters, but then fell off. The complexity of the dependence of charge on filament geometry suggests that a simple mechanism is unlikely to be able to describe the process of charge transfer,

and it is proposed that further progress will be made by working with precisely-defined materials, such as alkali halides and transition-metal oxides, under simple and well-defined mechanical conditions.

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A THESIS

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CHAPTER I

INTRODUCTION

The effects of static electrification have been observed from ancient times (1). But until 1600, when Queen Elizabeth's Surgeon, Dr. William Gilbert, published De Magnete (2), the phenomena of static electricity were thought to occur only rarely. Gilbert published a list of some twenty substances in addition to the traditional and precious amber, diamond, and jet, that could be electrified. He did not, however, establish the existence of two kinds of electricity. The basis for this discovery was laid by experimenters such as von Guericke, who, before 1672, discovered that electricity can repel as well as attract. It was left to DuFay, in 1733, to establish definitely that there are two kinds of electricity. Later the law of conservation of charge was suggested by the experiments of Franklin in about 1750, and of Priestley in 1767, and finally the law of force between localized charges was established by Coulomb after anticipatory experiments by other workers. The foundations for quantitative treatment of electricity were thus laid. Fruitful investigation of the relation between the chemical and physical nature

of materials and their electrical properties had to wait upon development first of atomic theory and then upon the development of solid-state theory. Even then, not much attention was devoted to this field until industrial interest demanded it. Effects of static electricity are beneficial in such applications as spray painting, insecticide dusting, dust precipitation, fiber orientation, electrostatic imaging, and some other highly specialized uses. Electrostatic effects are harmful in the textile processing mills, in plastic processing and utilization, and in photographic film processing. Technological development in all these instances has been slowed down by the dearth of fundamental knowledge concerning the charge transfer between solids.

Problems in textile technology, specifically those attendant upon the increase in processing speeds for the hydrophilic and therefore readily conducting fibers (cotton, wool, silk, and rayon), and upon the increase in electrical resistivity for the hydrophobic fibers (nylon and most of the other synthetics), have motivated several groups to undertake fundamental studies on the static electrification of fibers. The Textile Research Institute in Princeton, New Jersey, in 1951 started a program based on measuring the charge

transferred between filaments rubbed together under controlled ambient and mechanical conditions (3). The program, with refinements of apparatus and techniques, was continued at Princeton (4) and was developed further at Michigan State University (5,6).

In the studies up to the present one, certain regularities were observed. Cunningham and Montgomery (6,7), in an effort to systematize the data, developed an expression for the net charge q remaining on one object when two objects are rubbed together and then separated. The expression is given as

$$q = q_o f \quad ,$$

where q_o is the total charge transferred during contact, and f is the fraction of the total charge retained after separation. One then attempts to study q_o and f separately. The fraction f approaches a constant value, presumably unity, with increasing rub speed and increasing resistivity. Therefore by working under suitable conditions it is possible to keep f constant and study q_o separately.

The charge q_o has been decomposed formally into the product of two terms, a factor b dependent on the atomic parameters of the material (5), and a factor g, dependent on the geometry of the sample and mechanics of contact. By working with specimens of identical

chemical composition, it is hoped to keep b constant and thereby be able to study g. Cunningham in fact started such measurements with nylon against tantalum, but his results were inconclusive because there was some question as to the chemical identity of the nylon from one filament to another of different diameter.

In the study of static electrification of solids the effect of the size of the objects, specifically of the diameters of filaments, is important because of its value in making clearer the process of charge transfer. The work of Cunningham showed the likelihood of a diameter effect, but it was suspected that its source might be difference in chemical composition of the samples, rather than difference in the diameters. To try to resolve this question, a study of the effect of the diameter of nylon in rubbing nylon on tantalum and on polyethylene was undertaken by Montgomery, Smith, and Wintermute (8). For nylon against tantalum the charge transferred was found to be proportional to the square root of the product of the normal force and the diameter. For the nylon against polyethylene, the charge was found to be proportional to the square root of the normal force, but nearly independent of the diameter of the nylon. An explanation proposed for the observed effects suggested the

desirability of performing experiments where the diameter of not only the nylon filament but also of the tantalum filament is varied. The present thesis is concerned with the study of the effect of varying the diameter of the tantalum filaments as well as the diameter of the nylon filaments, on the charge transferred between the filaments when rubbed together under controlled mechanical and ambient conditions.

CHAPTER II

EXPERIMENTAL CONSIDERATIONS

A. Samples

In this experiment we are concerned with tantalum wires rubbed on nylon filaments. The nylon samples, specially prepared from nylon-66 obtained from the Polychemicals Department, E.I. Du Pont de Nemours and Company, had the following diameters; 62, 32, 17, and 9.2 mils. These filaments, though not all from the same melt, were from the same bag, to insure uniformity with respect to chemical composition. The diameters were measured and found to vary less than 10% from the mean values stated.

The tantalum wire, annealed, was obtained from the Fansteel Metallurgical Corporation in the following diameters and tolerances:

Diameter (mils)	Tolerance (mils)
3.0	0.2
7.0	0.25
14.0	0.3
33.5	0.4
62.0	0.8

B. Apparatus

An apparatus was designed by Cunningham for rubbing two filaments together under controlled mechanical and ambient conditions. He describes the apparatus in detail in his thesis (6). Many mechanical details of the apparatus have been modified for the present experiments, but the principle of the experiment remains the same. Accordingly a detailed description is omitted here.

In short, the apparatus rubs two filaments together, measures the charge left after separation on one filament, and then neutralizes the system to prepare it for a succeeding rub. The apparatus may be placed on automatic cycling, wherein the fibers are rubbed together and then neutralized, or they may be rubbed together as many times as desired without neutralizing. The system may be described in four parts; (1) a rubbing mechanism; (2) a control system; (3) a measuring device; (4) and a neutralizing mechanism.

The rubbing mechanism rubs the filaments together at a fixed orientation and velocity. Figure 1 is a photograph of the filaments in the rubbing mechanism. Three standard orientations are: 0^{o} - 90^{o}, 90^{o} - 0^{o}, and 45^{o} - 45^{o}. This nomenclature refers to the top filament with respect to the bottom filament (See Figure 2).

Thus in the 0^{o} - 90^{o} rub the surface of contact of the top filament stays the same and the bottom filament presents a constantly changing surface of contact. In the 90^{o} - 0^{o} rub the top filament saws across the bottom filament, which presents the same surface during the rub. In the 45^{o} - 45^{o} rub, the orientation chosen for this work, the axis of each filament is at an angle of 45^{o} to the direction of motion of the top filament holder or top yoke, and at an angle of 90^{o} with respect to the axis of the other filament. In this orientation the only one used in the present work, each filament presents a fresh surface to the other during an individual rub.

The rubbing is accomplished by a pair of master-slave selsyn motors that drive the rubbing mechanism through a roller chain. The bottom filament remains stationary while the top filament is rubbed across it at a given speed for a predetermined length of rub. The "overlap" of the two filaments when in contact is controlled by the vertical coordinate of the bottom filament, which can be changed at will (cf.Figure 3). When the two filaments are directly over one another, the top filament is lowered to push against the bottom one by means of two rotary solenoids that rotate a shaft on which the top filament holder rides. The top filament is lowered to the same point

each time, whence, as mentioned, the overlap is determined by the vertical height of the bottom filament. The shaft is then raised after the filaments have rubbed for the predetermined distance. After the shaft is raised, the top filament holder proceeds along the shaft and stops at the end, at the point of maximum separation and therefore minimum capacitance. A system of cams and microswitches connected to the shaft driving the master selsyn motor determines the length of rub and the point where the top filament assembly stops at the completion of a rub.

The control system has the function of regulating the variables connected with the experiment. These variables may be considered in two parts, the mechanical and the ambient. The mechanical part of the system is the automatic control, consisting of a set of three cams that are run by a 1-rpm motor and a set of microswitches actuated by the cams. This arrangement enables the apparatus to cycle by itself. In the present experiment it is necessary to neutralize the bottom filament after every rub. The neutralizing mechanism accomplishes this. A radioactive source (polonium) is lowered over the bottom filament so that enough ions are created in the air surrounding the filament to neutralize any

charge that has accumulated on the bottom filament. The first cam in the automatic control closes a microswitch that allows the radioactive source to be lowered over the filament for a given length of time, and then the second cam closes another switch to raise the source out of the path of the upper yoke. A few seconds after the source is raised, the third cam closes a switch to activate the drive motor and begin another rub. A complete cycle takes one minute.

The ambient variables—temperature, pressure, and composition—are controlled as follows. The apparatus is inclosed in an insulated box. The humidity is maintained at 33.5% by placing open trays of magnesium chloride inside the box. The humidity is monitored by measuring the a-c resistance of a calibrated humidity-sensitive element (salt-impregnated plastic). The temperature is controlled with light bulbs as heaters turned on by a relay tripped by a device sensitive to the height of the Hg column in a thermometer in the test chamber. The temperature was maintained at $30 \pm 0.5^{\circ}C$.

The charge-measuring system shows the charge left on the bottom filament. The top filament is grounded and the bottom filament is connected to a plate insulated from the rest of the system by four polystyrene stand-off insulators. The filament itself is close

to the plate, and the system behaves almost as a Faraday ice-pail. To the plate is connected the input to a Keithley electronic electrometer, Model 210. The electrometer measures the voltage change on the bottom-filament assembly, and sends a signal to an Esterline-Angus recording milliammeter to provide a continuous record.

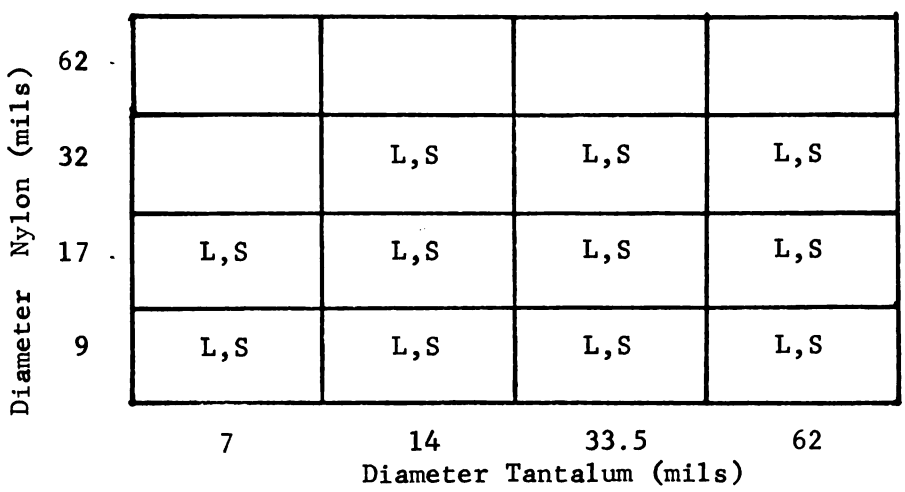
The capacitance of the system and the leakage resistance are determined by observing the voltage decay when known high resistances are connected between the electrometer input and ground. From the observed time constants the capacitance and resistance can be directly obtained.

CHAPTER III

RESULTS

A. Sample Schedule

The combinations of nylon and tantalum available to us for the present experiment are shown in the diagram below. Although it was intended to test all available combinations, this was found to be impractical. The very thin tantalum wires cut into the nylon severely and the very heavy nylon filaments could not be stretched straight with reasonable loads, so these were eliminated from experimental consideration. The combinations actually tested are indicated in the diagram by L for one type of test and by S for another, in accordance with a scheme to be described below.



B. Rub Schedule

Figure 4 shows the results for a typical combination of samples for a long series of rubs with neutralization between rubs. As can be seen there is a rather rapid rise in the charge transferred for the first few rubs and then a leveling off. As has been discussed in reference 7, p. 164, the behavior with successive rubbing is complicated, and it is necessary to choose a somewhat arbitrary rubbing schedule. In general, the charge generated changes only slightly with successive rubs after fifty to a hundred rubs. There will be very slow changes over periods of hundreds or thousands of rubs, as a result of wearing and ageing effects. However we believe that such changes reflect primarily mechanical rather than electrical effects, and we do not concern ourselves with them here. Hence the region of primary interest is around one hundred rubs, which we designate as long-term behavior, or for short, L behavior.

The short-term behavior, too, is of interest, both in itself and a means for shortening testing procedures. Since there appears to be a slowing down of the variation after a dozen or so rubs, this number was chosen to characterize the short-term behavior denoted by S.

C. Reproducibility

Reproducibility - rub-to-rub. As can be seen from Figure 4, the rub-to-rub reproducibility with a set of rubs for a given pair of filaments is within 3% of the mean course of the curve envelope. This finding is in accord with earlier experience.

Reproducibility - "set-to-set" for a given pair of filaments ("day-to-day"). A repetition of a set of rubs of the type depicted in Figure 4 usually gives the same L or S value within 10%.

Reproducibility - sample-to-sample ("Filament-to-Filament"). Replications of an experiment with different sections of the material from the same spool give results for the L values within 17% and the S values within 14%.

D. Effect of Velocity

Cunningham and Montgomery (6) conjectured, on dimensional-analysis arguments, that the fraction f of the charge retained would depend on the ratio of t_o, a time characteristic of the charge-transfer process, to τ, a time characteristic of the charge-distribution relaxation. The time t_o would be given by some characteristic distance l_o within the filament divided by the rub velocity v. The time τ would be equal to the dielectric constant ϵ multiplied by the electrical resistivity ρ. Thus f would be a function of $l_o/\epsilon v \rho$.

Moreover, f should attain an upper limiting value for small values of $(k/\epsilon\sigma\rho)$. Cunningham and Montgomery tested this conjecture by measuring the charge transferred from a nylon filament to a tantalum wire as a function of velocity, with the electrical conductivity as a parameter fixed by controlling the ambient temperature while holding the relative humidity constant. The results showed that this conjecture could be maintained, and that f attained its limiting value easily within the capabilities of the apparatus (rub velocities, 2-10 cm/sec.), even for relative humidity as high as 75% and temperatures up to 35°C, where the volume resistivity of nylon is 10^{10} ohm-cm. In the present experiments, typical conditions were 33% relative humidity and 30°C, under which conditions the volume resistivity of nylon is 2×10^{12} ohm-cm. Hence f would appear to be at its limiting value, so that small variations in rub speed or in electrical properties of the material would not change it. This point was checked directly at 40% relative humidity and 30°C for 32-mil tantalum on 17-mil nylon by varying the speed from about one-fifth the normal value used in the experiment to the normal value. As seen in Figure 5, the charge produced was constant to within the rub-to-rub reproducibility.

This finding made it possible for us to relax certain of

the experimental conditions with respect to temperature and relative humidity, in order to obtain data more rapidly and conveniently. Some of the later data have been obtained at room temperature (24-28°C) and room humidity (15-45%).

E. Effect of Normal Force

The normal force between the filaments is controlled by the weight W hung on the lower filament, in conjunction with the geometrical arrangement of the apparatus. Consideration of Figure 3 shows that the normal force between the filaments is given approximately by twice the tension (equal to the weight W under the conditions of the experiment) multiplied by the ratio of the overlap to half the span of the lower yoke, so long as the upper filament is at high enough tension that its deflection is negligible.

It has been found (4,6,8) that almost always an increase in the normal force increases the charge transferred, typically as F to some power between ½ and 1. A set of representative data is shown in Figure 6, where the points show the measured values of q against F for a 14-mil tantalum wire rubbing against a 17-mil nylon filament. The solid curve shows the relation $q \sim F^{\frac{1}{2}}$.

It is easier to visualize the functional dependence with the

aid of logarithmic plots, and we use such plots henceforth. The fundamental data are conveniently presented in this form, and since their precision is not high, it is sufficient to use these graphs instead of tables. The data for the long-term behavior (L) are given in Figures 7a-d. and for the short-term behavior (S) in Figures 8a-d. For each set of figures a pair of parallel lines of slope one-half is drawn to bracket the data and permit easy evaluation of the adequacy of this power-law representation. For the L set, the lines are drawn at a separation corresponding to a ratio of 2:1. Virtually all the data for a given figure are included between these limits. For a given diameter of nylon filament the points lie pretty well parallel to the bracketing lines. For the S set, where the spread in the data is much greater, it is necessary to draw the bracketing lines of slope one-half at a separation corresponding to a ratio of 3:1. The set of points for a given combination of filament diameters does not always lie parallel to the bracketing lines: indeed with the 9.2-mil nylon filaments a line of slope unity fits the data better. Moreover with these samples the filament-to-filament variability is higher.

F. Effect of Filament Diameter

Although the postulation $q \sim F^{\frac{1}{2}}$ is far from perfect, it can be used to reduce the mass of data to more nearly manageable proportions. To illustrate the techniques of this reduction, Figure 9 shows a logarithmic plot of q against F for the data of Figure 6. There are shown also the values of $q/F^{\frac{1}{2}}$, which is seen not to deviate far from a constant over the whole range of varying force. We can then take this constant as a parameter to describe the electrostatic behavior of this particular combination of filament diameters over the whole range of varying force. This parameter can then be studied as a function of filament diameter. We shall adopt this procedure to show the behavior of charge transferred with filament diameter, instead of merely making crossplots of the data in Figures 7 and 8.

G. Long-term results (L)

Figure 10 shows a plot of $q/F^{\frac{1}{2}}$ against d_{Ta}, the diameter of the tantalum wire, with d_{Ny}, the diameter of the nylon filaments, as a parameter. Individual values of $q/F^{\frac{1}{2}}$ are shown, their spread along the vertical representing both the departure from constancy for a given d_{Ny}, and the variation from one d_{Ny} to another. The dependence on

d_{Ny} is so slight that coding of the points for the separate nylon diameters is not practical. We note that $q/F^{\frac{1}{2}}$ increases at first with increasing d_{Ta} roughly as the square root (represented by the dashed line of slope one-half), and then falling off at the largest diameter of tantalum used. Here a few points lie nearly on the dashed line, but they are remote from the main body of points and we do not believe that their existence can be taken to justify maintaining the square-root law. Perhaps there occurs sporadically electrical breakdown or rolling rather than sliding of one filament on another, to reduce the charge below normal; but we have no evidence to support this conjecture.

Figure 11 shows a plot of $q/F^{\frac{1}{2}}$ against d_{Ny}, with d_{Ta} now serving as parameter. Of course, no new information is contained in this plot, but the effect of nylon diameter is easier to visualize. We see that $q/F^{\frac{1}{2}}$ varies little with d_{Ny}, as we knew implicitly from Figure 10. The vertical spread of the points reflects of course the variation with d_{Ta} that appeared explicitly in Figure 10.

H. Short-term results (S)

Figure 12 shows a plot of $q/F^{\frac{1}{2}}$ against d_{Ta}, the diameter of the tantalum wire, with d_{Ny}, the diameter of the nylon filament,

as a parameter. Individual values of $q/F^{\frac{1}{2}}$ are shown, their spread along the vertical again representing both the departure from consistancy for a given d_{Ny}, and the variation from one d_{Ny} to another. The dependence on d_{Ny} is appreciable, but to code the points on the scale of the drawing is again impractical. We note that there is very little dependence on d_{Ta}.

Figure 13 shows a plot of $q/F^{\frac{1}{2}}$ against d_{Ny}, with d_{Ta} now serving as parameter. We might note a tendency for a maximum at intermediate diameters, but one would be hard put to certify its reality.

CHAPTER IV

DISCUSSION

The dependence of transferred charge on filament diameter has significant technological and scientific consequences. Hence considerable effort is justified in establishing this dependence. The history of the diameter effect is very confusing. Hersh (4), in his exploratory experiments on size effect, reported no dependence. Cunningham (6), in later and more refined experiments, found that the charge transferred decreased with increasing filament diameter, on rubbing 8-mil nylon on varying diameters of polyethylene. He warned, however, that possible difference in chemical composition from diameter to diameter might be masking the true diameter dependence. Montgomery, Smith, and Wintermute (reference 8, hereinafter referred to as MSW) sought to eliminate this possibility by working with special samples extruded from the same melt and therefore chemically identical. In running 12-mil tantalum against several different diameters of nylon, MSW found that the charge transferred was proportional to the square root of the nylon diameter. In running 12-mil polyethylene against nylon, they

found no effect of nylon diameter. To explain these findings, MSW suggested an explanation based on detailed consideration of the area of true contact as influenced by the diameters of the filaments. They proposed that their conjecture be tested by studying a wider range of nylon diameters and by varying diameters of tantalum or polyethylene. It was the intention of this work to test the conjecture of MSW. Several changes were made in the apparatus to give better control over the mechanical variables. The fluctuations in charge measured from rub to rub were thereby brought to less than 3%, as compared with the 5% reported by MSW. The variability from filament to filament was brought to 17% for the long-term runs and to 14% for the short-term runs, as compared with the 20% reported by MSW.

So far as dependence of charge on normal force is concerned, most of the results in the present work are in agreement with earlier findings that the charge increases more or less as the square root of the force, as can be seen in Figures 7 and 8. As pointed out in Chapter III, such a simple relationship makes it possible to assess any diameter effect readily. But when the dependence of charge on diameter of the nylon filament is considered,

the results for the L tests of the present work fail to agree with the results of MSW, as can be seen from Figure 11. Here, instead of the increase of charge as the square root of the diameter, a decrease is found at the largest diameter (following a slight increase at the smaller diameters). Hence, we cannot apply the conjectures of MSW to the present data.

For the dependence of charge on diameter of the tantalum filament, there is evidence in the L runs for the square-root law for 7-mil, 14-mil, and 32-mil wires, but not for 62-mil wire, as seen in Figure 10. It is difficult to say whether the few points at the highest diameter represent an artifact or not.

Concerning the S tests - which are not supposed to be described by the MSW explanation - we note that the diameter of the nylon filament exerts almost no effect on the charge transferred. In conjunction with the L tests for the smaller-diameter filaments, the S tests indicate that the charge transferred during the first few rubs does not depend on the filament diameter, but that with increasing number the charge builds up to a limiting value proportional to the square root of the diameter. Such circumstances render understandable some of the conflicting findings and opinions about the diameter effect. So far as effect of diameter of tantalum wire is concerned, no strong trend appears.

It becomes increasingly clear that the complexity of the geometric effects is so great that they cannot be unraveled without resort to simpler experimental arrangements. Closer examination of the dependence of charge on normal force bears out this conclusion For example, the behavior of charge-versus-force for the 9.2-mil nylon filament is better described by a first-power law rather than a square-root law (cf. Fig. 7a). This finding is quite consistent and reproducible. Indeed, earlier works did obtain some curves not following a square-root law, but they believed that the effect was spurious in view of the lower degree of refinement in their apparatus and procedures (8). Hence we conclude that our studies have reached the stage where the changes in the electrostatic behavior due to different origin of material, changing normal force, and varying filament diameters, all demand better defined substances and better defined conditions for their elucidation (10).

Specifically, materials of precisely-defined chemical composition (such as alkali halides, but especially transition-metal oxides) of well-defined geometry (probably circular cylinders) need to be studied in carefully- controlled atmospheres (including vacua, and inert gases at high and low pressures) with well-defined

mechanical conditions (say with solidly-backed specimens in precisely-loaded holders). We fear that the cost of such an apparatus makes it impractical to consider its development at this time.

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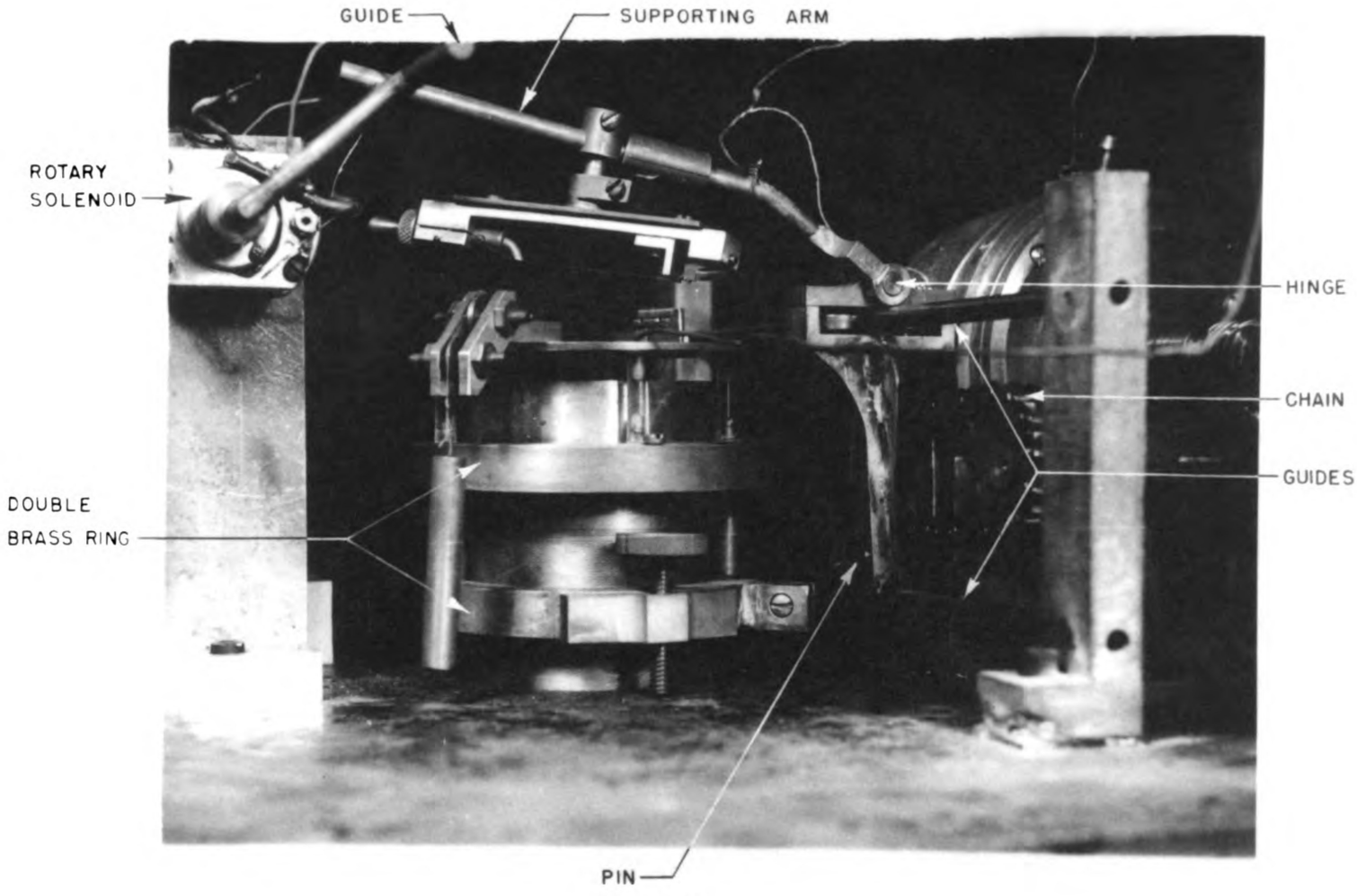

FIGURE 1

RUBBING APPARATUS

Photograph of rubbing apparatus. At the left are the rotary solenoids that lift the arm holding the upper yoke shown in the middle of the picture. At the upper right is the slave selsyn. At right angles just under the upper yoke is the lower filament. (After Cunningham 1957.)

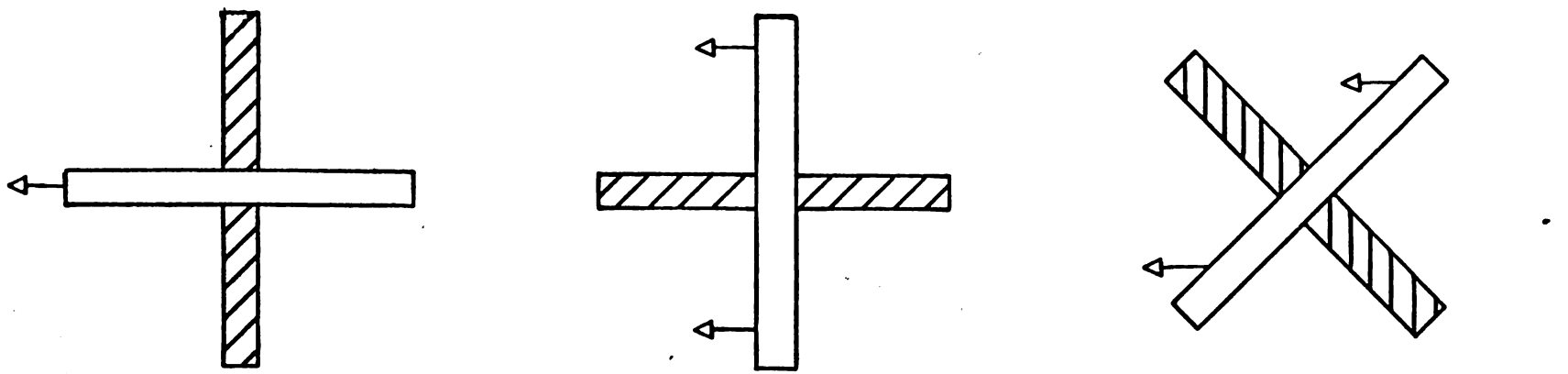

Figure 2. Schematic diagram of rub type.

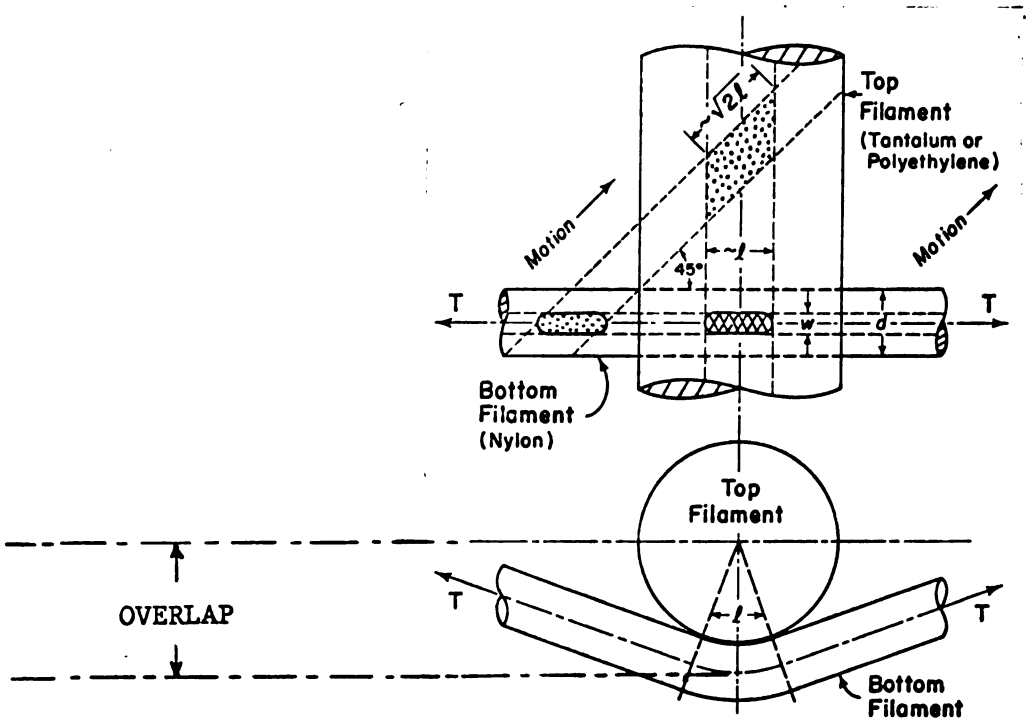

Figure 3. Diagram to illustrate geometrical configuration of filaments. The tension T on the bottom filament, equal to the weight W, acts to press the bottom filament against the top filament through a length of contact ℓ. The overlap is the vertical distance between the center lines of the two filaments. (After Montgomery, Smith, and Wintermute 1961.)

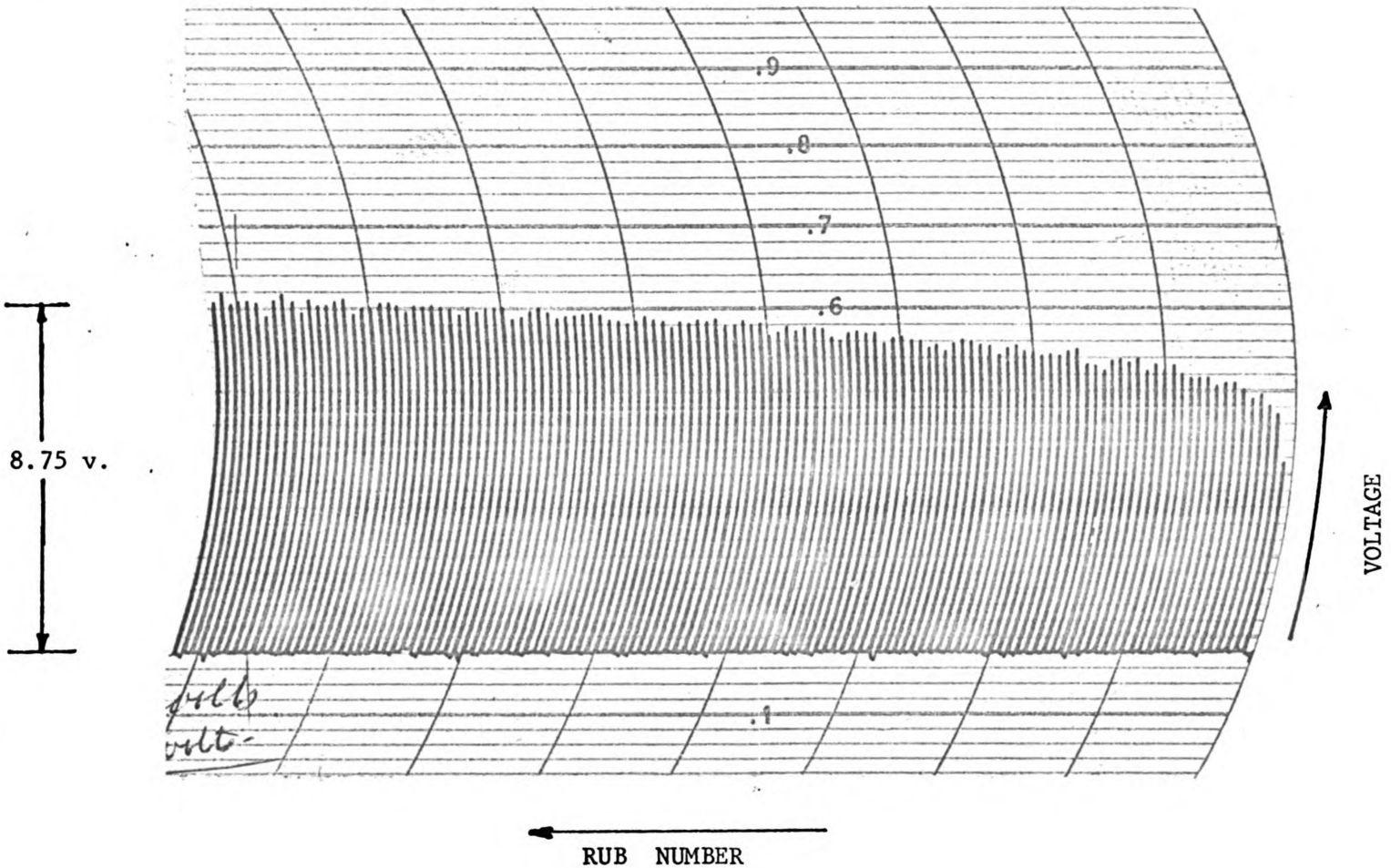

Figure 4. Reproduction of actual chart record of electrometer voltage V as a function of rub number. Filament combination: 14-mil tantalum (-) rubbing on 17-mil nylon (+); relative humidity 33%, temperature 30°C.

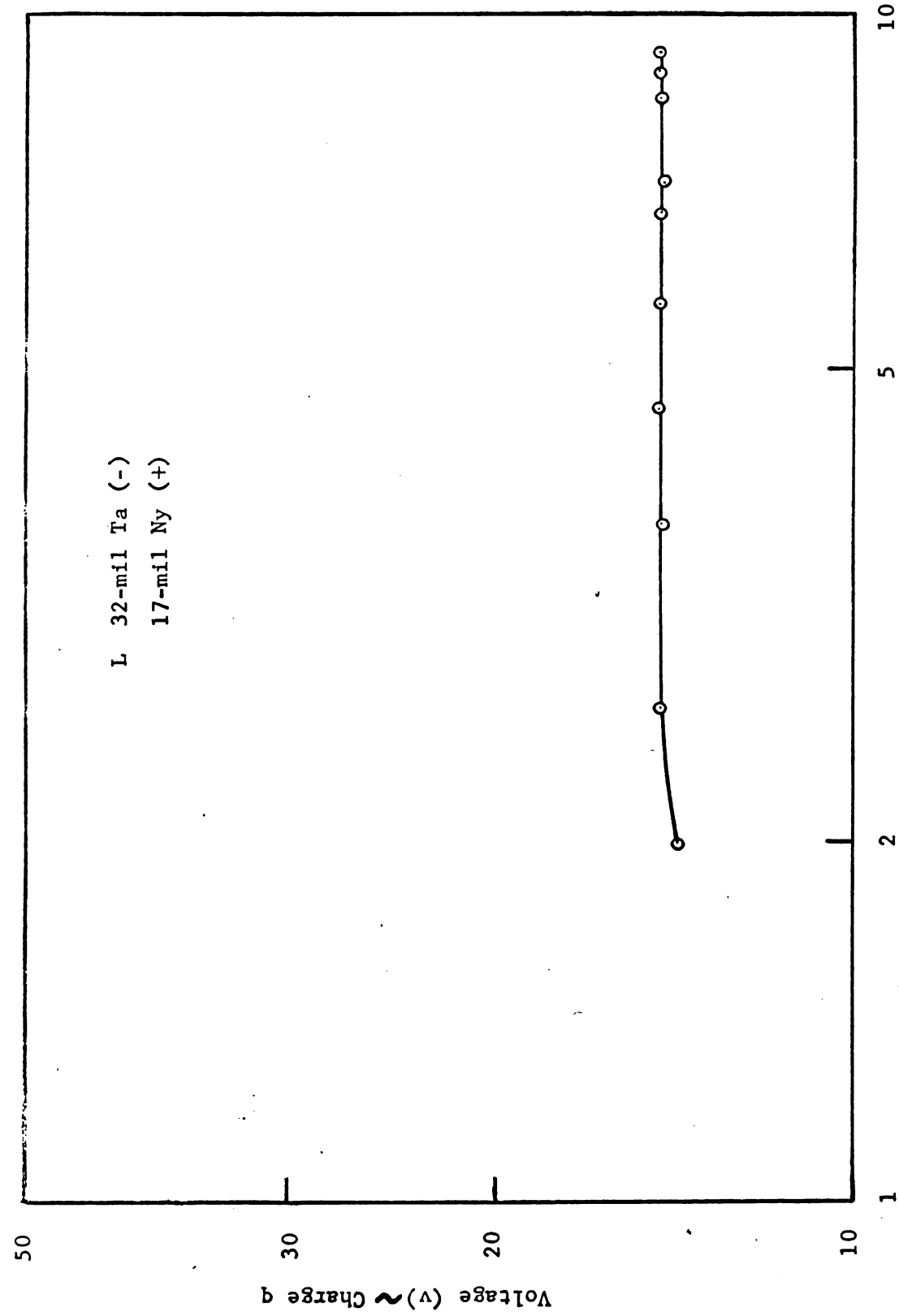

Figure 5. Logarithmic plot of electrometer voltage V (proportional to charge q) against rub velocity, for 32-mil tantalum on 17-mil nylon.

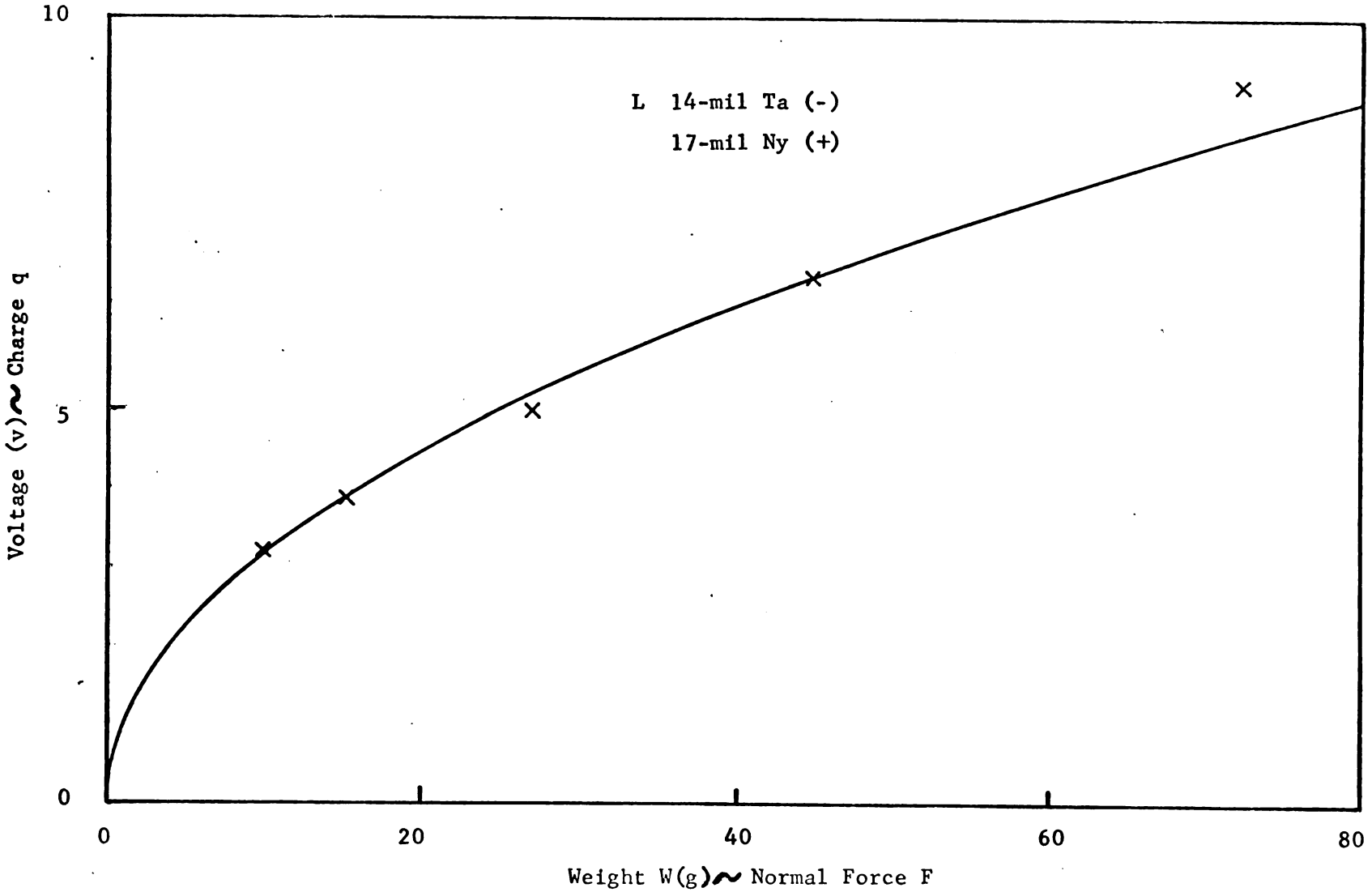

Figure 6. Linear plot of voltage V (proportional to transferred charge q) against weight W on lower filament (proportional to normal force F) , for 14-mil tantalum (-) rubbing on 17 mil nylon. (Long-term.)

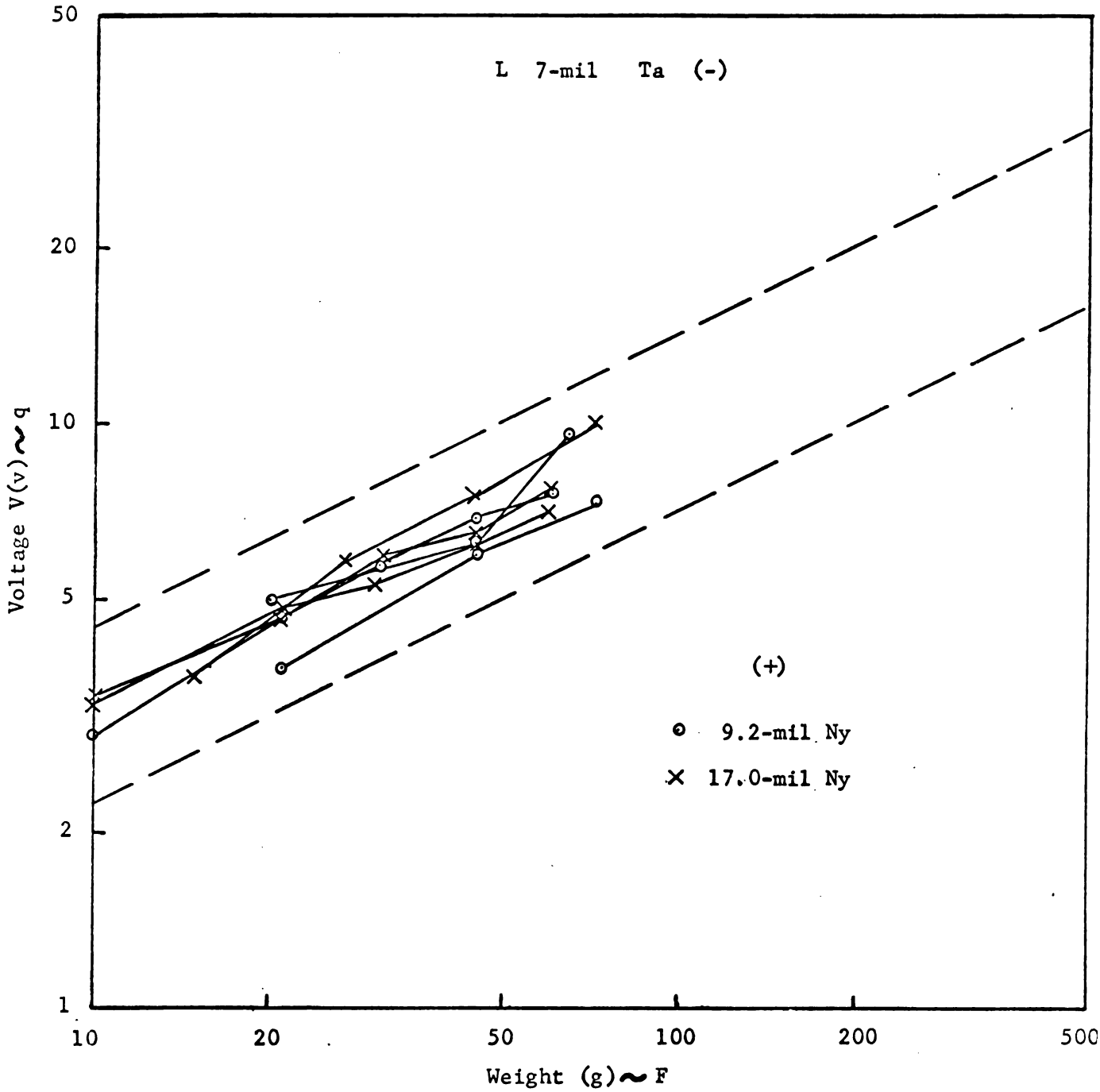

Figure 7a. Logarithmic plot of voltage V (proportional to charge q) against weight W on lower filament (proportional to normal force F), for 7-mil tantalum wire rubbing on nylon filaments of various diameters as shown. (Long-term.)

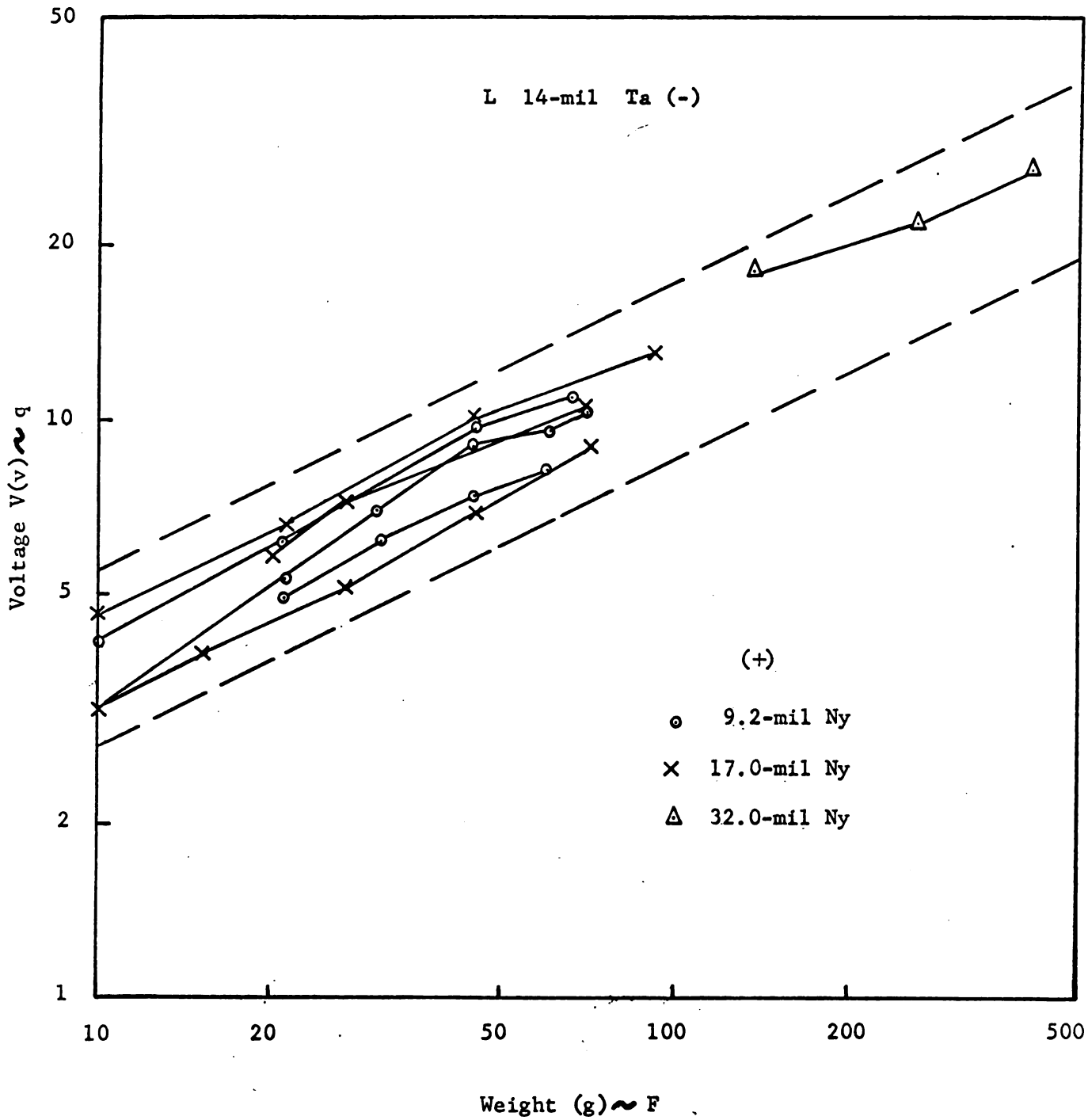

Figure 7b. As in Figure 7a, but for 14-mil tantalum wire. (Long-term.)

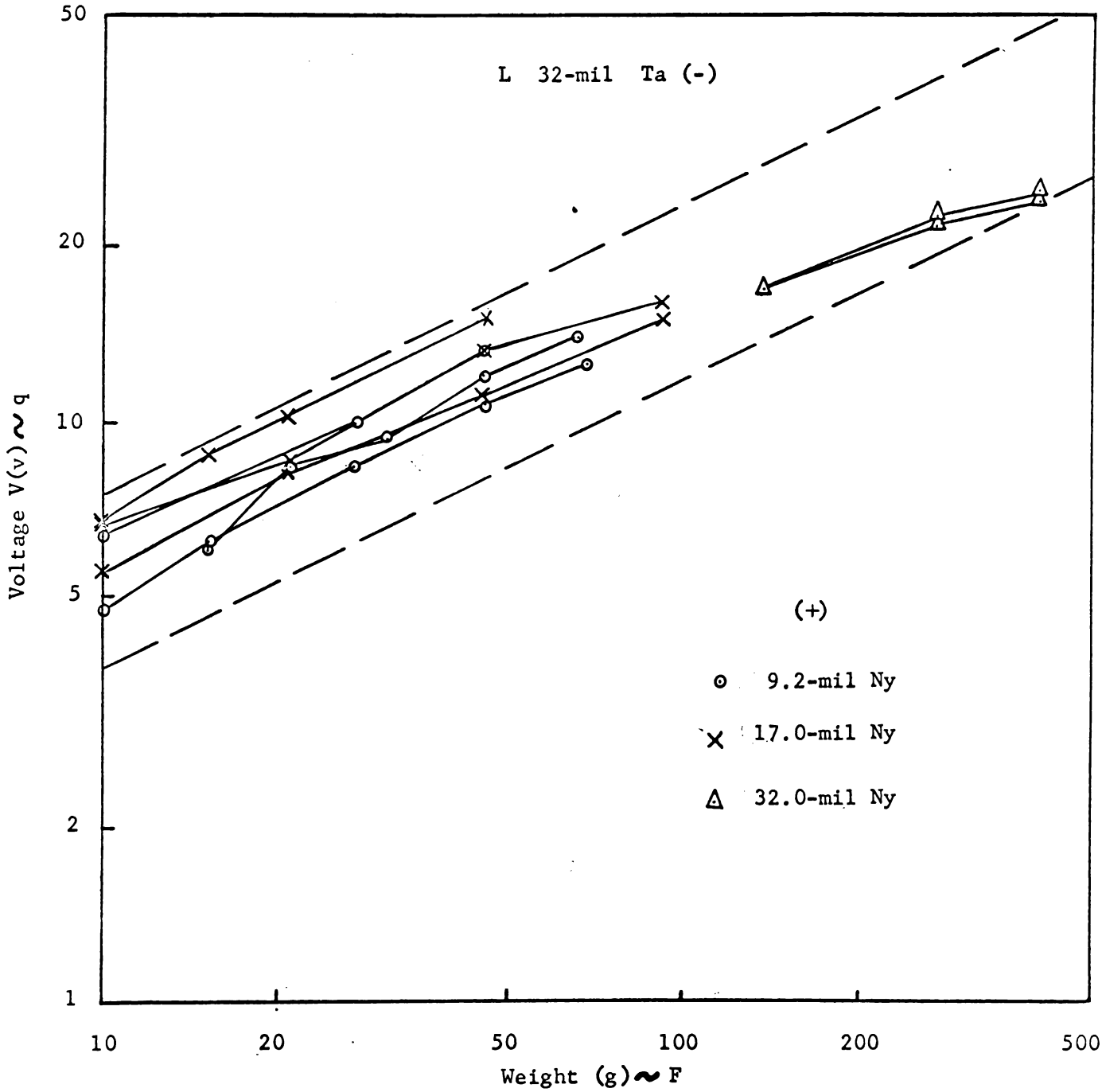

Figure 7c. As in Figure 7a, but for 32-mil tantalum wire. (Long-term.)

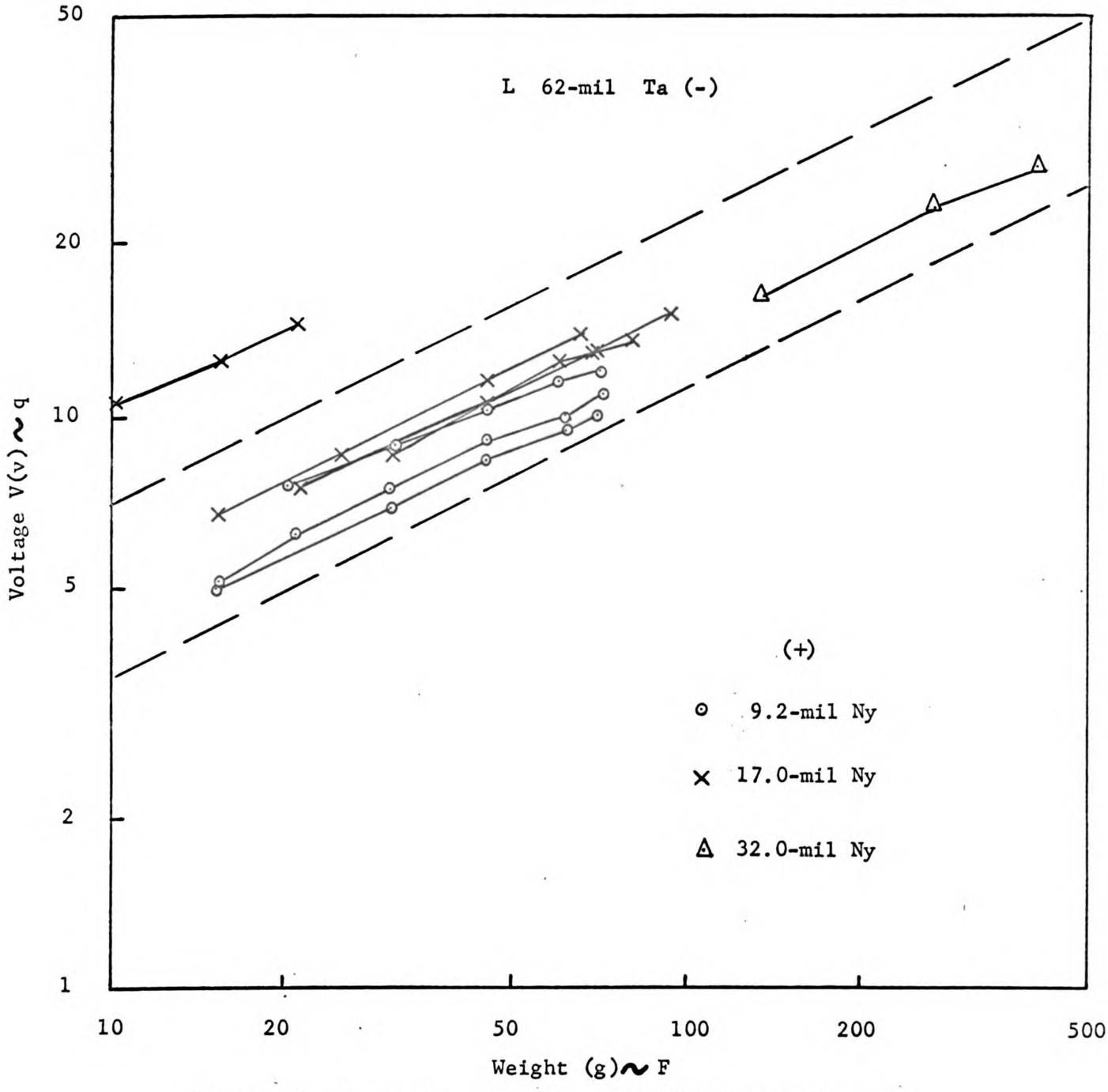

Figure 7d. As in Figure 7a, but for 62-mil tantalum wire. (Long-term.)

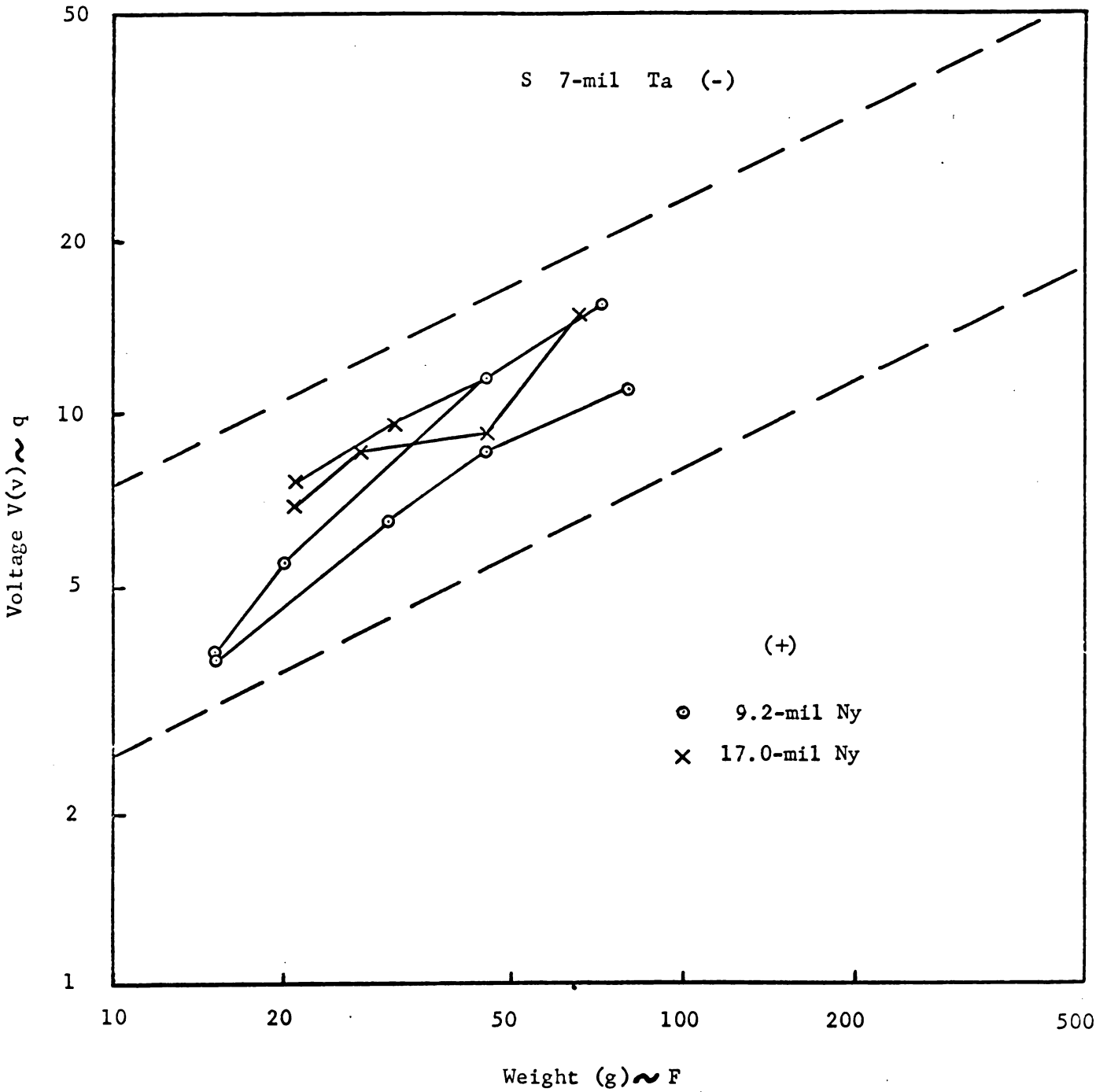

Figure 8a. Logarithmic plot of voltage V (proportional to charge q) against weight W on lower filament (proportional to normal force F), for 7-mil tantalum wire rubbing on nylon filaments of various diameters as shown. (Short-term.)

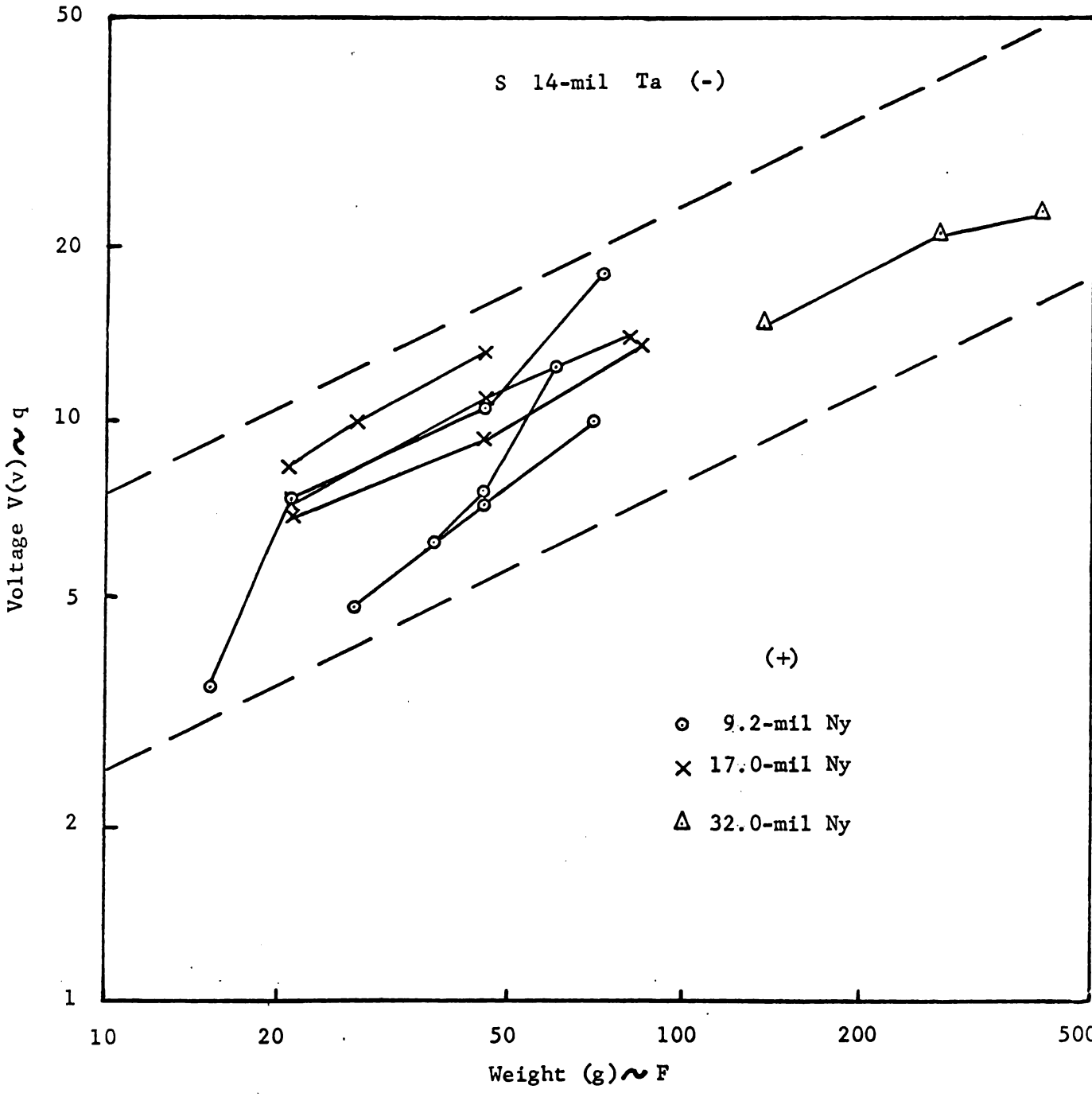

Figure 8b. As in Figure 8a, but for 14-mil tantalum wire. (Short-term.)

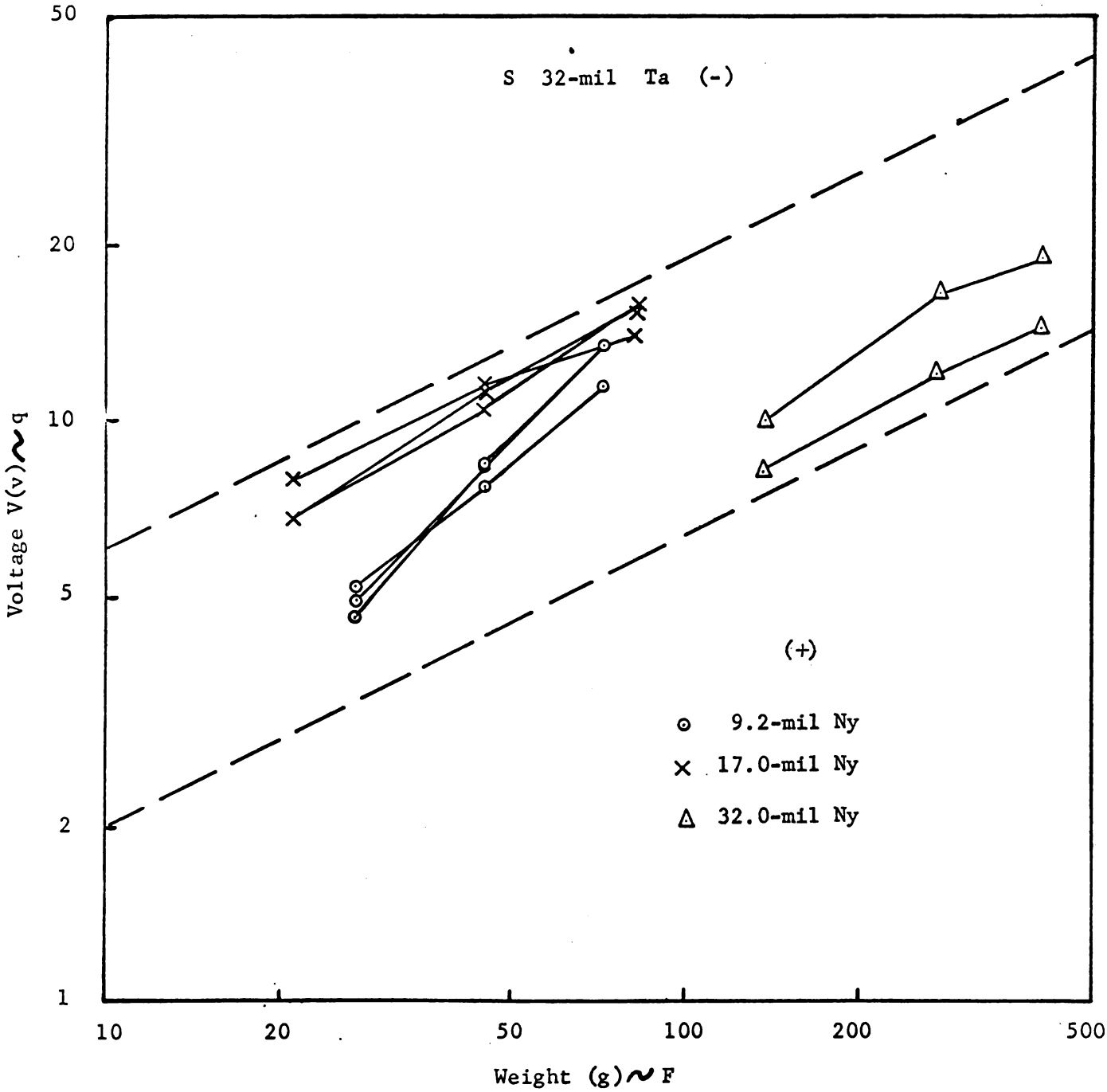

Figure 8c. As in Figure 8a, but for 32-mil tantalum wire. (Short-term.)

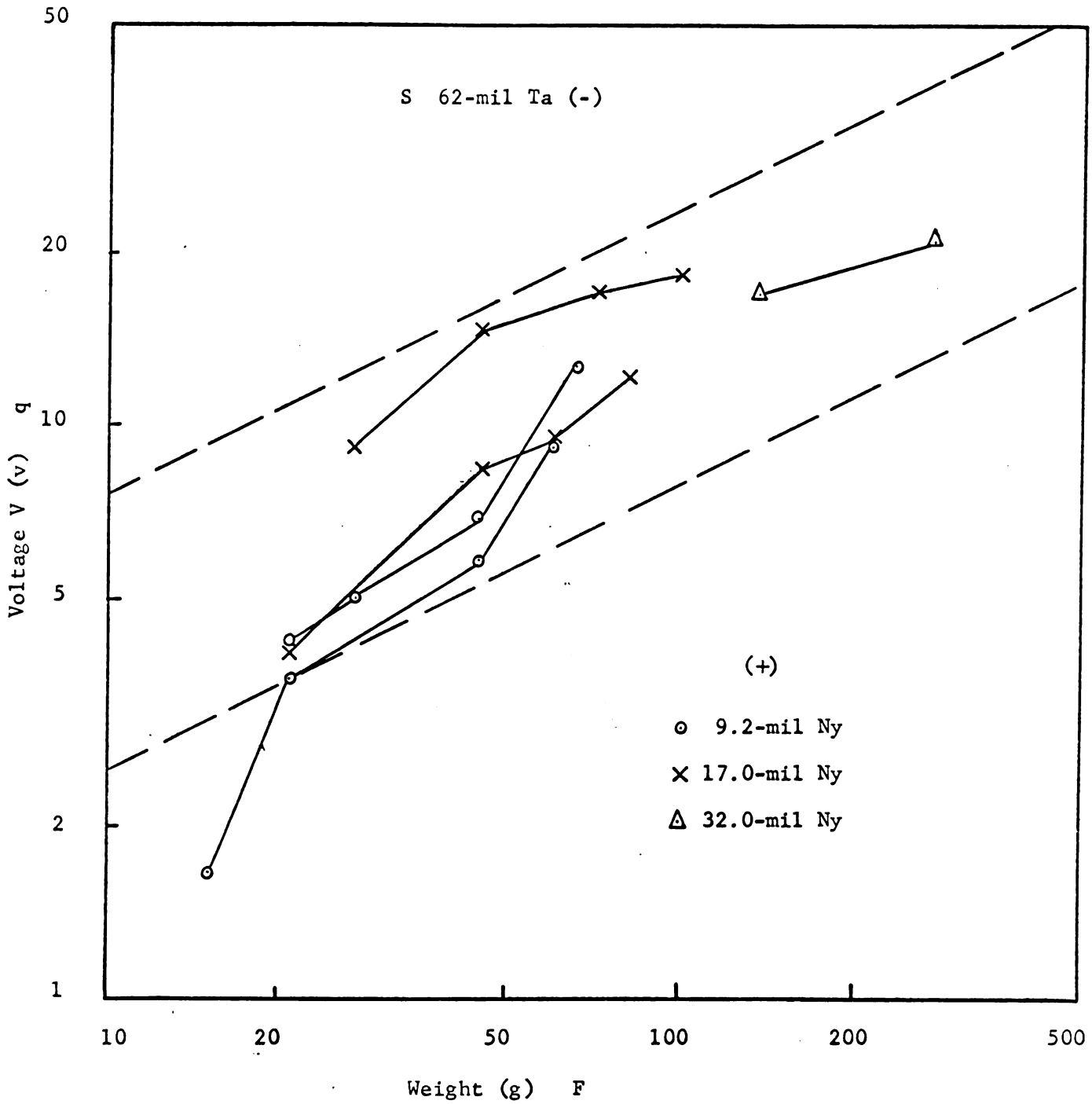

Figure 8d. As in Figure 8a, but for 62-mil tantalum wire. (Short-term.)

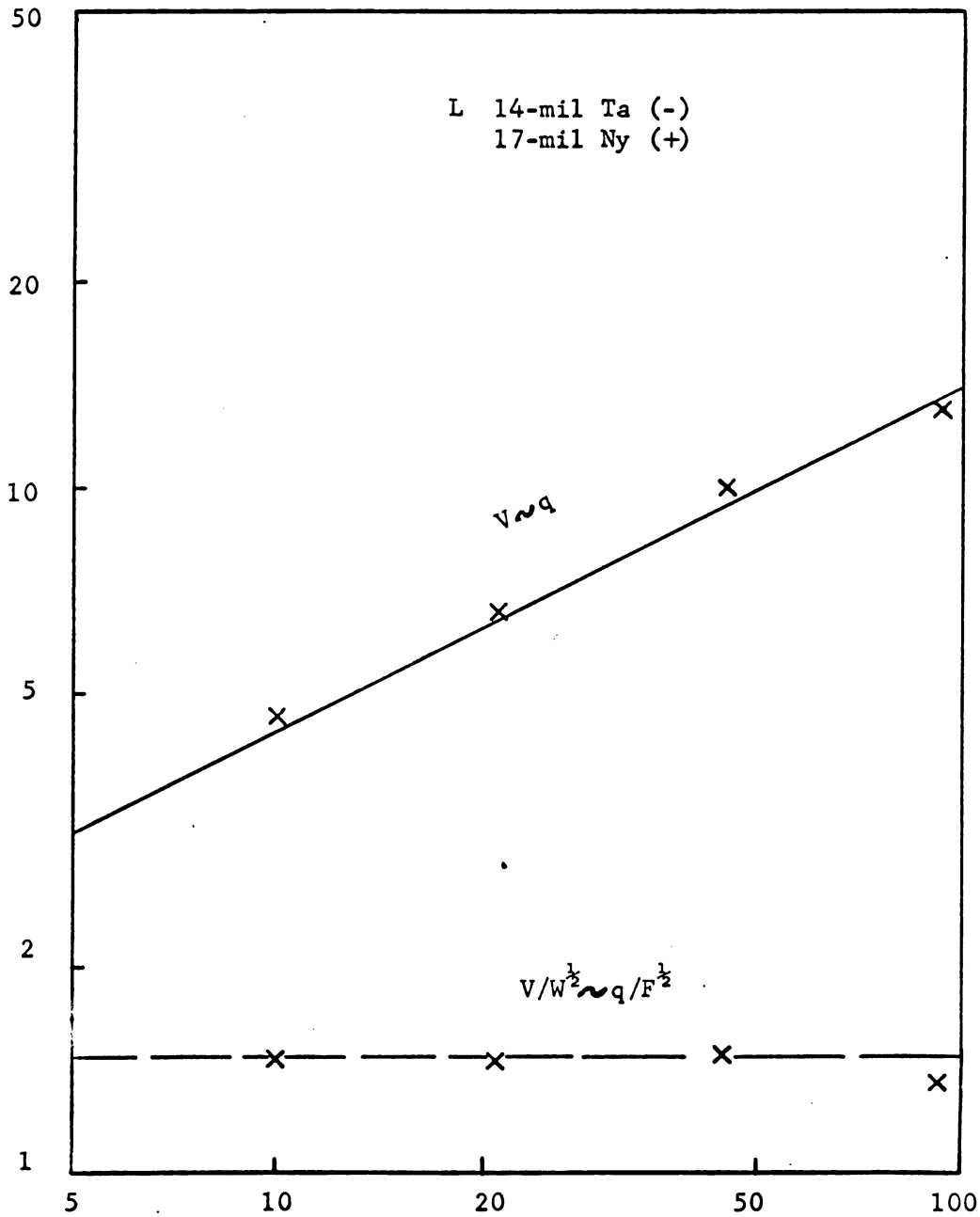

Figure 9. Logarithmic plot of voltage V (proportional to q), and of $V/W^{\frac{1}{2}}$ (proportional to $q/F^{\frac{1}{2}}$) against W (proportional to F) for 14-mil tantalum against 17-mil nylon. (Long-term.)

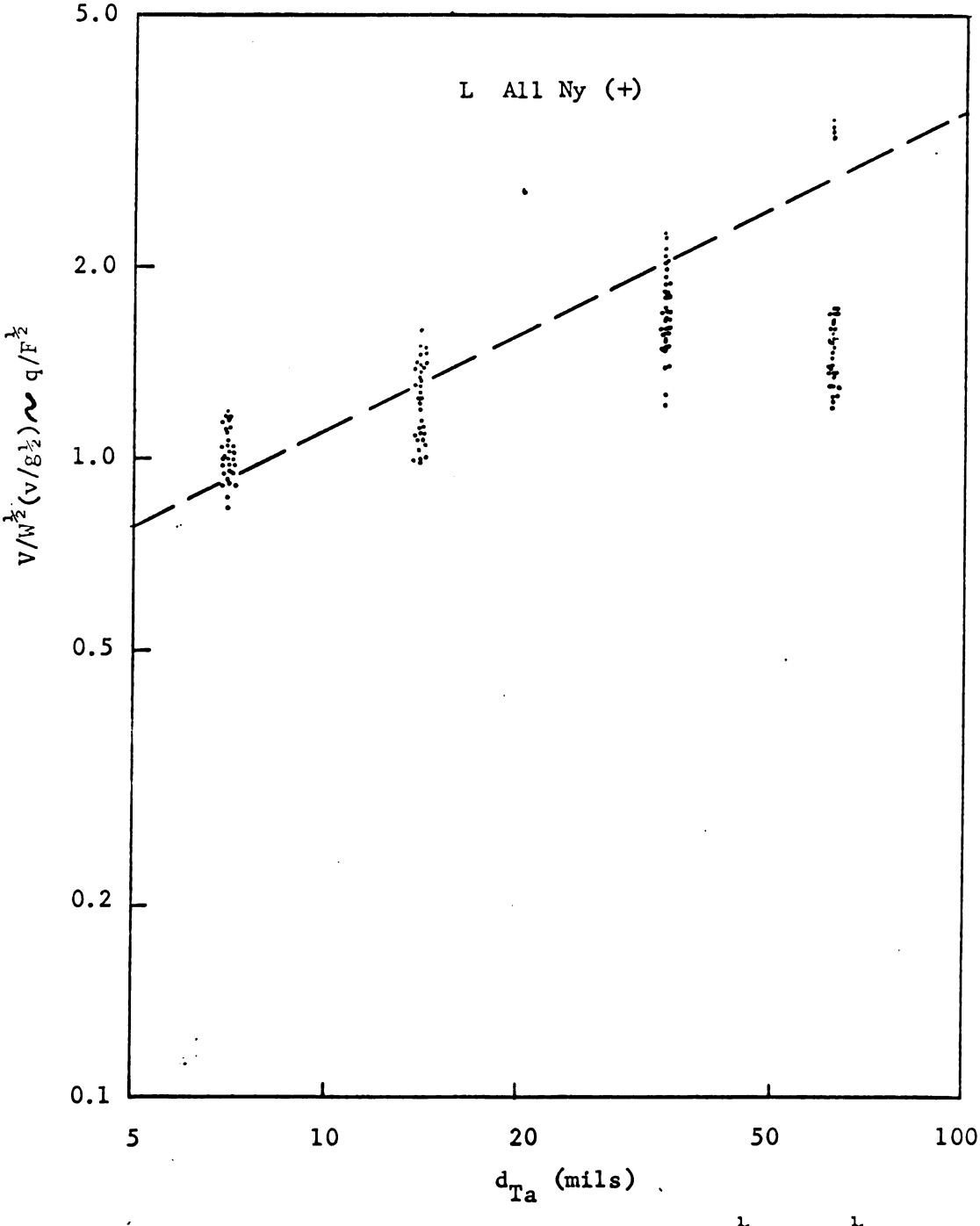

Figure 10. Logarithmic plot of $V/W^{\frac{1}{2}}$ ($q/F^{\frac{1}{2}}$) against d_{Ta}, for nylon filaments of various diameters in mils, (9.2, 17, 32). (Long-term.)

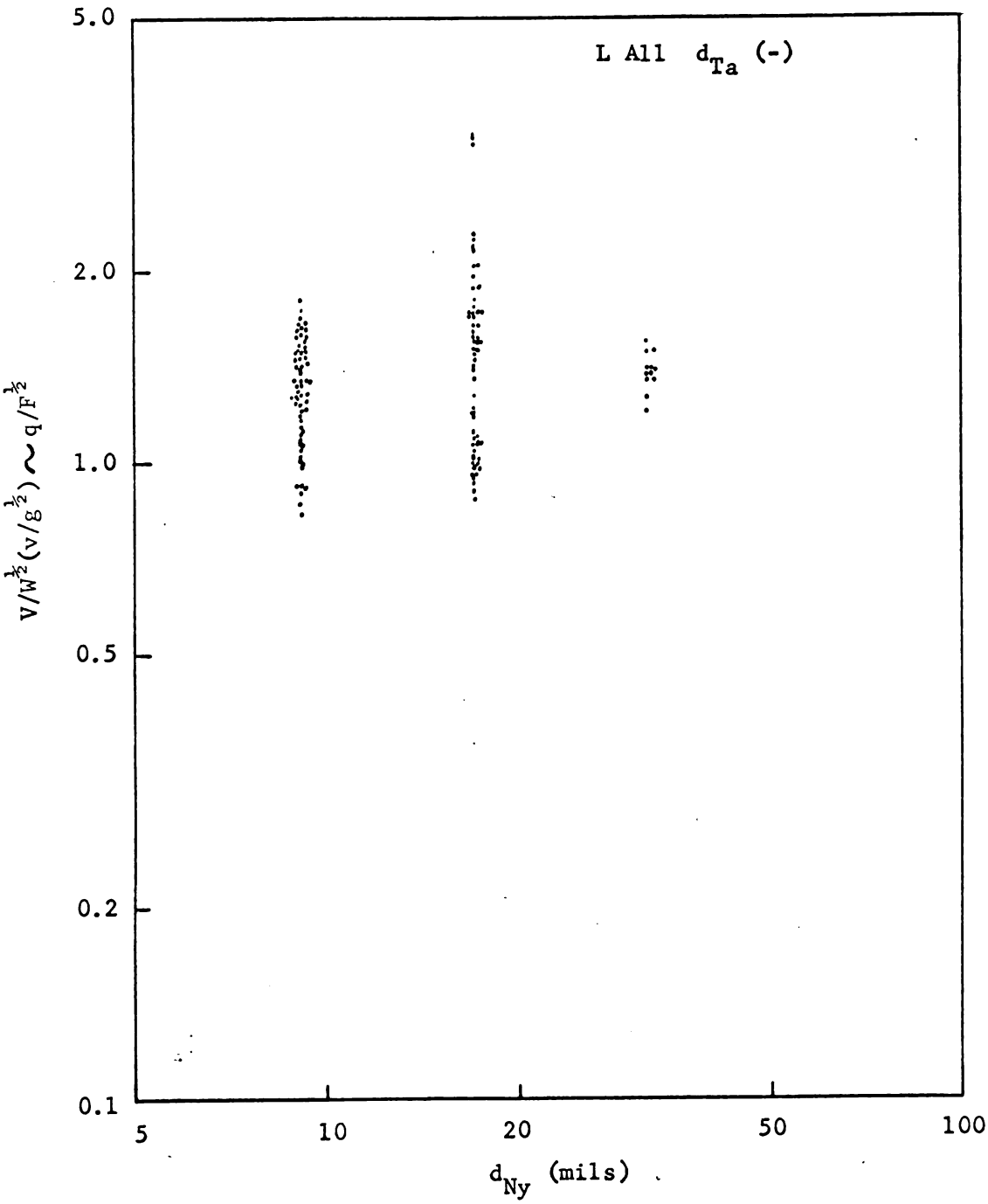

Figure 11. Logarithmic plot of $V/W^{\frac{1}{2}}$ ($q/F^{\frac{1}{2}}$) against d_{Ny} , for filaments of various diameters d_{Ta} in mils (7, 14, 32, 62). (Long-term.)

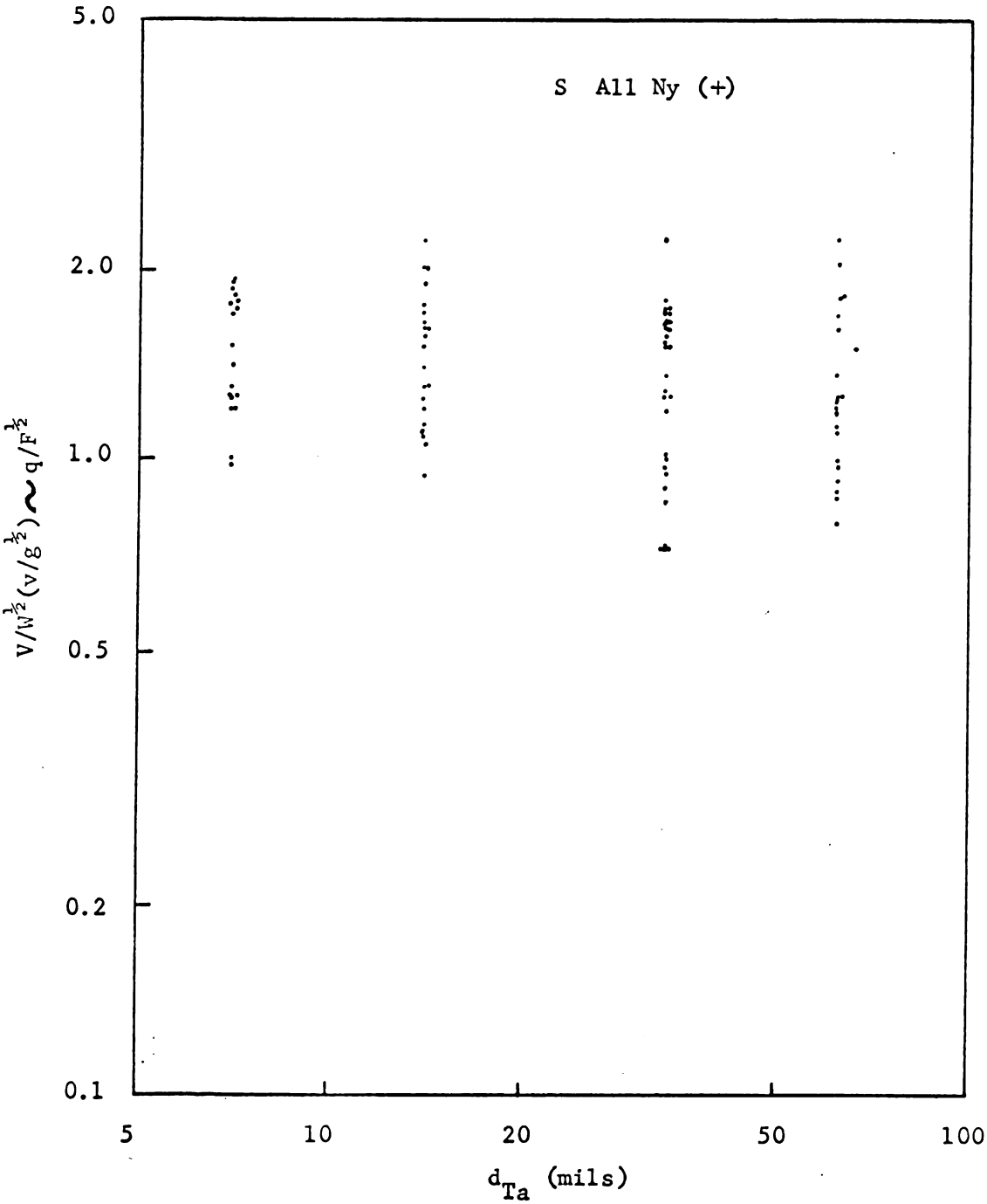

Figure 12. Logarithmic plot of $V/W^{\frac{1}{2}}$ ($q/F^{\frac{1}{2}}$) against d_{Ta}, for nylon filaments of various diameters in mils, (9,2, 17, 32). (Short-term.)

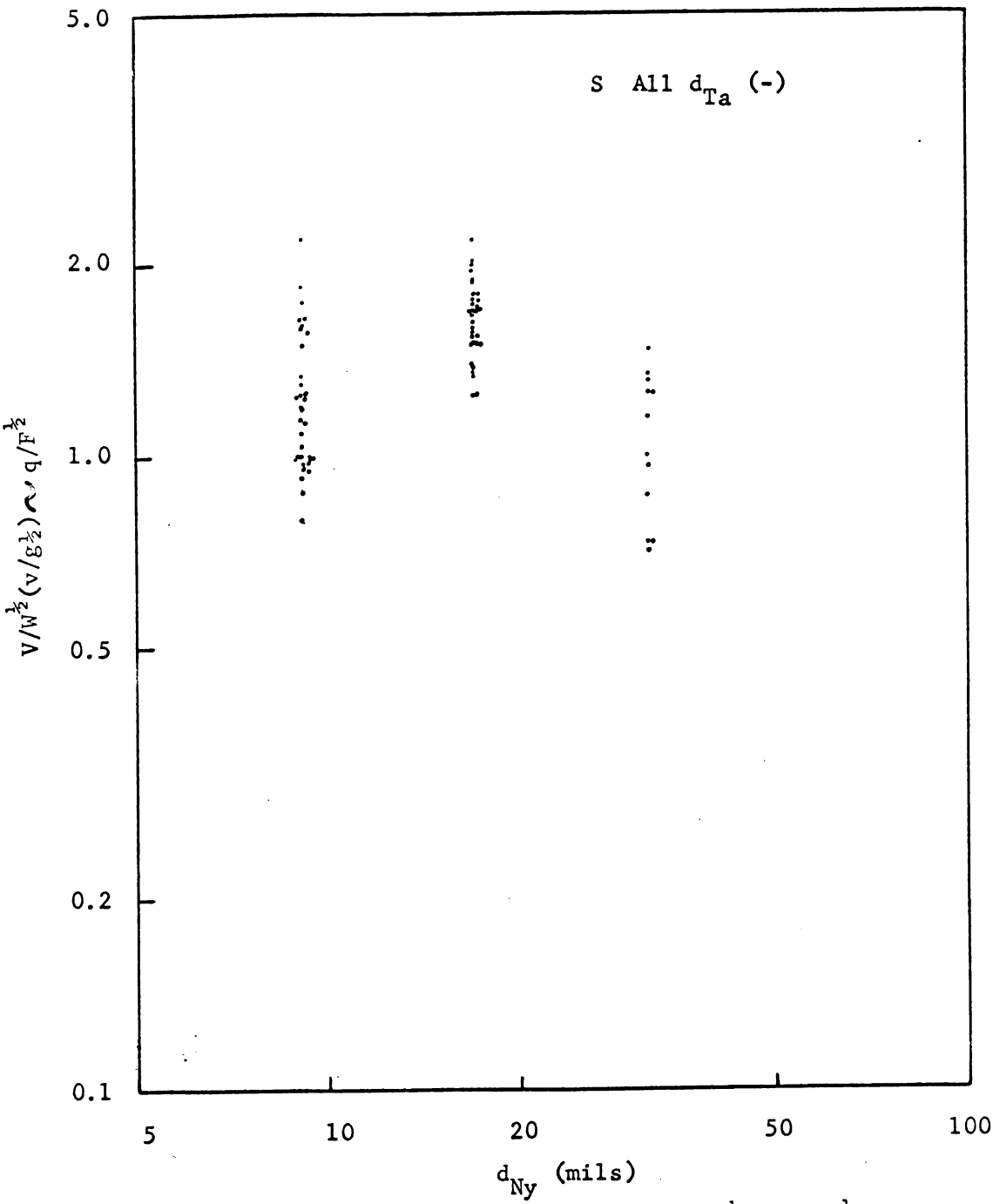

Figure 13. Logarithmic plot of $V/W^{\frac{1}{2}}$ ($q/F^{\frac{1}{2}}$) against d_{Ny}, for filaments of various diameters d_{Ta} in mils (7, 14, 32, 62). (Short-term.)

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APPENDIX

Calculation of absolute charge per unit length

The charge Q on the system is equal to the voltage V read by the electrometer, multiplied by the capacitance C of the system. The charge per unit length is equal to Q/L, where L is the rub length. Hence

$$Q/L = CV/L = (25\ \mu\mu\text{farad}/5\ \text{cm})\ V\ (\text{volts}) = 5\ V\ (\text{volts})\ \ \mu\mu\text{c/cm}.$$

Calculation of absolute normal force

The normal force F between the filaments is equal to twice the tension T multiplied by the overlap, and divided by half the span. Moreover, the tension T is equal to the weight W. Hence

$$F = 2\ W\ (\text{overlap})/\tfrac{1}{2}(\text{span}) = 4\ W\ (0.46/10.2) = 0.136\ W\ (\text{grams force}).$$