THE SYNERGISTIC EFFECTS OF SLIP RING-BRUSH DESIGN AND MATERIALS

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July 1971

Interim Report for Period March - June 1971

Prepared for
GODDARD SPACE FLIGHT CENTER
Greenbelt, Maryland 20771

1. Report No.

2. Govt. Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle

The Synergistic Effects of Slip Ring-Brush Design and Materials

5. Report Date

July 1971

6. Performing Organization Code

7. Author(s)

N.E. Lewis, S.R. Cole and E.W. Glossbrenner

8. Performing Organization Report No.

9. Performing Organization Name and Address

Poly-Scientific Division
Litton Systems, Inc.
1213 North Main Street
Blacksburg, Virginia 24060

10. Work Unit No.

11. Contract or Grant No.

NAS 5-21146

12. Sponsoring Agency Name and Address

Goddard Space Flight Center
Greenbelt, Maryland 20771
Technical Officer: Charles E. Vest
Code 721

13. Type of Report and Period

Interim Report for Period March - June, 1971

14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

The preliminary results of a program involving the design, fabrication and subsequent testing of four power slip rings for vacuum application have been presented. Details of the environmental and instrumentation systems necessary for monitoring electrical noise, friction and brush wear under earth-bound conditions and a vacuum condition of less than 5×10^{-8} torr have been described. The four material combinations represented have been evaluated during run-in at 150 RPM under ambient conditions and during a humidity sequence at 0.1 RPM. Electrical noise, friction and brush wear data recorded during these periods have been discussed. Significant among the conclusions drawn was that after 12×10^5 inches of ring travel all material combinations exhibited small quantities of wear debris, displayed no apparent correlation between the parameters of electrical noise, friction and brush wear and humidity and no differences in noise level were found to exist between inductive and resistive loading.

17. Key Words

Friction, Wear Electrical Noise
Composite Lubricants

18. Distribution Statement

19. Security Classif. (of this report)

20. Security Classif. (of this page)

21. No. of Page

22. Price

PREFACE

This program involves the testing of four slip ring brush combinations operated under high power conditions in an environment of 5×10^{-8} torr pressure. Frequent and simultaneous recording of friction, wear, electrical noise data and dielectric strength enable the synergistic effects of slip ring and brush design and materials to be studied. The total program encompasses the design, fabrication and testing of these fixtures for a one-week period of performance in atmosphere followed by two years at 0.1 RPM and a subsequent four-month test at two speeds 0.1 and 4 RPM in vacuum environment.

The four material combinations involved are Poly-Scientific ES384 brushes vs rings of rhodium plate over nickel plate on a brass substrate; Poly-Scientific ES384 brush material vs coin silver (silver-10% copper) rings; Poly-Scientific ES383 brushes vs rings of rhodium plate over nickel plate over brass substrate; Poly-Scientific ES383 brushes vs coin silver (silver-10% copper) rings.

The data presented herein are those recorded during periods of run-in at 150 RPM and the humidity sequence in air at 0.1 RPM which accumulated a total of 12×10^5 inches of ring travel. These data have indicated that:

1. Rings of coin silver yield lower noise levels, when employed with ES383 or ES384 brushes, than rhodium plate.
2. Differences in electrical noise levels for conditions of inductive loading and resistive loading do not appear to exist.
3. Rings of rhodium plate gave lower frictional forces (peak and stick-slip) than did rings of coin silver.
4. Wear rates for all combinations were low with ES383 brushes on rhodium plate yielding the lowest overall rate.

5. Correlations between the parameters of electrical noise, friction and brush wear and humidity do not appear.

It is recommended that the two year vacuum test continue and data be collected at a frequency of twice per week.

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THE SYNERGISTIC EFFECTS OF SLIP RING-BRUSH DESIGN AND MATERIALS

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I. INTRODUCTION

The increasing life of space missions is imposing more stringent requirements on sliding contact devices. These missions may require sliding contact devices to operate continuously for periods in excess of 10 years. The design and choice of materials necessary to fabricate a sliding contact device capable of satisfying long lifetime requirements must be supported by test data. To provide the data concurrent with the need it is necessary to perform experiments on an accelerated basis.

A program to study the synergistic effects of slip ring design and materials is currently underway to provide data for synchronous orbit power slip ring applications. This program involves the design, fabrication and testing of four power slip rings representing four ring and brush material combinations under a sequence of earth-bound conditions and a vacuum environment of less than 5×10^{-8} torr. The simulated life experiments are being conducted on an accelerated basis by running the fixtures at a speed of: (a) 150 RPM during a 10 hour run-in period, (b) 0.1 RPM during the 5-day earth-bound condition, and (c) 0.1 RPM during the two year vacuum condition. After completion of the two year test and a post test analysis the parts will be refurbished and a four month vacuum test alternating between rotor speeds of 0.1 and 4 RPM will be conducted. All tests are being conducted with a brush current density of 100 amps/sq. in.

The four ring and brush material combinations under evaluation are as follows:

(A) Poly-Scientific ES383 brushes vs rings of rhodium plate over nickel plate on a brass substrate (Combination A)

(B) Poly-Scientific ES383 brush vs coin silver (silver -10% copper) rings (Combination B)

(C) Poly-Scientific ES384 brushes vs rings of rhodium plate over nickel plate on a brass substrate (Combination C)

(D) Poly-Scientific ES384 brushes vs coin silver rings (Combination D).

Poly-Scientific ES383 is an engineering specification for brushes composed of 85% silver-12% molybdenum disulfide-3% graphite. ES384 similarly defines the 82% silver-15% niobium diselenide-3% graphite, composite. These specifications have been included in the Appendix. Electrical noise, friction and wear data are being collected during the run-in, earth-bound and vacuum conditions to evaluate the performance of the four material combinations.

At this point the 10-hour run-in period, the 5-day earth-bound test and the initiation of the two year vacuum test have been completed. Data are being presented that were generated during the run-in and 5-day earth-bound conditions.

II. Experimental

A. System Hardware

1. Test Fixtures

The fixtures being used in this study are 6-circuit assemblies which utilize two current-carrying brushes per ring (Figure 1).* The sixth ring of each fixture carries a third brush with mechanical loading only. Current is directed in one brush and out the other, thus giving a positive and negative brush on each ring. Each brush is located in a separate track to minimize the effect of wear debris from the other brushes on the same ring. Wear debris management has also been facilitated by the use of 50 mil high barriers between rings and open sections in the bottom of the frame.

Measurement of brush wear was accomplished by locating the core of a linear variable differential transformer LVDT (Item 20)* on the brush shaft. Wear stops (Item 25) located on the end of the brush shaft have been adjusted to constrain brush movement after 30 mils of wear has occurred. An electrical contact (Item 24) gauged 30 mils from the wear stop, has been located on the brush assembly as means of distinguishing 30 mils of wear from a brush-spring malfunction.

The entire brush assembly is attached to the frame by beryllium copper springs (Item 8) which form the ends of a parallelogram. These springs have been designed to permit linear motion in the direction of the frictional force and act as rigid members to forces in other directions. Negator™ springs were employed to yield a constant brush force (170 grams nominal) as the brush wears. The brushes have been mounted with a 15° trailing angle

* Various features of the fixture are identified by item number of Figure 1.

TM - Hunter Spring Company

with respect to the ring normal to minimize "stick-slip". The tangential friction force exerted on the brush by the ring is sensed as a brush block displacement using a proximity sensor (Item 28).

Transducers for measuring wear and friction are located on the positive, negative and neutral brushes on the sixth ring and the negative brush of the third ring.

2. Power System

The power system, a block diagram of which has been presented in Figure 2, was designed to permit three of the six rings on each fixture to be placed under an inductive and resistive (50 mh, 12 ohm) load and the remaining three on each fixture under a resistive (12 ohm) load only. Two Lambda model LB-705-FM power supplies were used to supply the current to the resistive and inductive rings of all fixtures. All the rings and brushes on the four fixtures having a common type of load were connected in a series circuit. In each circuit twelve one-ohm resistors were electrically located between the twelve rings to limit the current to 8.33 amperes at 100 volts dc (min). A silicon-controlled rectifier bypass network has been provided for each ring and brush pair in the event an open circuit condition lasting more than 50 miliseconds develops.

Switch panels have also been incorporated in each circuit which will permit the current to be rerouted in the even a short (or multiple shorts) occurs between any ring combination. Utilizing the series circuitry with the necessary bypass networks rather than a parallel arrangement allowed the current requirements to be dropped from 100 amps to 8.33 amps per power supply.

3. Friction, Electrical Noise and Wear System

A block diagram representing typical friction, noise and wear circuits has also been presented in Figure 2. The wear and friction circuits actually contain 16 transducers each. The primaries of the 16 LVDT's used for brush wear measurements are connected in a parallel circuit and excited by a single power supply and oscillator. The secondary outputs are fed into a 72 pole double throw "Measure-Calibrate" switch which is designed to switch the two secondary coils of each LVDT from a differential to sum voltage output. This provision provides a means of monitoring the condition of each transducer throughout the two years. From the Measure-Calibrate switch the signals are fed into a 16-level, 20-position stepping switch. This permits the use of only two amplifier demodulator channels to handle the 16 LVDT outputs. The amplifier demodulator outputs are displayed on two channels of an eight channel recorder.

The 16 proximity transducers used for friction measurements are connected in a circuit similar to the LVDT's. Utilizing a single power supply and oscillator for the 16 primaries required the addition of resistance to each to yield the proper circuit impedance. The out puts from the proximity secondaries are treated identically to the LVDT secondaries as described above.

Electrical noise measurements are made on each ring and brush pair as shown in Figure 2. As previously mentioned under "Test Fixtures", a third brush, carrying a mechanical load only, is located on the 6th ring of each fixture. This brush allows a noise signal to be measured across the positive and negative brush (sum noise), across the positive and neutral brushes (positive noise), and across the negative and neutral brushes (negative noise). The noise signals are also fed into the stepping switch referenced above and from there into 4 channels of an eight channel recorder.

The friction, wear and noise signals have been routed through the stepping switch in a fashion to permit simultaneous recording of these signals on the eight channel recorder. The columns in

Table I show the signals that are recorded simultaneously on the eight channel recorder.

4. Environmental Chambers

The 10-hour run-in and 5-day humidity tests were performed in a Blue M model VP-100A humidity chamber. The 10-hour run-in period for each fixture was performed with bell jar removed and therefore under ambient conditions. The 5-day humidity test was performed by adjusting wet and dry bulb controls to yield the lowest humidity condition possible (30-40%) for 24 hours and then adjusting these controls to yield 70-80% for 24 hours. This 48-hour cycle was repeated once with the fifth 24-hour period at 30-40%.

A Perkin-Elmer Ultek vacuum system, which has been shown in Figure 3 along with test console and recorder, equipped with conventional ion pumps and differential ion pumps, is being used for the vacuum environment. The pumping speeds for nitrogen, argon and helium are 700 L/S, 45 L/S and 100 L/S respectively. Roughing was achieved by using two sorption pumps. Four one foot-pound rotary motion feedthroughs driven by gear-reduced synchronous motors are being employed to rotate the slip rings at 0.1 RPM. The vacuum bearings in these units were lubricated using the Microseal lubrication process. All electrical connections were made through nine Deutsch 37 pin, 7.5 amp feedthroughs.

Clean, dry and empty this system was capable of less than $2X10^{-9}$ torr. The base pressure obtained to date with fixtures-transducers and associated lead wire with power on was $3X10^{-8}$ torr.

B. Calibration of Systems

The calibration sequence consisted of performing a preliminary calibration of all wear (LVDT) and friction (proximity) transducers before the 10-hour run-in period. Since the ring travel during the 10-hour run-in period at 150 RPM is greater than the total travel will be during the two year vacuum period at 0.1 RPM, it was anticipated that sufficient brush displacement and friction changes would occur which would necessitate resetting the zero points and recalibrating the transducers. Thus the transducers on each part were given a final calibration prior to installation in the vacuum chamber.

The LVDT's were calibrated by adapting a micrometer to the transformer support (Figure 1, Item 18), coupling the micrometer barrel to the brush shaft with a universal joint and shimming the case and transformer (Item 20) 0.040 with respect to the brush shaft. This arrangement provided an accurate means of moving the brush from the ring contact position radially outward over a displacement region which duplicates a brush displacement radially inward with shims removed. The proximity transducers were calibrated by lifting the brushes from the ring and hanging weights from the brush holder (Item 30). Applying the weight to this position provided a means of duplicating the point of application of the frictional force occurring between the ring and brush.

C. Brush Material Properties and Establishment of Specifications

Poly-Scientific has found that the properties of metal-solid lubricants composites vary greatly from lot to lot and vendor to vendor. At least part of the variation in material can be related to the fact that adequate specifications do not exist for instrument grade brushes. There is a need for specifications that adequately define the properties of metal-solid lubricants composites that are to be used in critical, high reliability applications. Presently, materials are often defined by vendor codes which relate to proprietory products. In many cases even the major constituents of the composites are not public knowledge. Specifications should define all critical physical and chemical properties and state how the properties can be measured on composites that may be quite small in size (e.g. .020"X.060"X.100"). There are published specifications (e.g. ANSI C64.1-1970) which cover composite brushes in general, but parts of the specifications cannot be applied, or are not applicable, to small brushes that are formed to size.

Extensive tests were made in order to define the properties of the brushes procured for this specific contract and to obtain data that could be used as a basis for engineering specifications. Hopefully, tribological data can be related to the physical and chemical properties of the brush material.

Composite strength can be expected to affect wear character as well as determine structural design limitations. The standard method for measuring composite strength is to use three-point loading and measure the transverse strength (reference paragraph 4.6, ANSI C64.1-1970). This method is not practical for small instrument brushes that are molded to size. The strength of this type brush can be readily measured by direct shear. Figures 4 and 5 show the apparatus used by Poly-Scientific for measuring the shear strength of the composites. It was constructed from a Model 6-092-01 Unitek Micropull Strength Tester and a jeweler's vice. Since the shear strength of a molded brush depends on the plane of shear, it is necessary to define the plane of shear relative to the direction of pressing (See Figure 1 of ES383 or ES384). The specific resistance of small composite samples was measured with the brush assembly shown in Figure 6. Current was passed through the composites via the end brush. Potentiometer leads were connected to the brushes adjacent to the current carrying ones. The six center pairs of brushes were insulated from each other and served only to hold the sample. The current was held to the minimum necessary to obtain an accurate voltage reading in order to minimize resistive heating. Specific resistance was calculated in the standard manner (e.g. paragraph 4.4.3

ANSI C64.1-1970).

Apparent density is widely referenced as an indication of composite soundness. It is easy to measure and is one indication of the degree of uniformity from lot to lot. A composite with a very low density (<70% theoretical) is likely to fracture or crumble. The apparent density was specified as grams per cubic centimeter and as a percent of theoretical density. The theoretical density was calculated on the basis of published densities for pure constituents (e.g., Ag-10.5 g/cm^3; graphite-2.25 g/cm^3). The actual shear strength, density, and resistivity data used for the establishment of ES383 and ES384 are listed in Tables II, III, and IV.

Three orthogonal sections were metallographically examined from at least two samples of each lot of material. Typical photomicrographs are shown in Figures 7, 8, 9 and 10. The metallographic sections indicate the composite structure, degree of particle bonding and number and types of foreign inclusions.

Semiquantitative chemical analyses were performed by use of an emission spectograph. The concentration of silver was verified by use of atomic absorption spectrophotometry.

Specifications ES383 and ES384 should allow one to obtain brush materials very similar to the ones that were used for this contract. They are considered preliminary only because of the small number of lots used to establish the requirements for strength and resistivity. These specifications were written with the assumption that the materials were to be used for high-reliability, instrument-grade slip rings.

III. DATA

A. Run-In Data

Electrical noise, friction and wear data collected from the four material combinations during the 150 RPM, 10-hour run-in period have been presented in Figures 11 through 23. The first material combination undergoing run-in was ES383 brush material on rings of rhodium plate on nickel plate on a brass substrate. Problems were encountered with the drive motor, rotary motion feedthrough bearings and common mode rejection circuits on the input to the eight channel recorder; therefore the data at zero inches of ring travel is not available. Subsequently, data were taken on this combination at frequent intervals throughout the run-in period to establish a test frequency. The second unit undergoing run-in, ES383 brushes on coin silver rings, was monitored at three intervals and finally the last two combinations, ES384 on rings of rhodium plate and coin silver, were only monitored at the beginning and termination of the run-in.

The electrical noise data for each of the four material combinations has been presented in Figures 11 through 14. Noise values for the first five circuits of each fixture have been presented together; the sixth circuit of each has been presented along with the positive and negative components. Each point represents the average peak-to-peak (P-P) noise value recorded during a period equivalent to 15-20 rotor revolutions.

The output signal from the proximity transducers was periodic with a frequency of 0.4 CPS. The peak amplitude of this signal, i.e. peak friction, occurred where the ring eccentricity was the greatest. The friction values reported are the peak values recorded during the 15-20 revolution period. (Figures 15 through 18.) Superimposed on the 0.4 CPS signal, there was an additional signal having a frequency in the range of 75 to 90 CPS. The peak-to-peak amplitude of this high frequency signal is assumed to be and has been reported as stick-slip friction (Figures 19 through 22).

A reference point on the wear trace was selected, which in all cases corresponded to the maximum ring run-out, for monitoring the brush displacement. The net brush displacement occurring during the run-in period was therefore determined by the shift in each reference point (Figure 23). A radially inward brush displacement (wear) has been presented as a positive number while radially outward displacements have been shown as a negative number.

B. Humidity Test Data

The electrical noise and friction data collected during the 5-day humidity test period have been presented in the same fashion as that collected during the 10-hour, 150 RPM run-in period. In the case of electrical noise, each point graphed represents the maximum peak-to-peak (P-P) noise recorded during one revolution (Figures 24 through 27). The peak friction and peak-to-peak (P-P) stick-slip friction values occurring during the one revolution period have been presented in Figures 28 through 35. Although the rotor speed was changed from 150 to 0.1 RPM, the frequency of the stick-slip signal was relatively constant. Each entry on the brush displacement illustrations represents the total brush displacement that has occurred from the beginning of the humidity test (Figures 36 through 39).

In general, data were collected at the beginning of the first cycle, either 7 or 16 hours later and 24 hours later. While the transition between humidity levels was being made data were also collected. Significant changes were not detected during these transitions and therefore, for clarity, have not been graphed. On subsequent cycles data were collected at 7 or 16 and 24 hours after the transition.

IV. DISCUSSION OF RESULTS

In reviewing the data for each of the four material combinations an attempt will be made to compare only levels and ranges rather than perform formal statistical analyses. All data of a common type have been presented using identical scales for both the run-in and humidity test periods for ease of comparison. The humidity levels have been presented with the 5-day test data to facilitate correlations.

Beginning with electrical noise data recorded during run-in for ES383 brushes on rhodium plate, it can be seen that initially the noise ranged from 9-30 mΩ and finally the values increased to 15-50 mΩ (Figure 11). Upon entering the low humidity cycle this combination remained in the 15-50 mΩ region with some circuits reaching 60 mΩ before the 5-day cycle was completed (Figure 24). Comparison of the noise fluctuations for this combination with the humidity changes indicates that a significant correlation does not exist. The noise level recorded for the positive brush is significantly lower than the negative brush during run-in and humidity tests. The noise values for the inductive circuits 1L, 2L and 3L during both periods do not appear to be different from the resistive circuits 4R, 5R and 6R.

The ES383 brush - coin silver ring combination started run-in with noise values of 4-9 mΩ and terminated run-in with values ranging from 4-15 mΩ (Figure 12). This level was constant when the humidity test was initiated with the exception of the 5R ring (Figure 25). After 16.5 hours under the low humidity condition, the spread was 7-20 mΩ and remained so throughout the remainder of the humidity test. The only correlation between humidity level and noise for this combination appears to be that occurring at the negative brush on the sixth ring. This brush dropped to a lower noise level with increasing humidity, whereas the positive brush remained nearly constant. Similarly with the previous combination, the inductive and resistive circuits have noise values that are interdispersed, thus a difference in performance cannot be detected.

The combination exhibiting the greatest change of noise from the beginning of run-in to the completion of humidity operation was ES384 brush material on rhodium plate (Figures 13 and 26). Initially noise values ranged from 4-7 mΩ and increased to a level of 7-20 mΩ at the end of run-in. The transition to the beginning of the humidity test was nearly constant. The greatest rate of change occurred from the beginning of the humidity test until the end of the second cycle. From this point the level, 100 mΩ, was nearly constant to the completion of the fifth cycle. No correlation between humidity level and noise was evidenced for the combination. As was the case with ES383 brushes on rhodium plate, the positive brush on this combination had significantly lower noise than the negative brush during the humidity test cycles. Inductive and resistive differences were not found during either period.

ES384 brush material on coin silver started 150 RPM run-in with noise values ranging from 5-35 mΩ (Figure 14). After completion of the run-in this range narrowed to 4-15 mΩ. Throughout the humidity test sequence a range of 12-25 mΩ, which was not affected by humidity level, was recorded (Figure 27). At the beginning of run-in a difference existed between the positive and negative brushes, but this difference was not apparent at the termination of run-in nor throughout the humidity operation. As was the case with the other three combinations, an inductive and resistive difference could not be singled out.

Comparing all four combinations for the conditions tested, these data indicate ES383 and ES384 gave similar noise levels on coin silver rings. A higher noise level resulted when these materials were employed on rhodium plate, with the ES384 brush material giving the higher overall noise level.

Turning to the brush frictional forces it can be seen that the ES383 brushes on rhodium plate gave the lowest results during 150 RPM run-in and 0.1 RPM humidity test periods. The results for this combination during run-in ranged from 35 to 110 grams while those during humidity dropped to a range of 20-50 grams (Figures 15 and 28). A performance similar to the above was obtained for ES383 brushes on coin silver during run-in (Figure 16). However, the range of 37-110 grams remained the same throughout humidity test, thus this combination exhibited higher friction forces during humidity cycling than the above. (Figure 29). The performance of ES384 on rhodium plate ranked third highest among all combinations with a range of 55-165 grams and 55-120 grams during run-in and low speed humidity tests respectively. (Figures 17 and 30). The highest frictional forces recorded and thus the fourth ranking material combination was ES384 brushes on coin silver rings. Forces ranging from 90-160 grams during run-in and from 55-225 grams were obtained for this combination (Figures 18 and 31). These results also indicate that the coin silver rings gave higher frictional forces than the rhodium plate.

From Figures 28 through 31 it appears that a correlation between brush frictional forces and humidity does not exist for any of the combinations. Examining certain brushes in detail, such as the negative ES384 brush on coin silver, an inverse proportion between humidity and friction seems to exist until the fourth 24-hour period occurs. At this point the friction started to increase nearly 8 hours before the transition to high humidity was made and thus would appear to remove a correlation (Figure 31). Other correlations similar to the above can be found to exist at various times within the humidity test, but in general they do not hold all throughout the test.

Brush stick-slip action was more pronounced on the ES384 brush vs. coin silver ring combination as evidenced in Figures 19 through 22. The amplitude of the stick-slip force decreased from a range of 70-90 grams to a range of 35-60 grams during run-in. Initially the ES383 vs. rhodium plate combination had the largest stick-slip amplitude of all combinations but dropped to a range of 10-40 grams after 6.5 hours of high speed running. The run-in period improved the ES383 vs. coin silver combination very little in that a range of 25 grams remained constant, and the average dropped from the initial 43 grams to a final average of 33 grams. The ES384 on rhodium plate combination maintained the lowest average and scatter throughout high speed run-in.

After the transition to the humidity test and a ring speed of 0.1 RPM was made, all combinations, with the exception of ES383 vs. coin silver, dropped to a stick-slip amplitude of less than 27 grams (Figures 32 through 35). The exception mentioned above exhibited more scatter and a higher average than the others throughout the humidity test cycle. A correlation between this parameter and humidity was not found for any of the four combinations.

The net brush displacement occurring during run-in for all four material combinations has been illustrated in Figure 23. These results indicate that the only significant displacements, i.e. anything greater than 1/2 mil, occurred on three of the four combinations.

Maximum wear measurements of 3.8 and 1.75 mils were recorded for the positive brushes on the sixth ring of combinations B and D (ES384) respectively. Large displacements corresponding to an LVDT core and brush movement away from the ring were recorded for the negative brushes on the third and sixth ring of combination D. The interpretation of this is difficult to explain when considering the mechanisms for producing a displacement in the outward direction. One mechanism of an outward displacement is the brush shaft expansion resulting from resistive heating. Measurements have indicated resistive heating results in greater brush and brush shaft thermal changes than that caused by ambient flucuations. Observation of the LVDT core position with power on and power off indicates changes of less than 0.5 mil occur as the brush shaft temperature changes. Another mechanism for an outward displacement is the film deposited on the ring by the brush. A film thick enough to account for the displacements of 5.65 and 3.5 mils seems unlikely, but is most likely the cause of the outward displacements which were less than 0.5 mil. (It should be noted that the measurements being presented are the net result of brush wear and film build-up since the actual brush height is not being measured). The remaining possibility would be that resulting from a rotation of the LVDT core on the brush shaft. Prior to run-in, cement was applied to the threads of the shaft and core. After completion of run-in and humidity testing the cores were broken loose and readjusted to a near zero LVDT output. At this point it was not noted that the cores were loose. The outward displacements on combination D are therefore unexplained at this time.

The zero displacement level graphed in Figures 36 through 39 correspond to the brush position after completion of run-in. For the most part brush displacements did not occur during humidity testing other than fluctuations about the zero level which could have been caused by wear particles and changes in film thickness. An outward trend was indicated for all ES384 brushes on rhodium plate (Figure 38). These displacements are in regions which could have been caused by a film build-up.

Visual examination of the fixtures after the completion of the run-in and humidity periods revealed very little wear debris. The debris left by the ES383 brushes on both types of ring materials was of a particulate nature and tended to lie along the edge of the brush track. The ES384 brushes left a film in the brush track on both types of ring material; this film has a black amorphous-like appearance.

When reviewing all parameters with respect to operation in air, little significant effect can be found within the relative humidity range of these tests. This could be due to the brief periods at each humidity level. This behavior and the insignificant wear debris and wear rates noted seem to be in conflict with previously published reports.[1,2,3] The explanation may have to await further data from post test analyses.

V. NEW TECHNOLOGY

The system, experimental techniques and results reported to date do not directly represent a form of new technology.

VI. PROGRAM FOR NEXT REPORTING PERIOD

The vacuum test will continue throughout the next quarter. The report covering this period will also contain data generated during the first 1000 hours under vacuum.

VII. CONCLUSIONS

The results compiled under conditions of run-in at 150 RPM and 5 days of humidity at 0.1 RPM indicate the following:

1. Brushes fabricated from ES383 and ES384 materials give similar noise levels when employed on coin silver rings.
2. ES383 and ES384 materials when employed on rings of rhodium plate exhibited higher noise levels than when employed on rings of coin silver.
3. ES384 brushes on rings of rhodium plate resulted in the highest overall noise levels.
4. Inductive vs. resistive differences were not found to exist in terms of electrical noise.
5. The lowest frictional forces were recorded for ES383 brushes on rhodium plate while the highest were recorded for ES384 brushes on coin silver rings. ES383 on coin silver and ES384 on rhodium plate ranked second and third, respectively.
6. Rings of rhodium plate gave lower frictional forces than did rings of coin silver.
7. In terms of the stick-slip parameter and peak friction, the four combinations ranked the same.
8. All materials combinations yielded very low wear rates; the lowest wear rate was measured for ES383 brushes on rhodium plate.
9. No apparent correlation was found to exist between any of the measured parameters and humidity. It is felt that this may be related to the length of each humidity period.

VIII. RECOMMENDATIONS

This program should continue with the data collection frequency of twice per week until the completion of two years at less than $5X10^{-8}$ torr. At that time a post test analysis should be performed, the parts refurbished and the four-month test at speeds of 0.1 and 4 RPM should be completed.

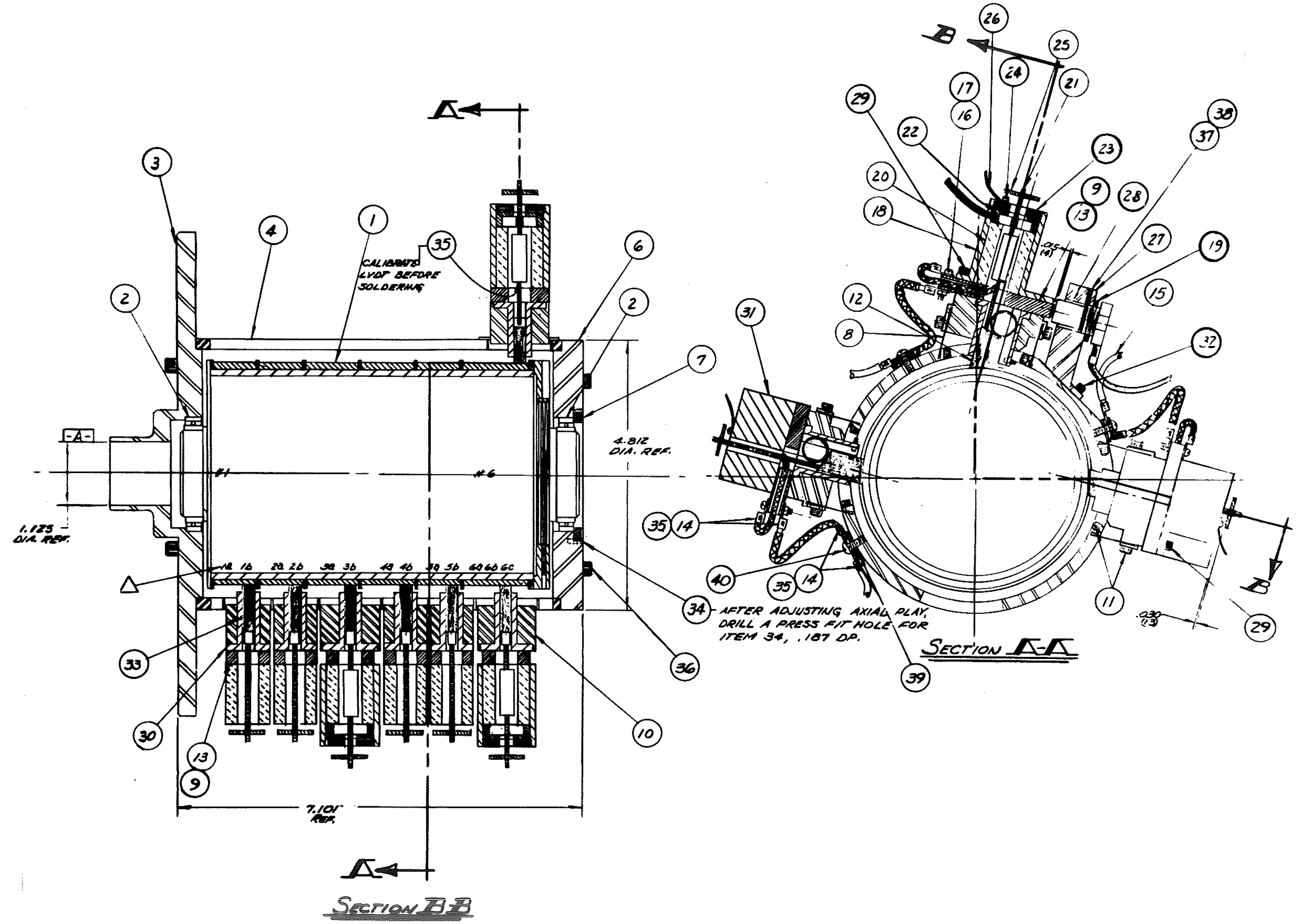

FIGURE 1. CAPSULE ASSEMBLY DRAWING SHOWING TRANSDUCER MOUNTING

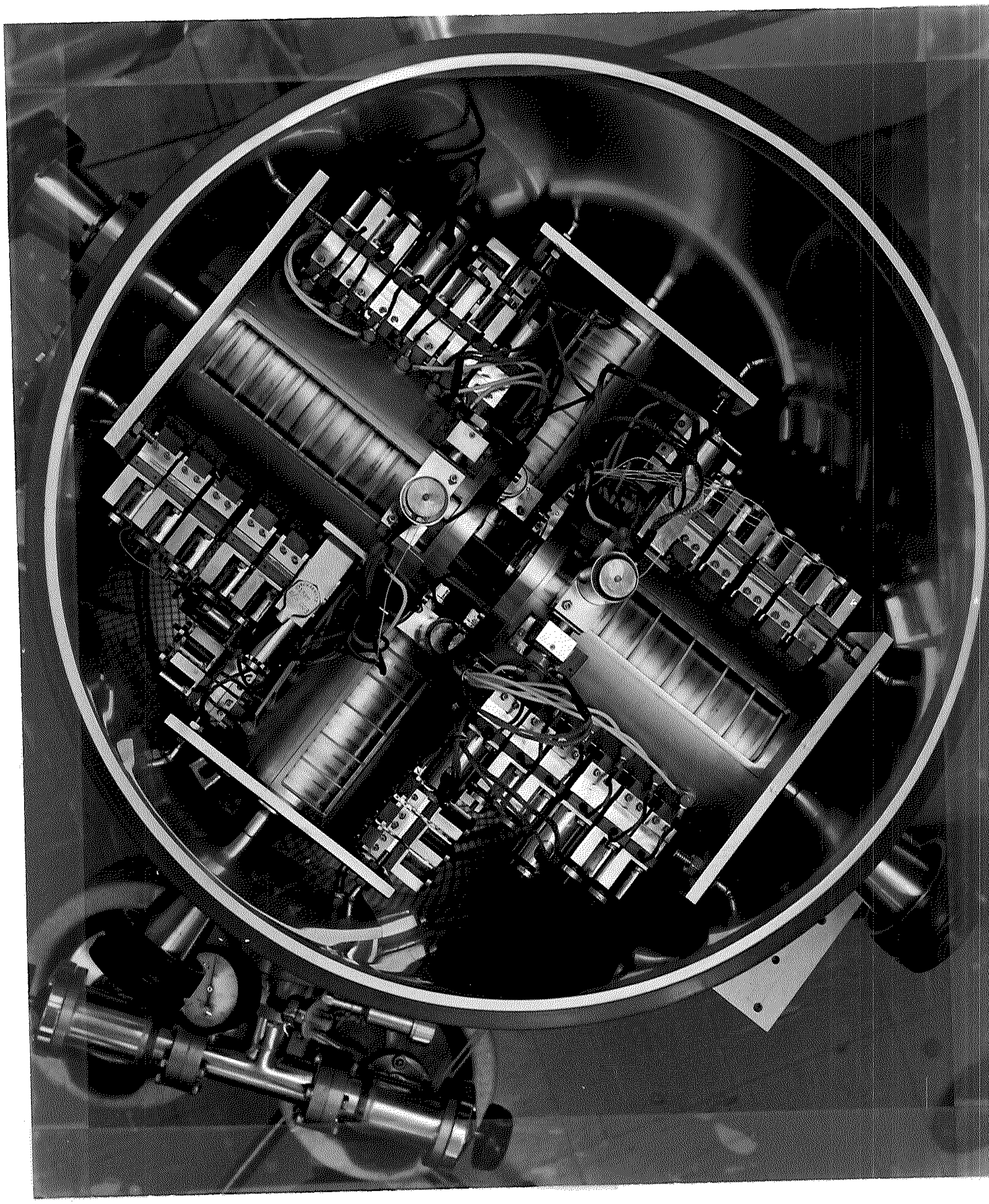

FIGURE 1-A. TEST FIXTURES MOUNTED IN VACUUM CHAMBER

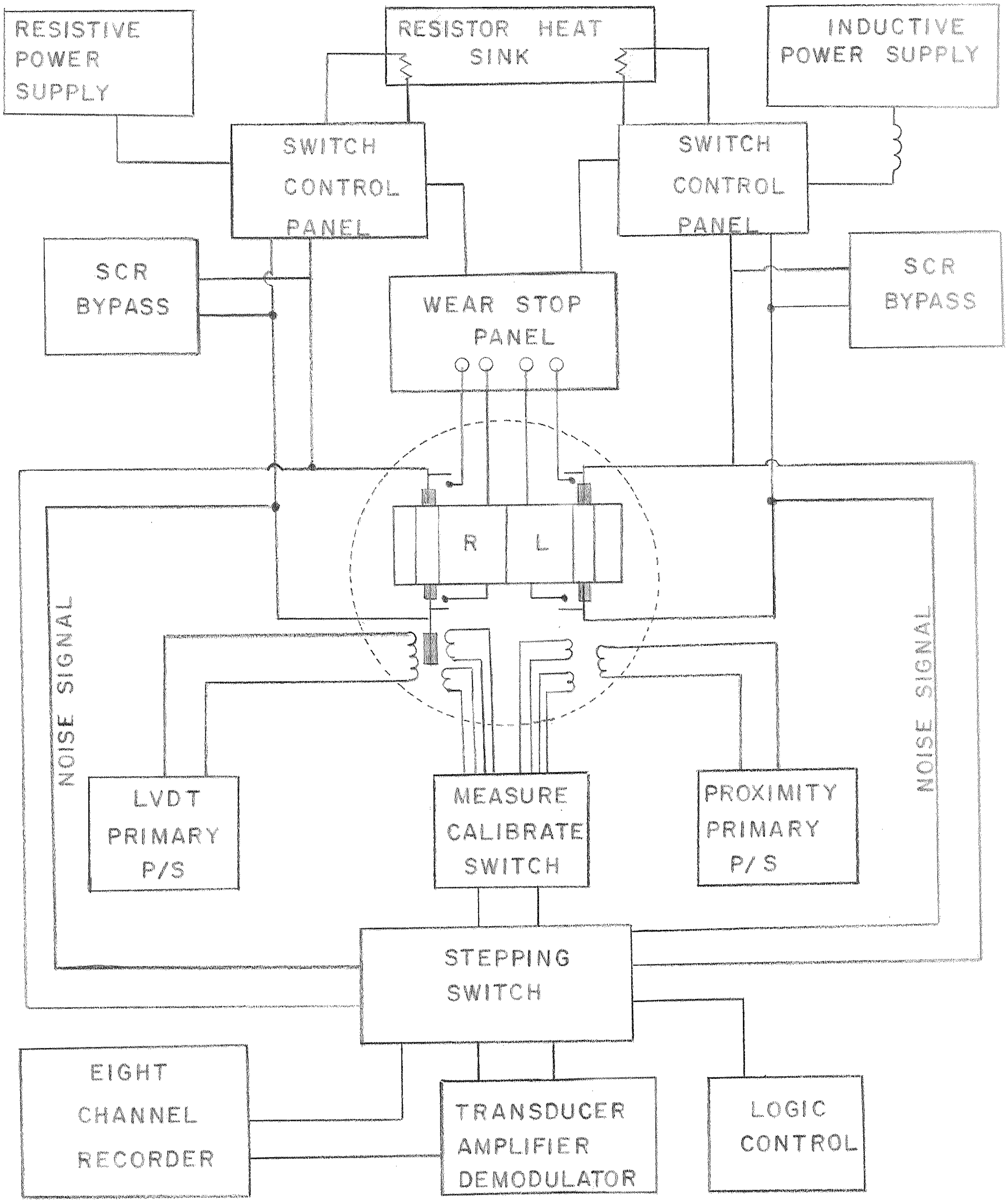

FIGURE 2 BLOCK DIAGRAM OF POWER AND TRANSDUCER SYSTEMS. SINGLE INDUCTIVE AND RESISTIVE CIRCUITS ALONG WITH SINGLE WEAR AND FRICTION CIRCUITS ON ONE FIXTURE HAVE BEEN SHOWN.

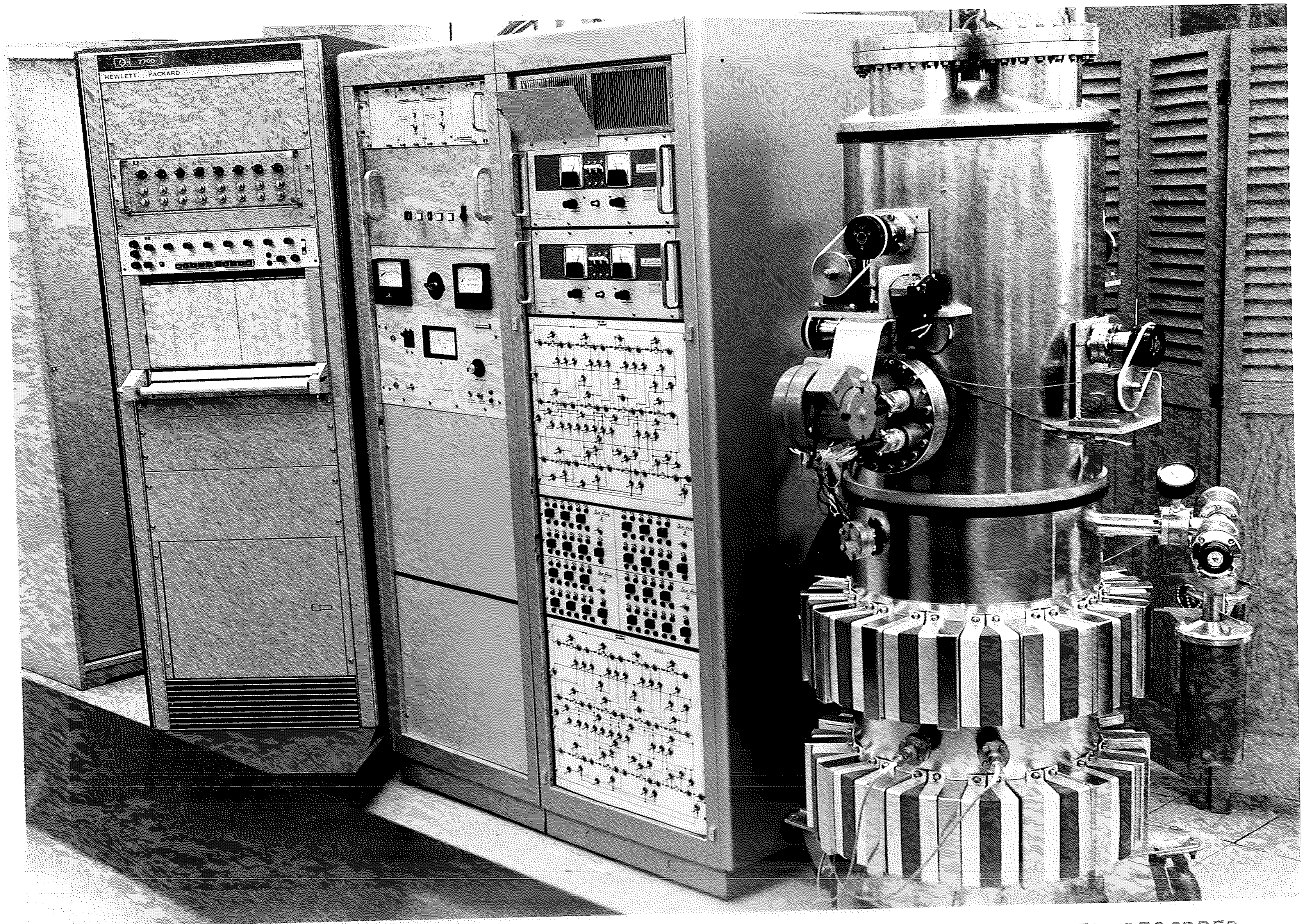

FIGURE 3. VACUUM CHAMBER AND TEST CONSOLE WITH EIGHT CHANNEL RECORDER

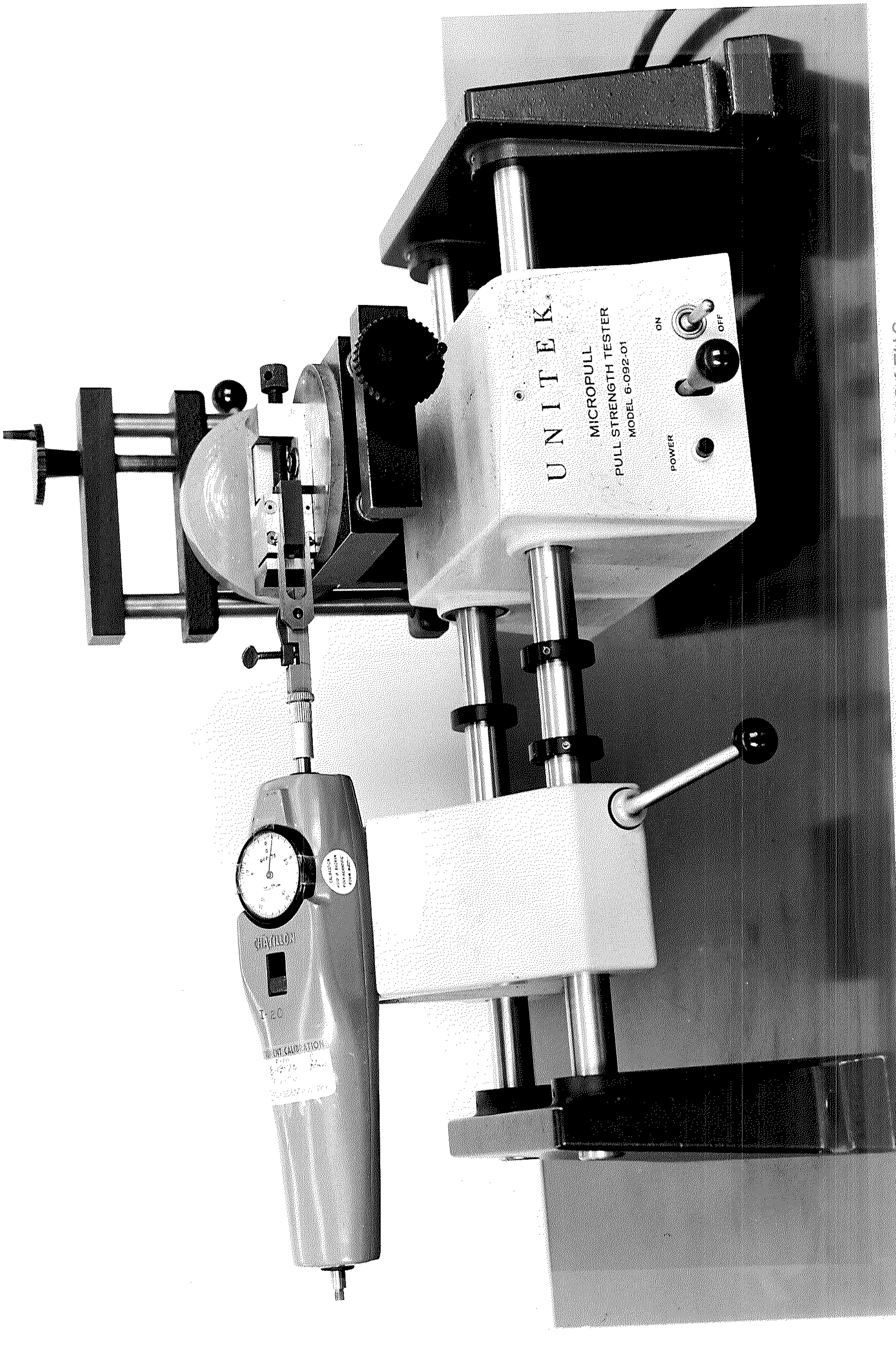

FIGURE 4. SHEAR STRENGTH TEST APPARATUS

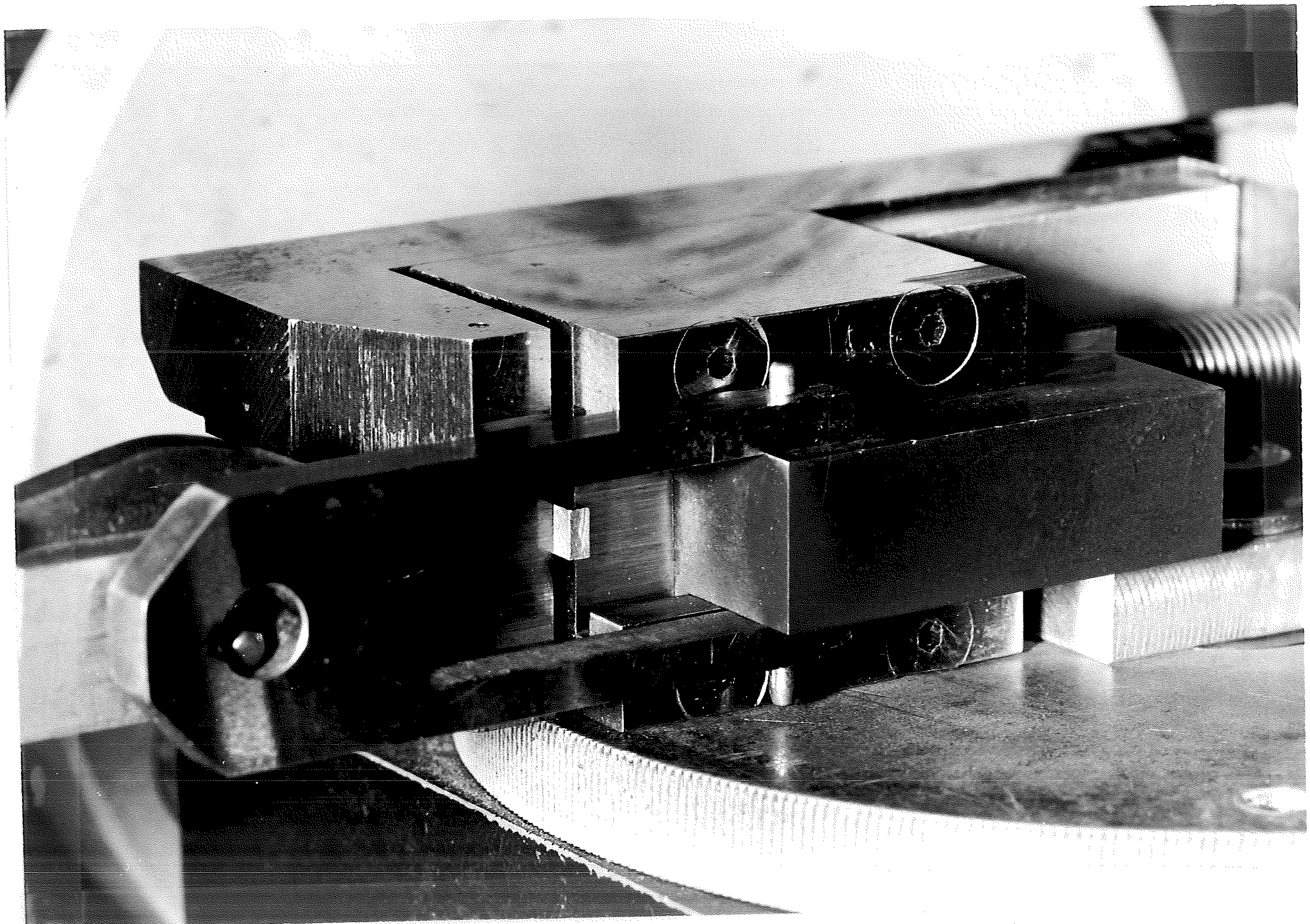

FIGURE 5. SHEAR STRENGTH APPARATUS CLOSE-UP

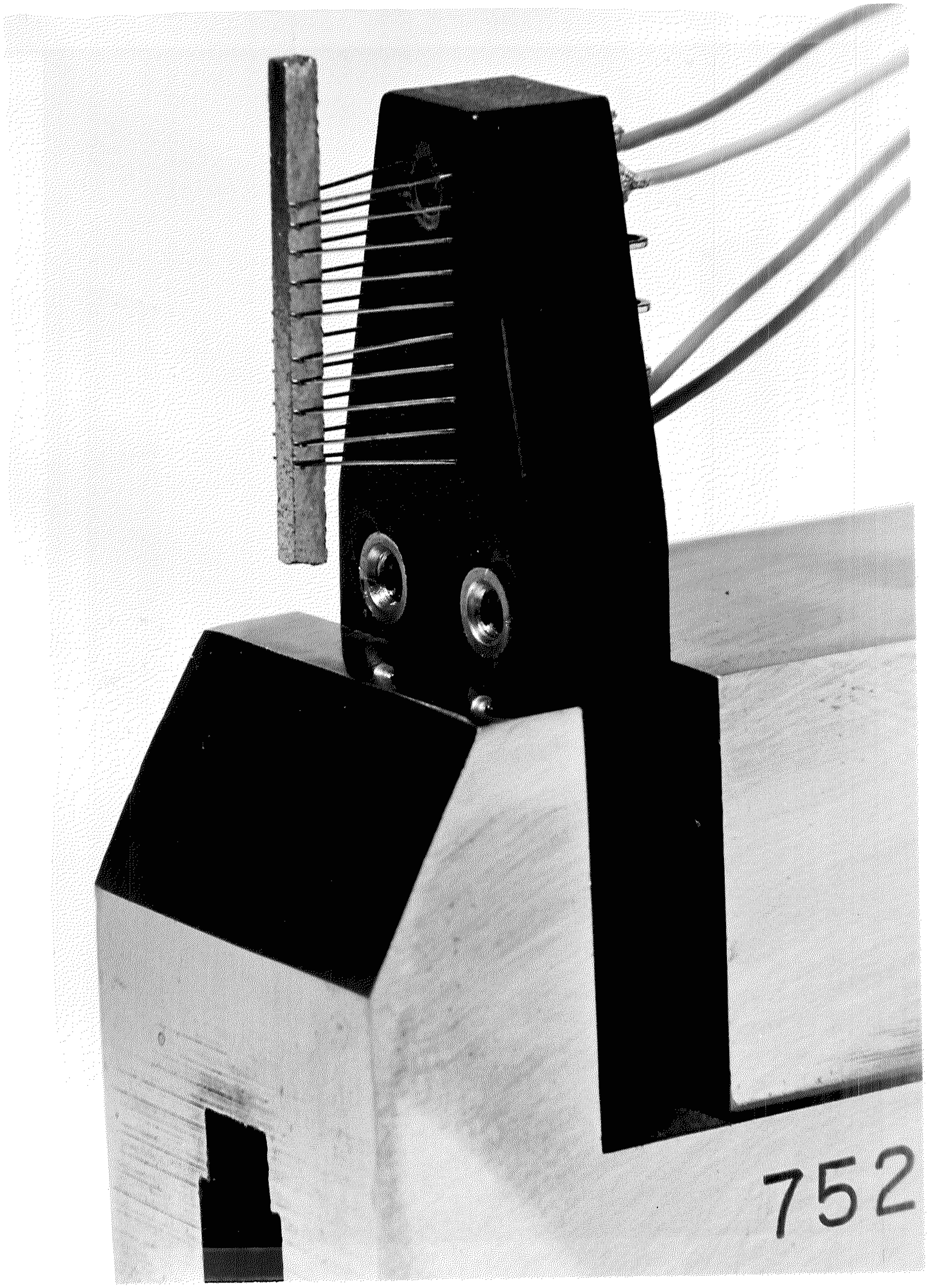

FIGURE 6. RESISTIVITY SAMPLE TEST CLOSE-UP

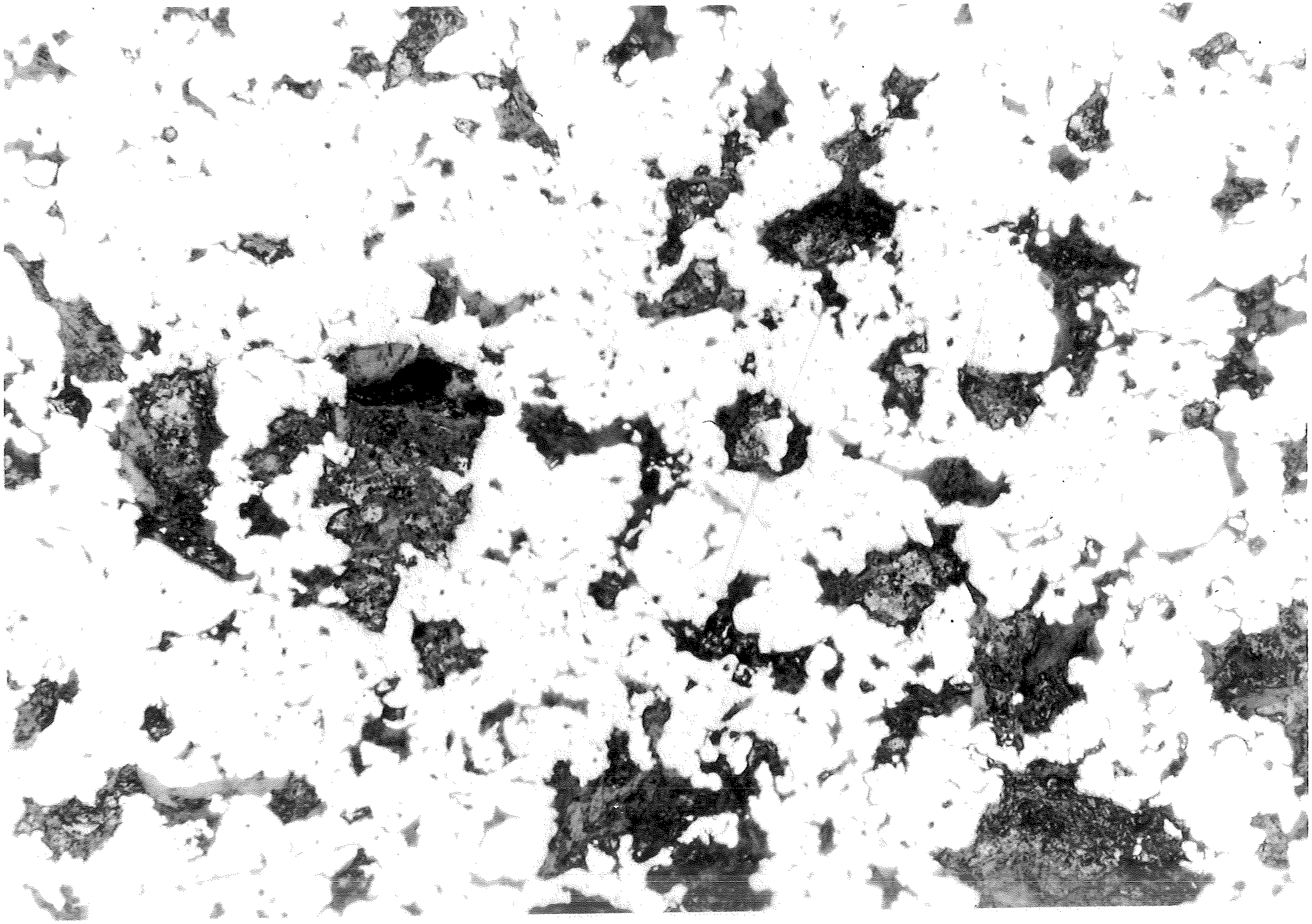

FIGURE 7. NORMAL SECTION OF E.S. 383; WHITE, Ag; DARK GRAY, GRAPHITE; LIGHT GRAY, MoS_2 400X

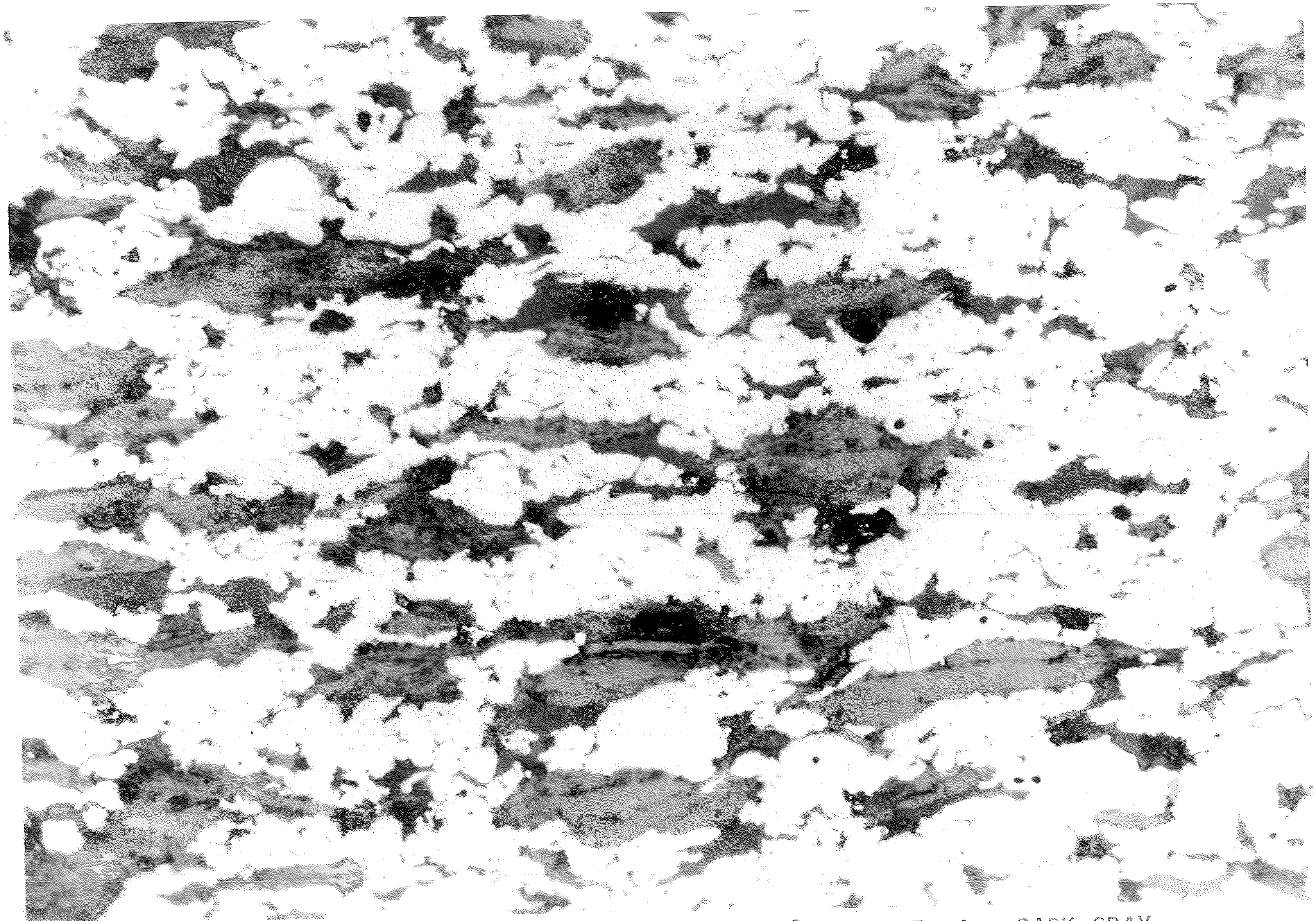

FIGURE 8. LONGITUDINAL SECTION OF E.S. 383; WHITE, Ag; DARK GRAY, GRAPHITE; LIGHT GRAY, MoS_2 400X

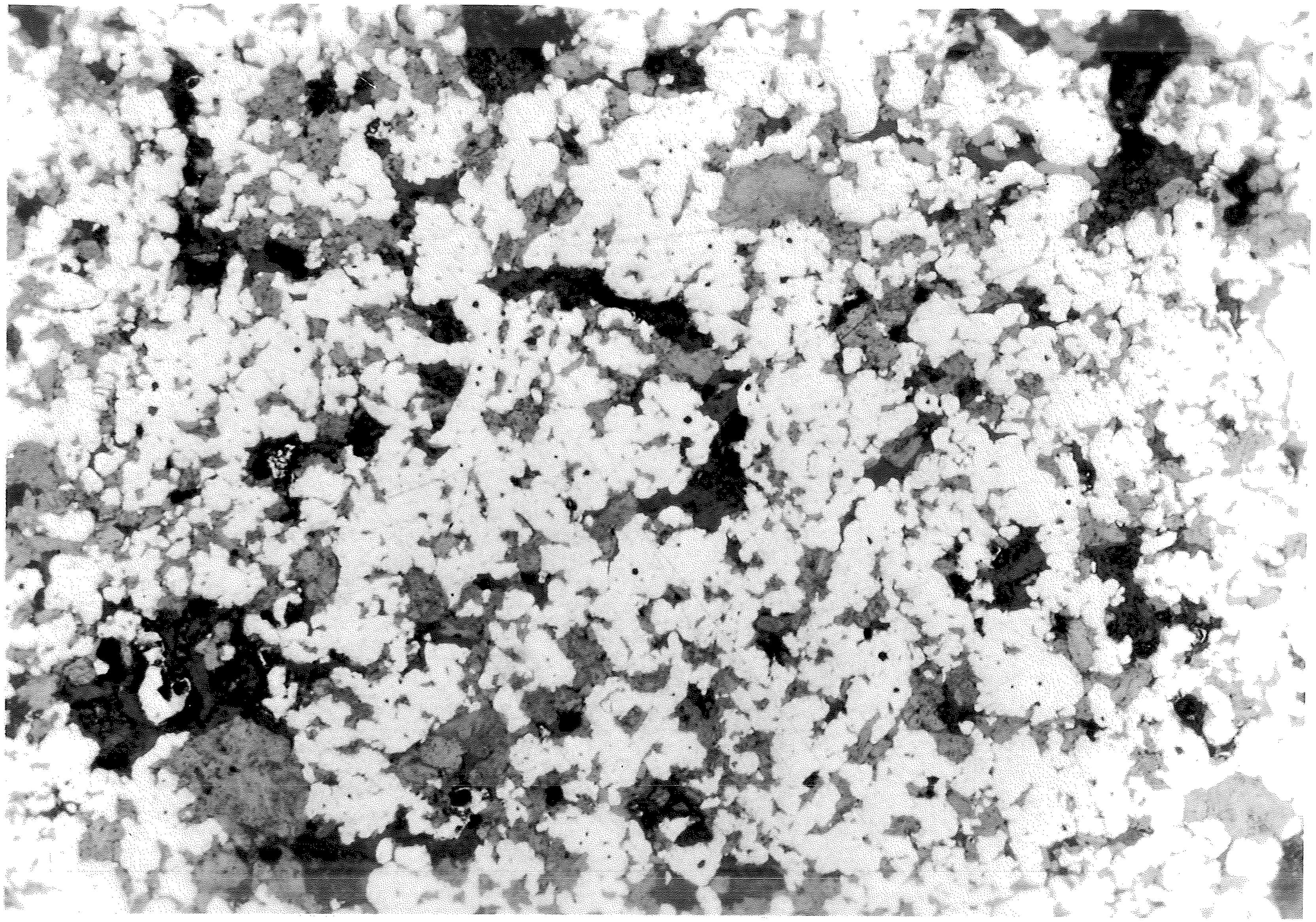

FIGURE 9. NORMAL SECTION OF E.S. 384; WHITE, Ag; DARK GRAY, GRAPHITE; LIGHT GRAY, $NbSe_2$ 400X

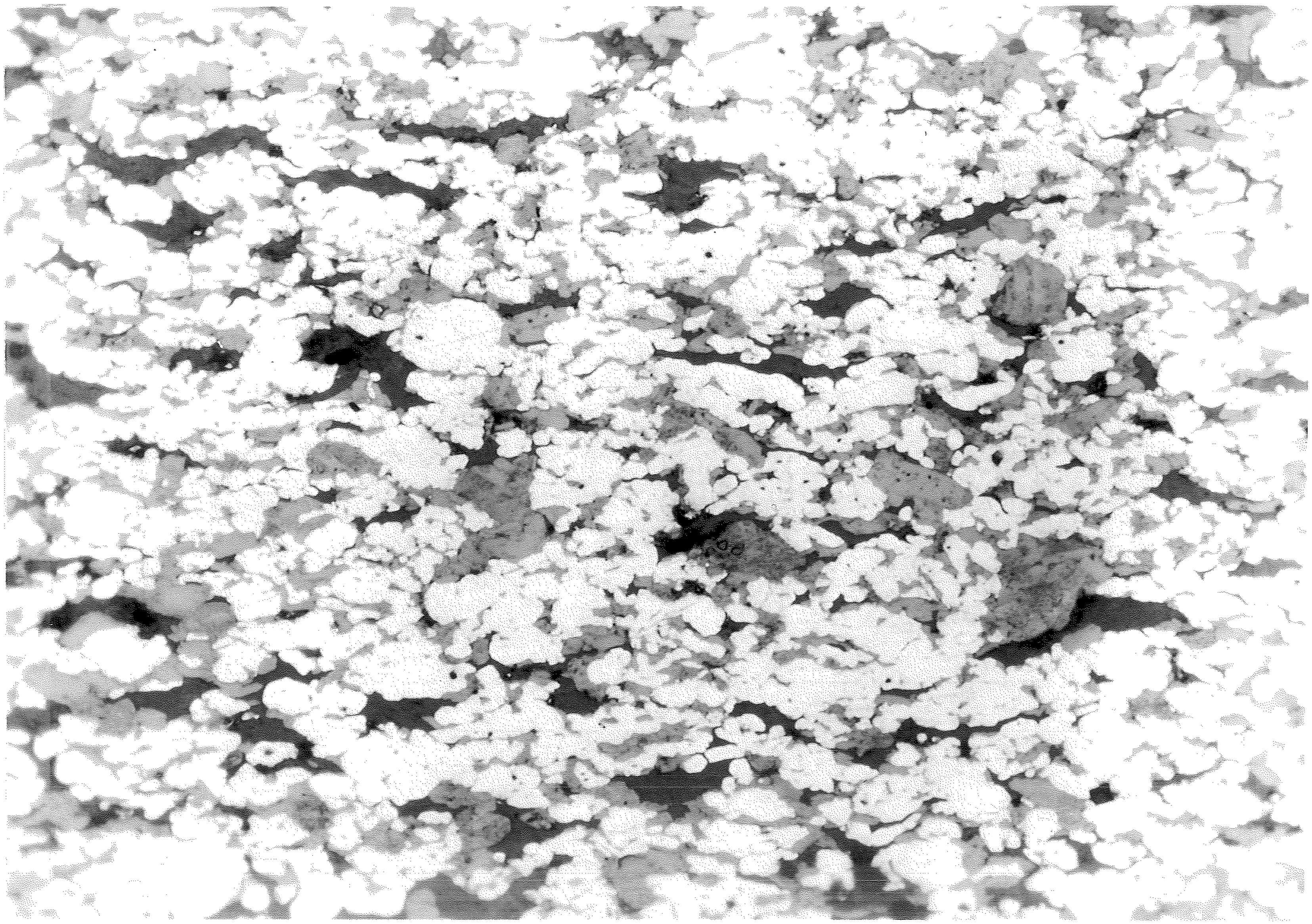

FIGURE 10. LONGITUDINAL SECTION OF E.S. 384; WHITE, Ag; DARK GRAY, GRAPHITE; LIGHT GRAY $NbSe_2$

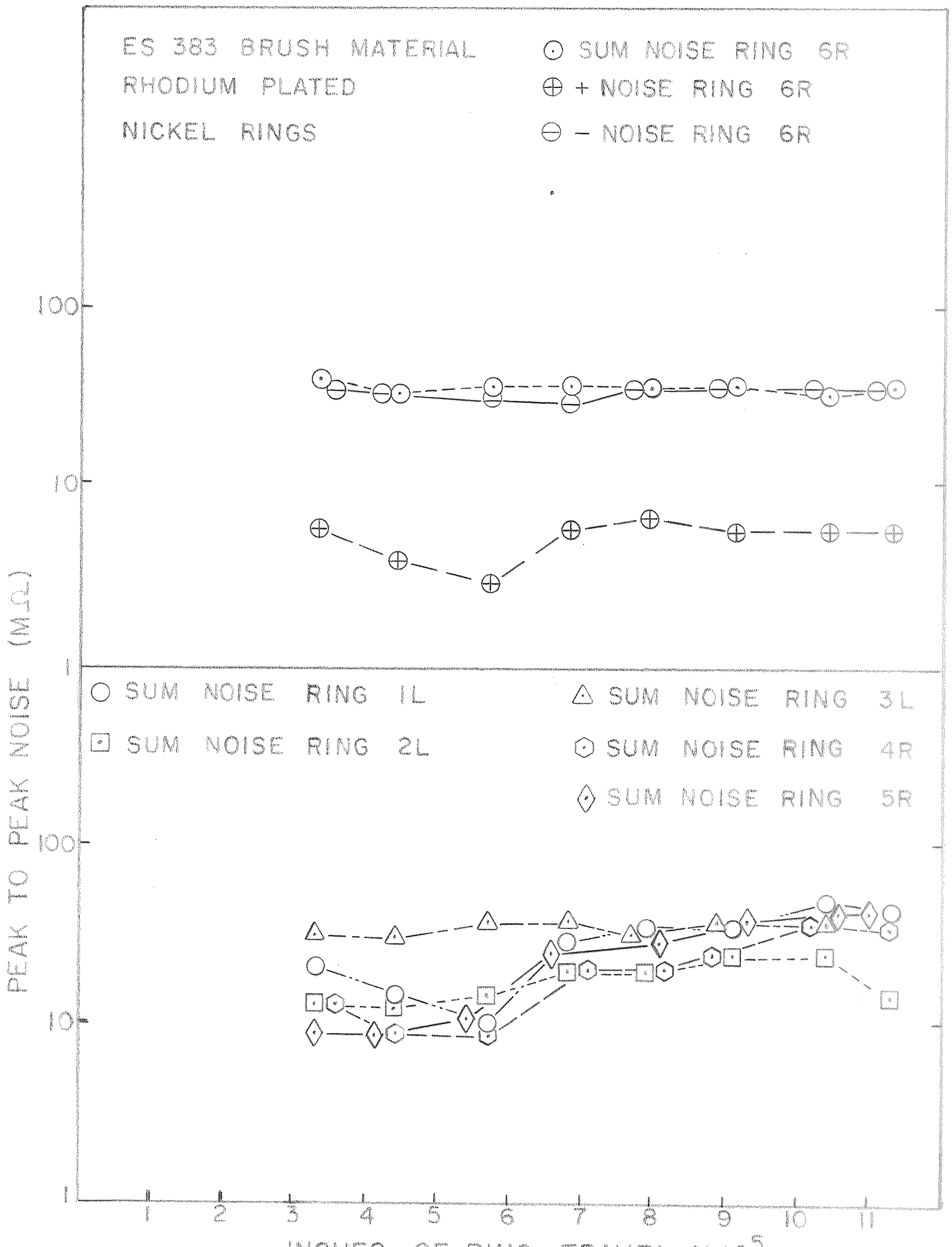

FIGURE 11. NOISE (P-P) DURING RUN-IN AT 150 RPM

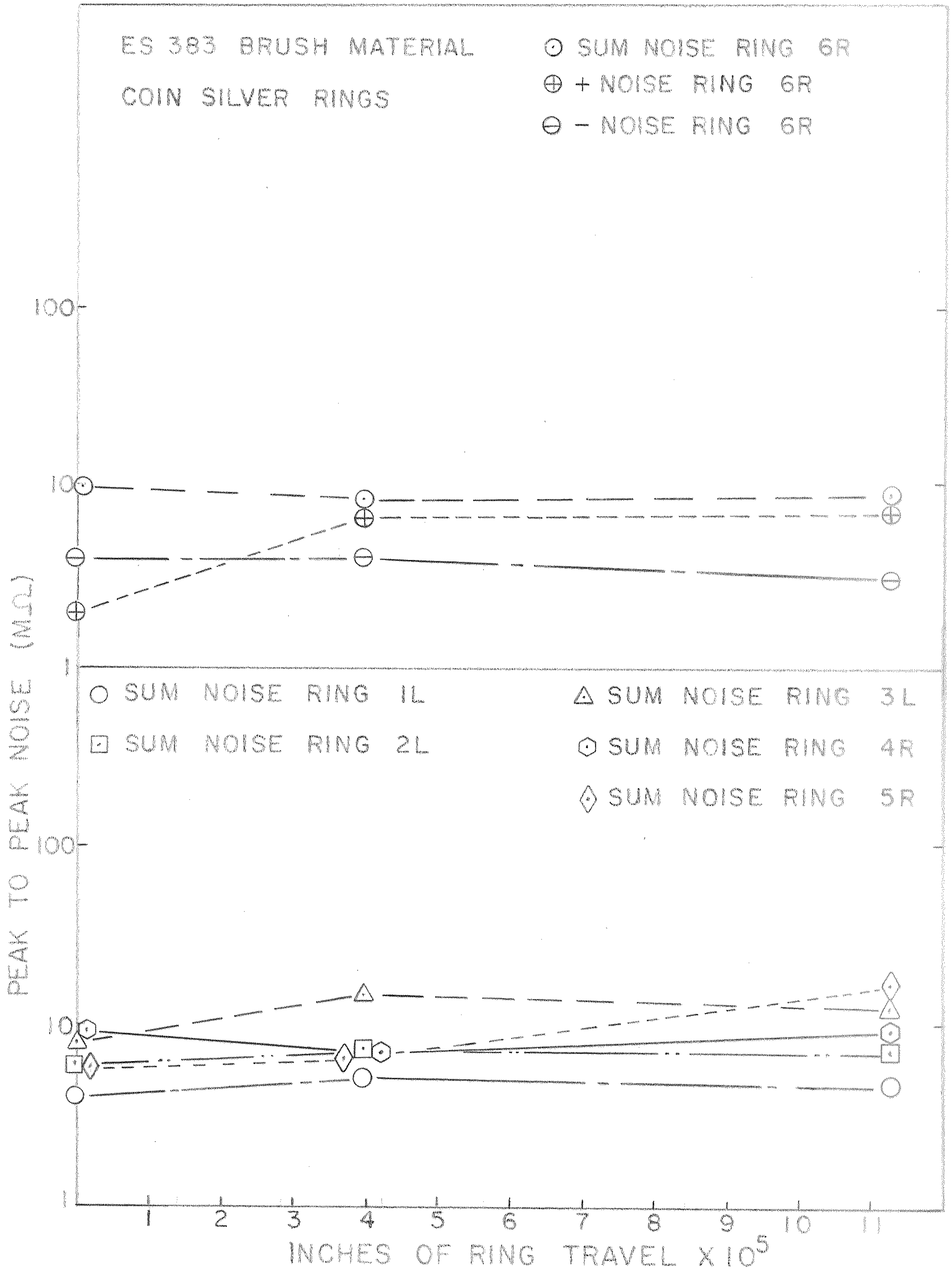

FIGURE 12. NOISE (P-P) DURING RUN-IN AT 150 RPM

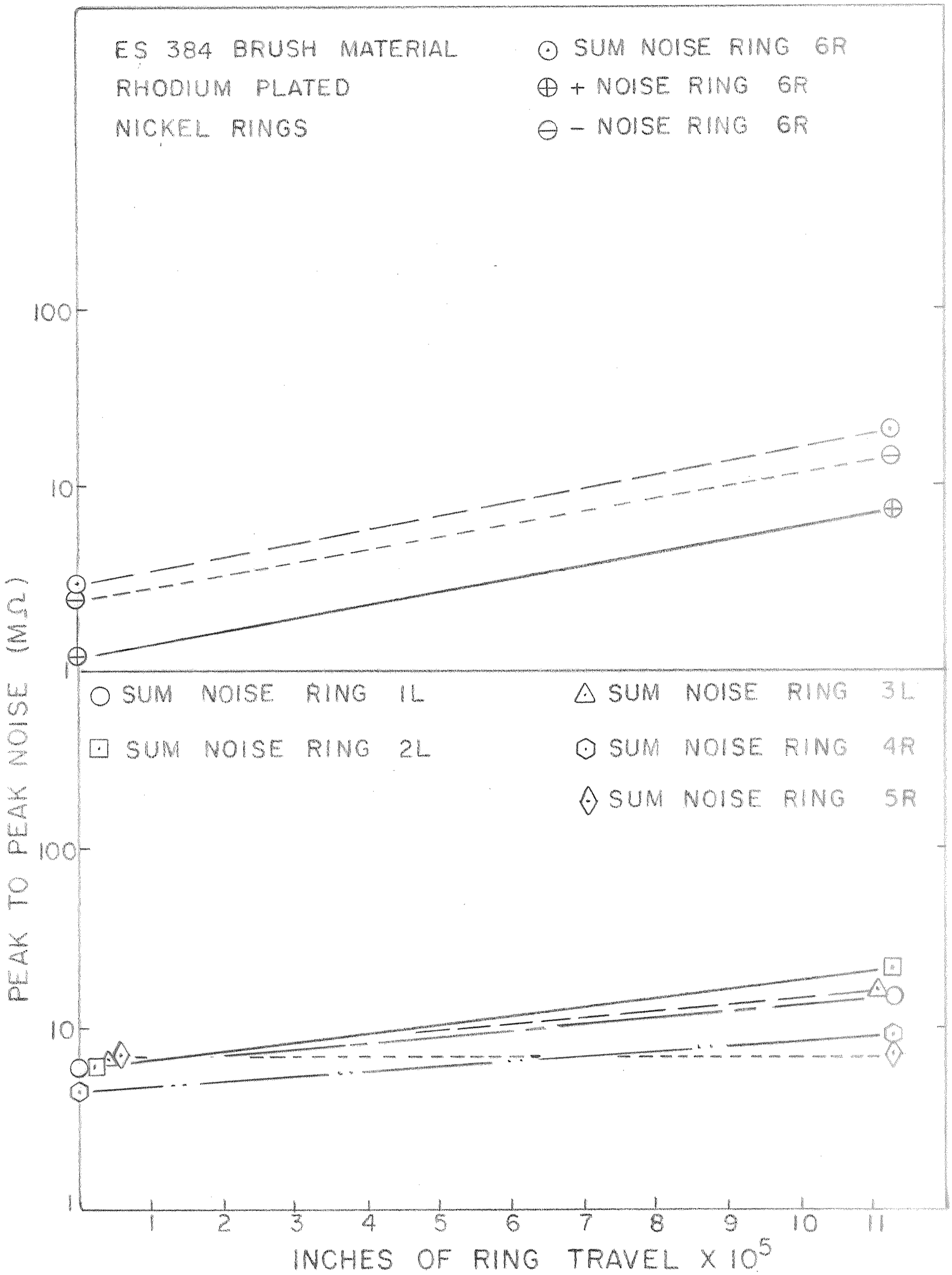

FIGURE 13. NOISE (P-P) DURING RUN-IN AT 150 RPM

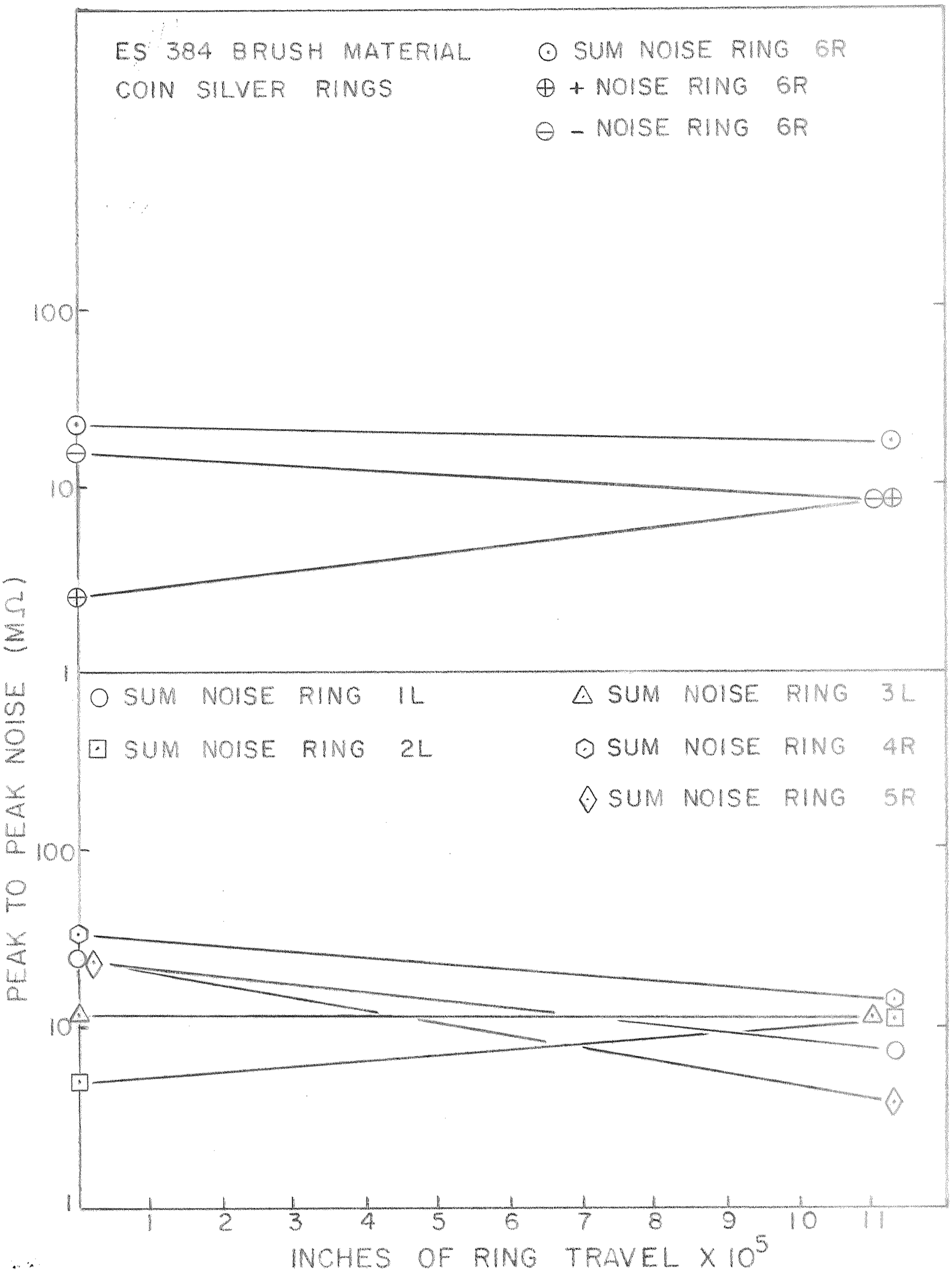

FIGURE 14. NOISE (P-P) DURING RUN-IN AT 150 RPM

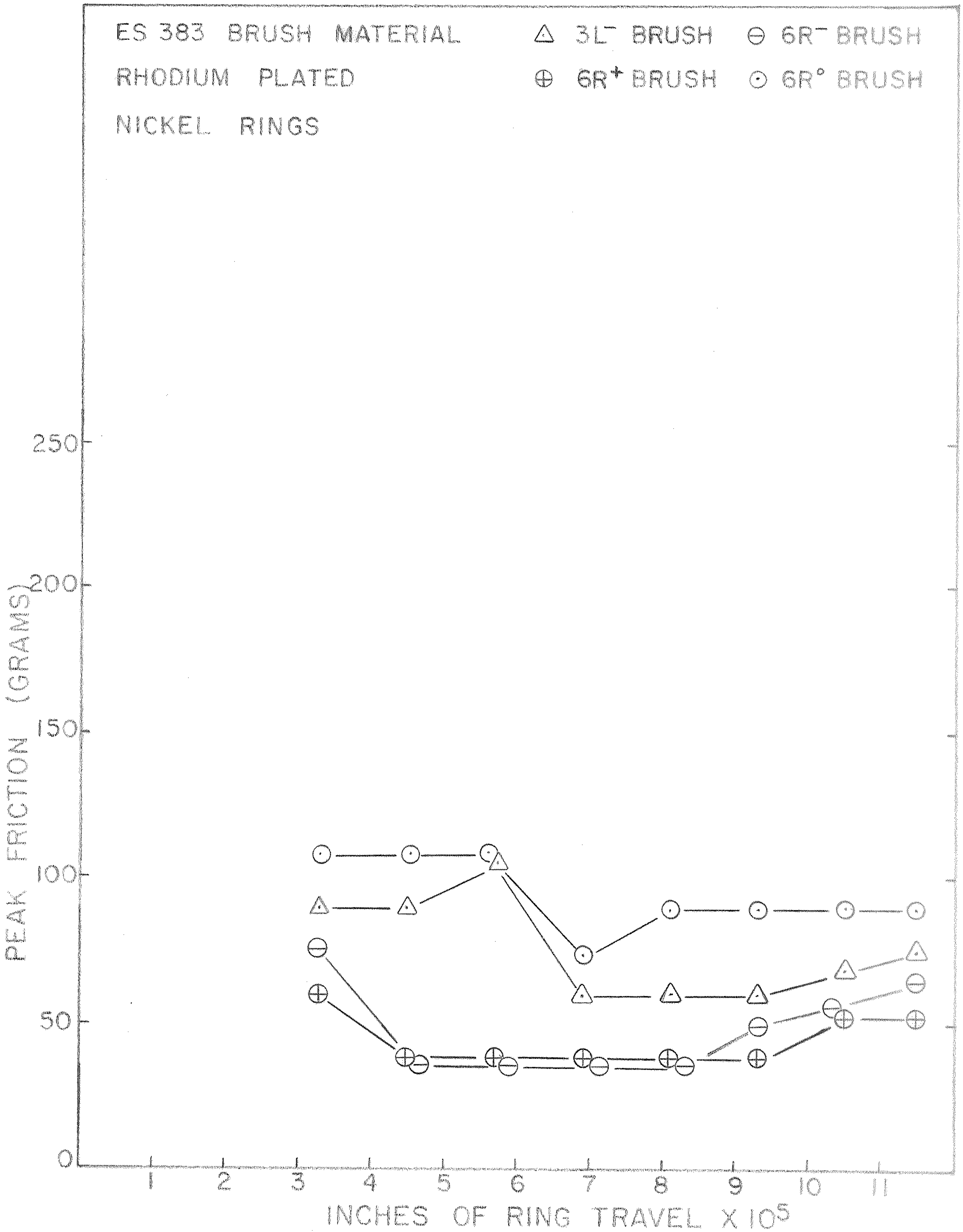

FIGURE 15. PEAK FRICTION DURING RUN-IN AT 150 RPM

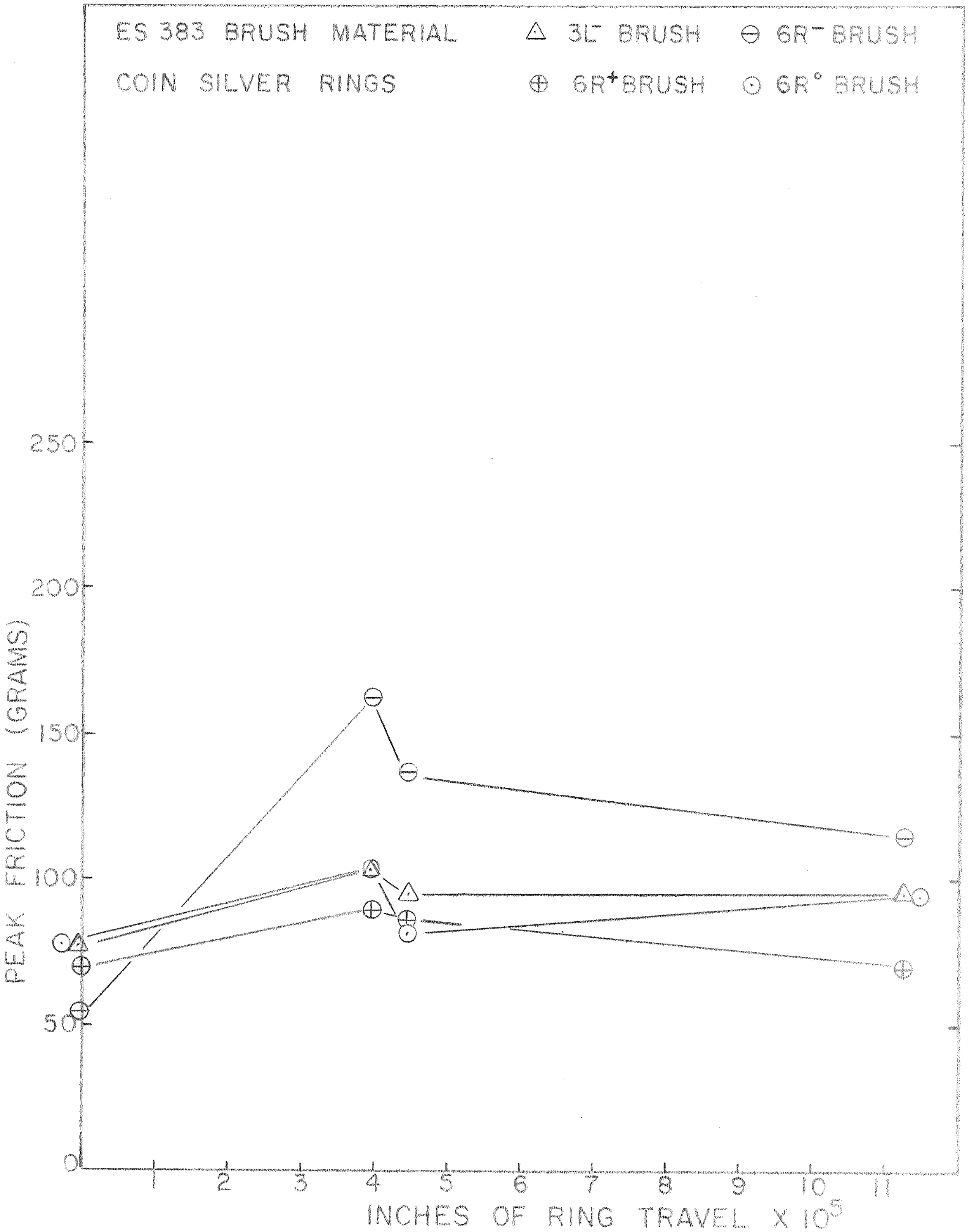

FIGURE 16. PEAK FRICTION DURING RUN-IN AT 150 RPM

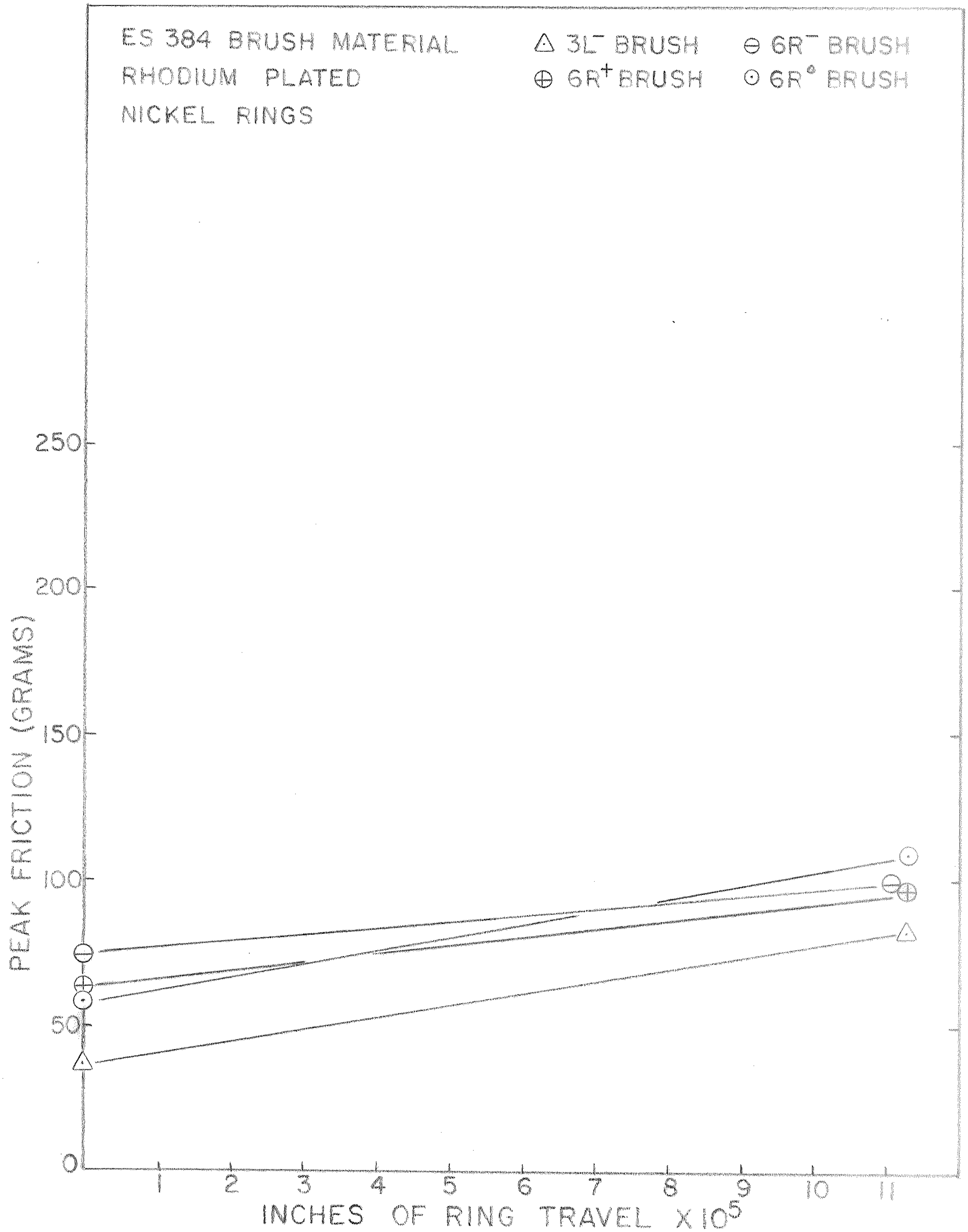

FIGURE 17. PEAK FRICTION DURING RUN-IN AT 150 RPM

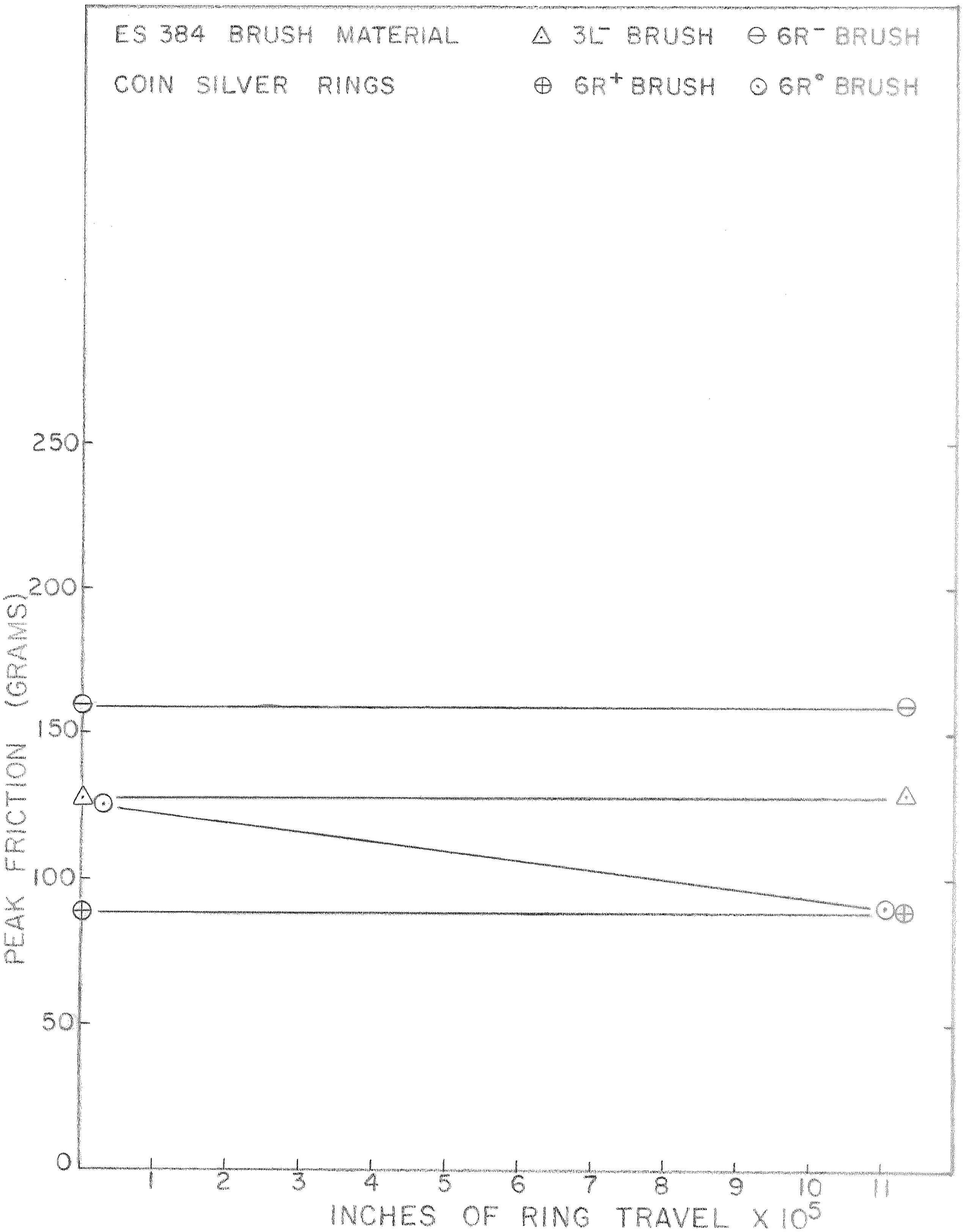

FIGURE 18. PEAK FRICTION DURING RUN-IN AT 150 RPM

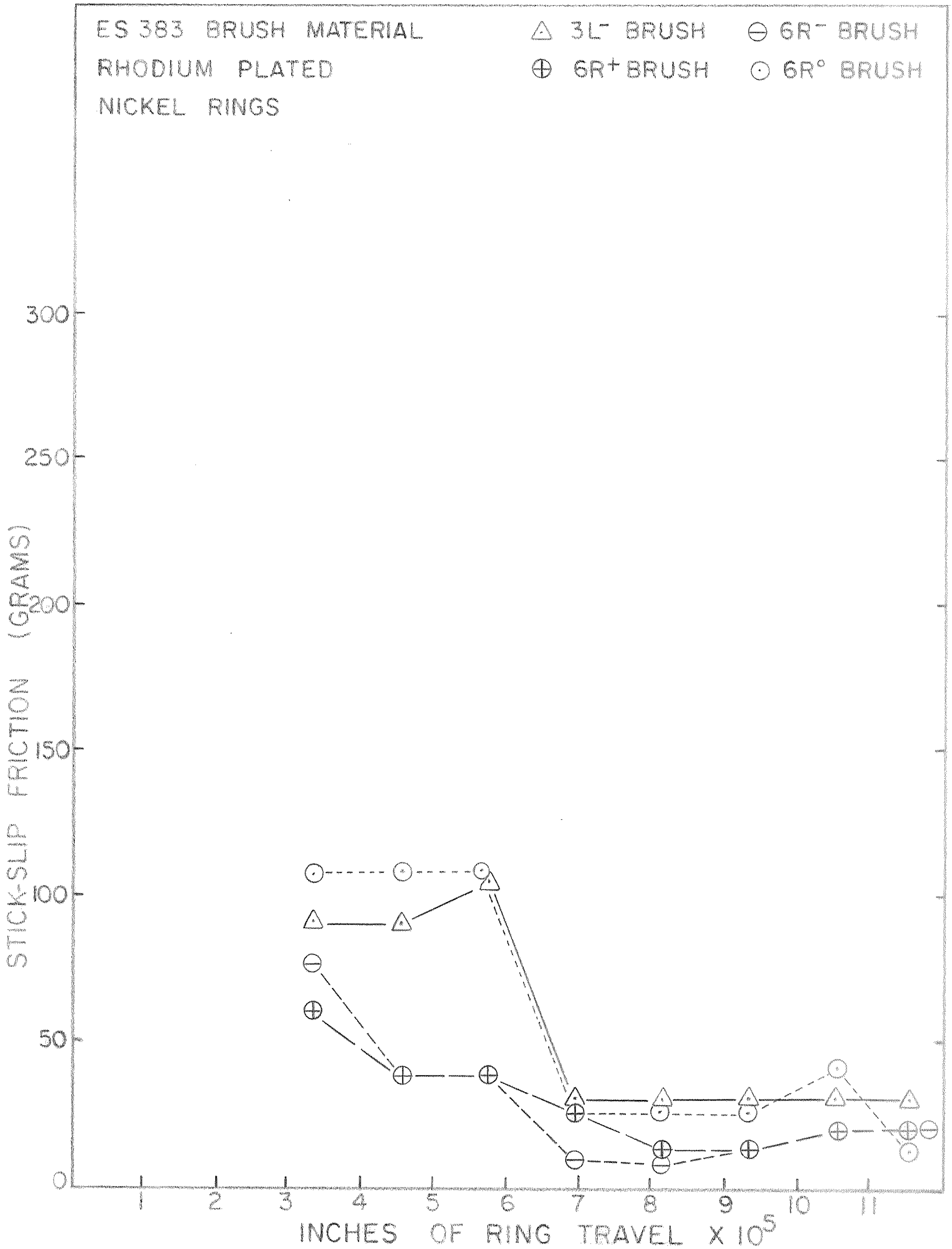

FIGURE 19. STICK-SLIP FRICTION DURING RUN-IN AT 150 RPM

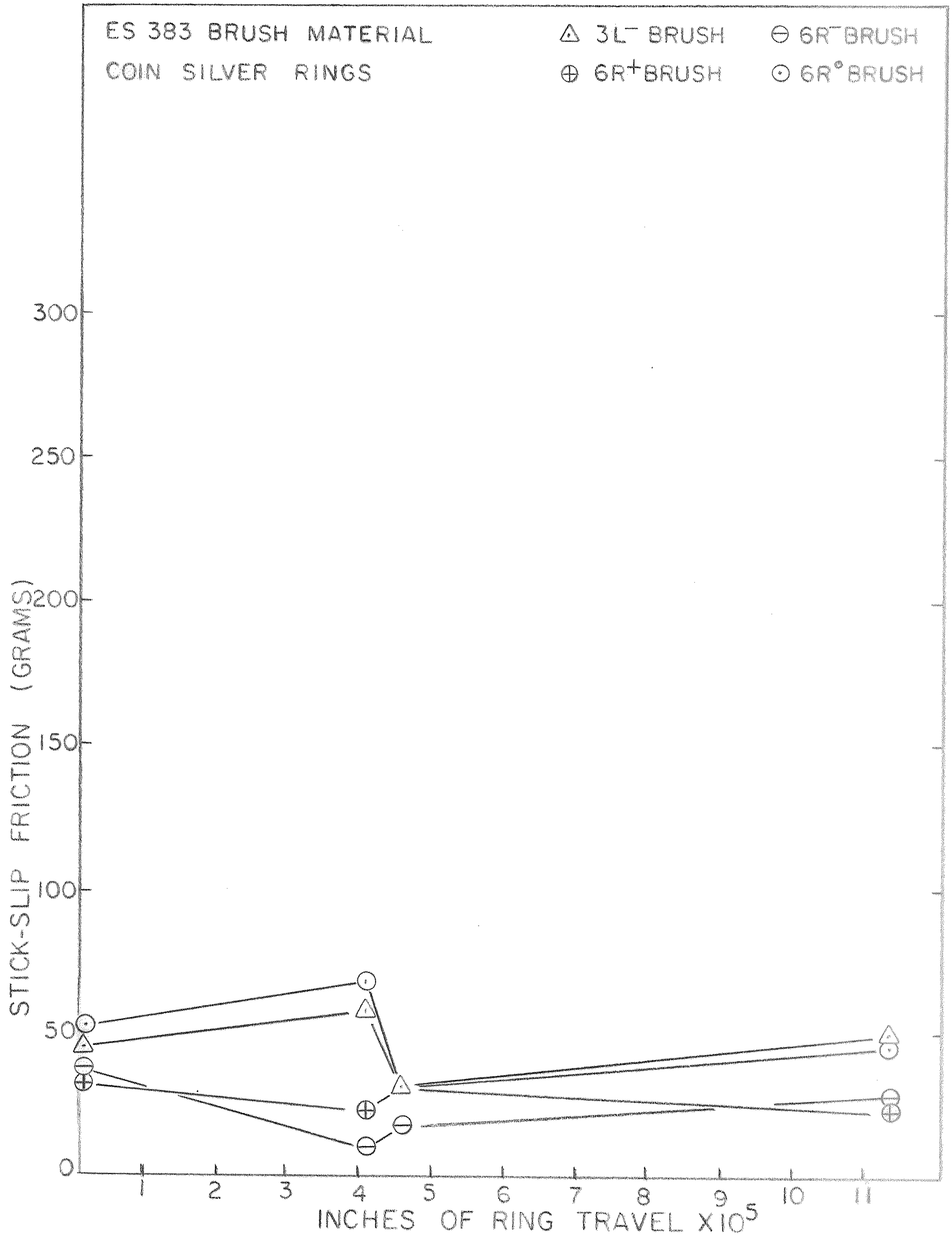

FIGURE 20. STICK-SLIP FRICTION DURING RUN-IN AT 150 RPM

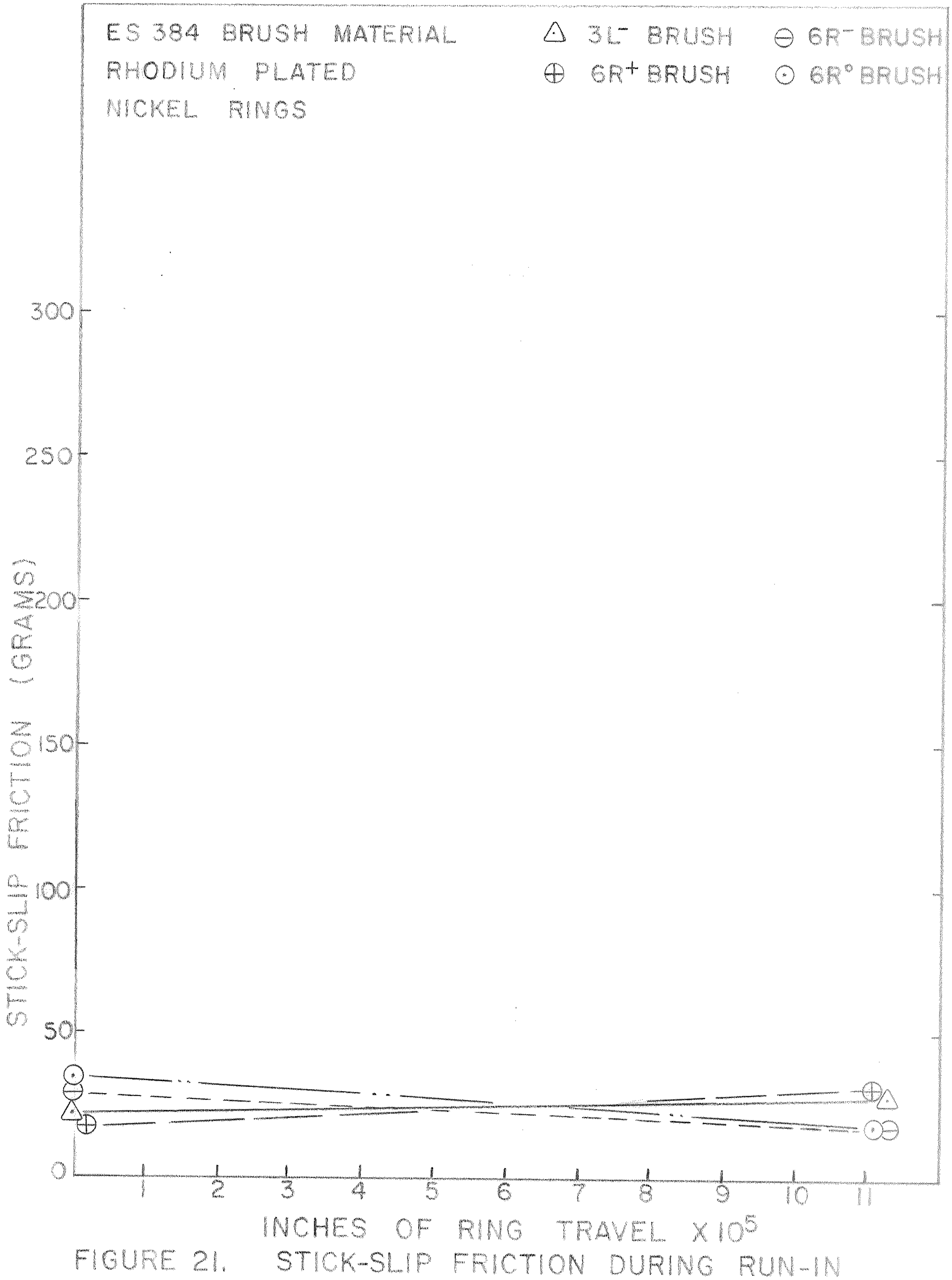

FIGURE 21. STICK-SLIP FRICTION DURING RUN-IN AT 150 RPM

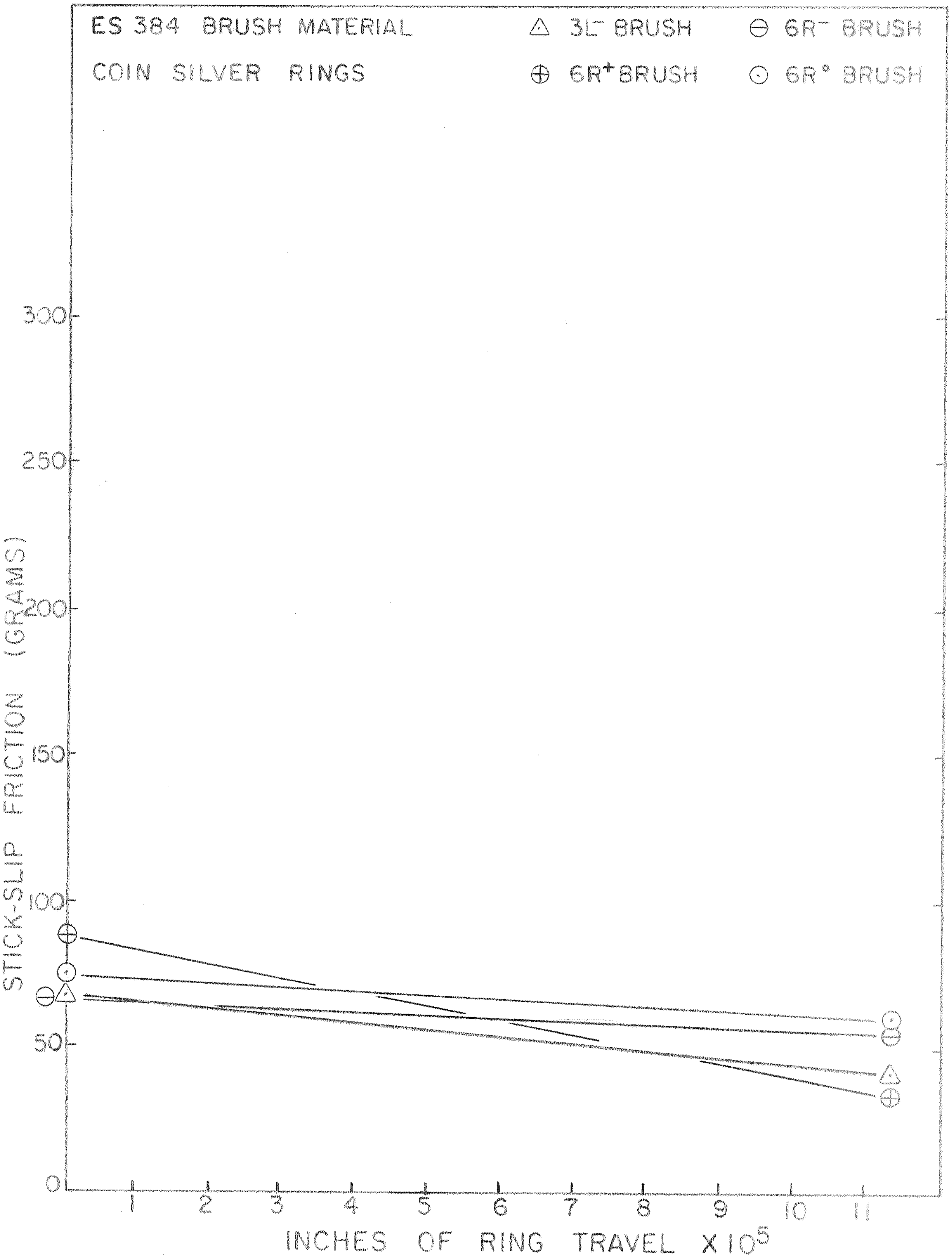

FIGURE 22. STICK-SLIP FRICTION DURING RUN-IN AT 150 RPM

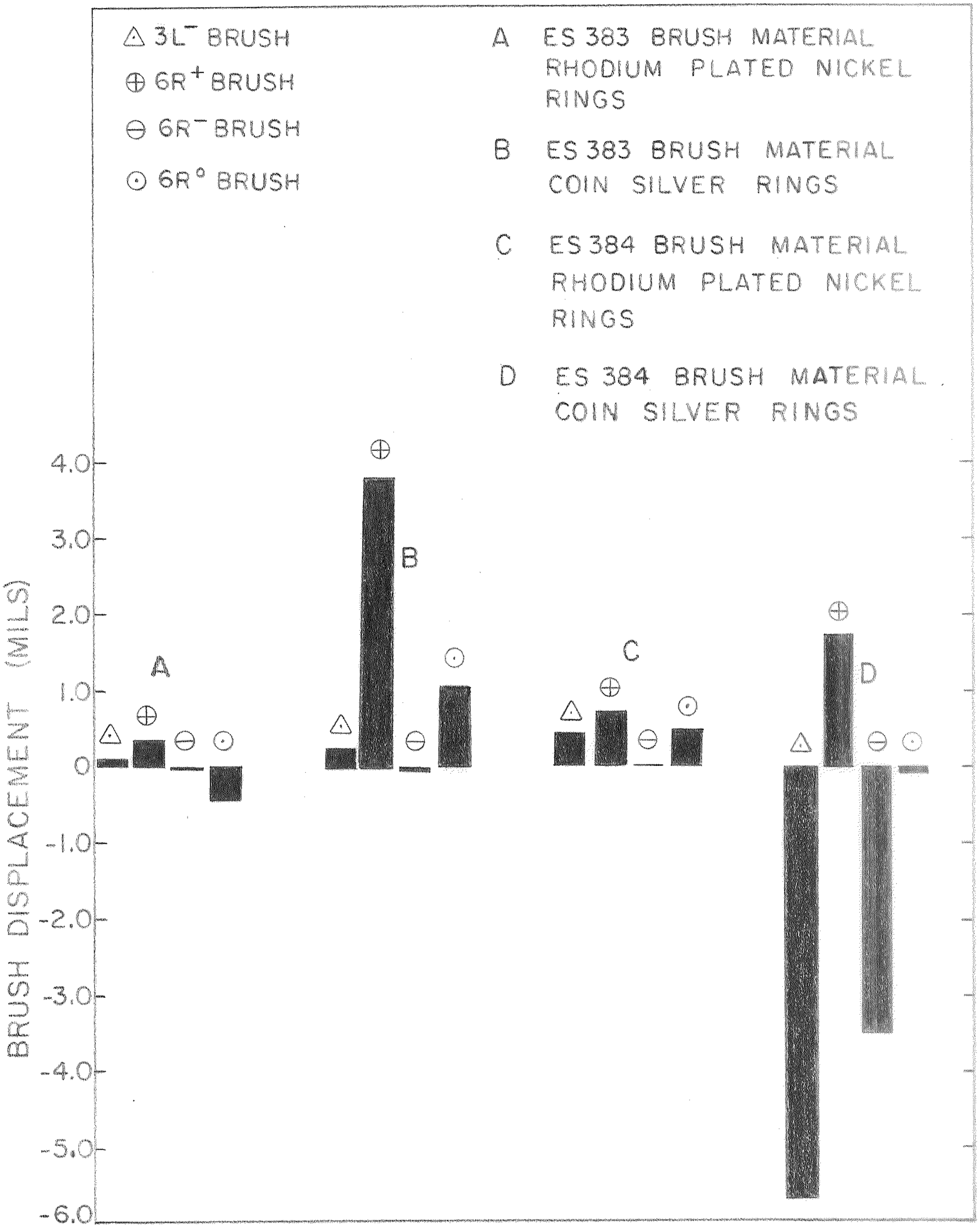

FIGURE 23. TOTAL BRUSH DISPLACEMENT DURING RUN-IN AT 150 RPM

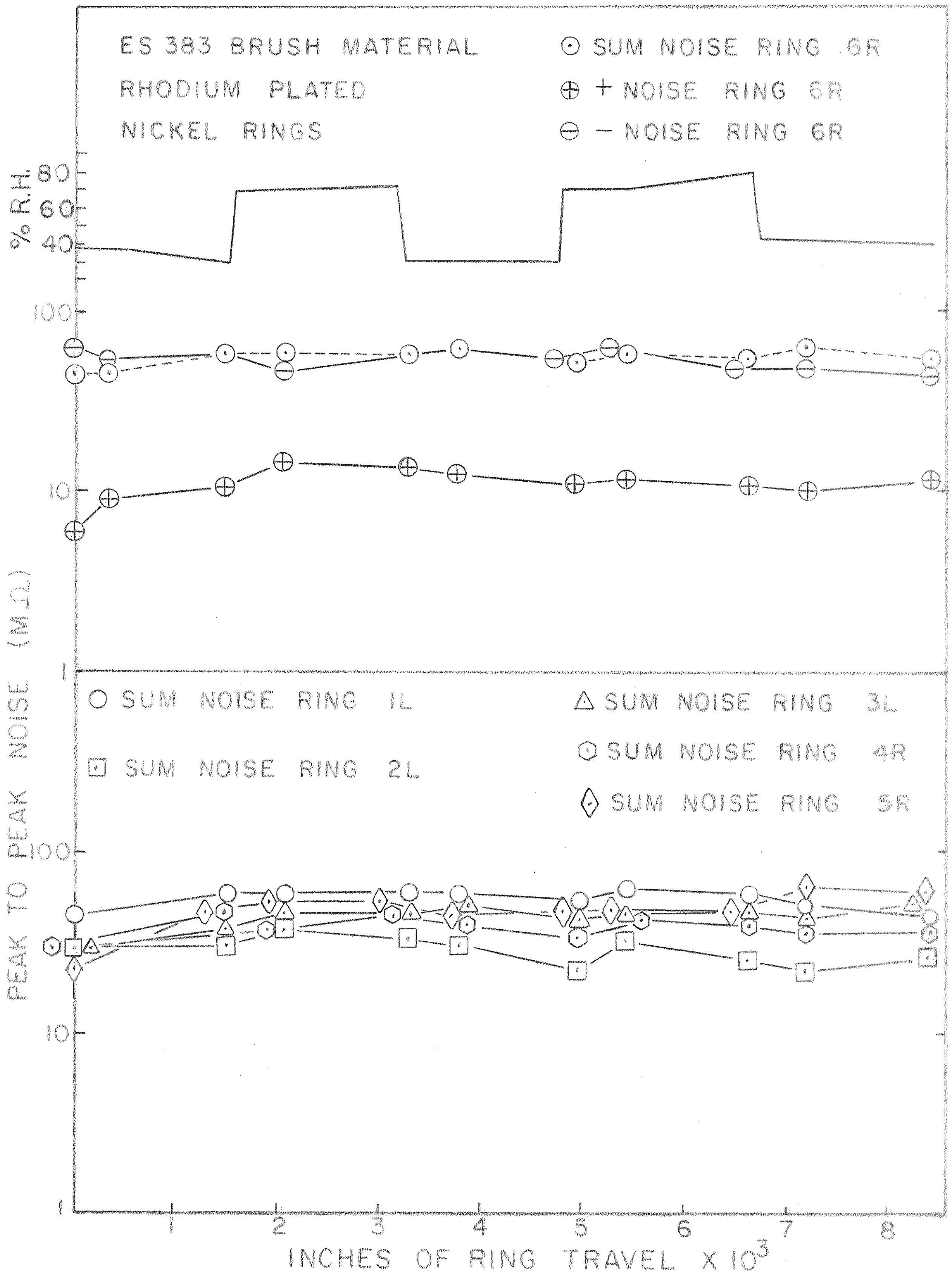

FIGURE 24. NOISE (P-P) DURING HUMIDITY AT 0.1 RPM

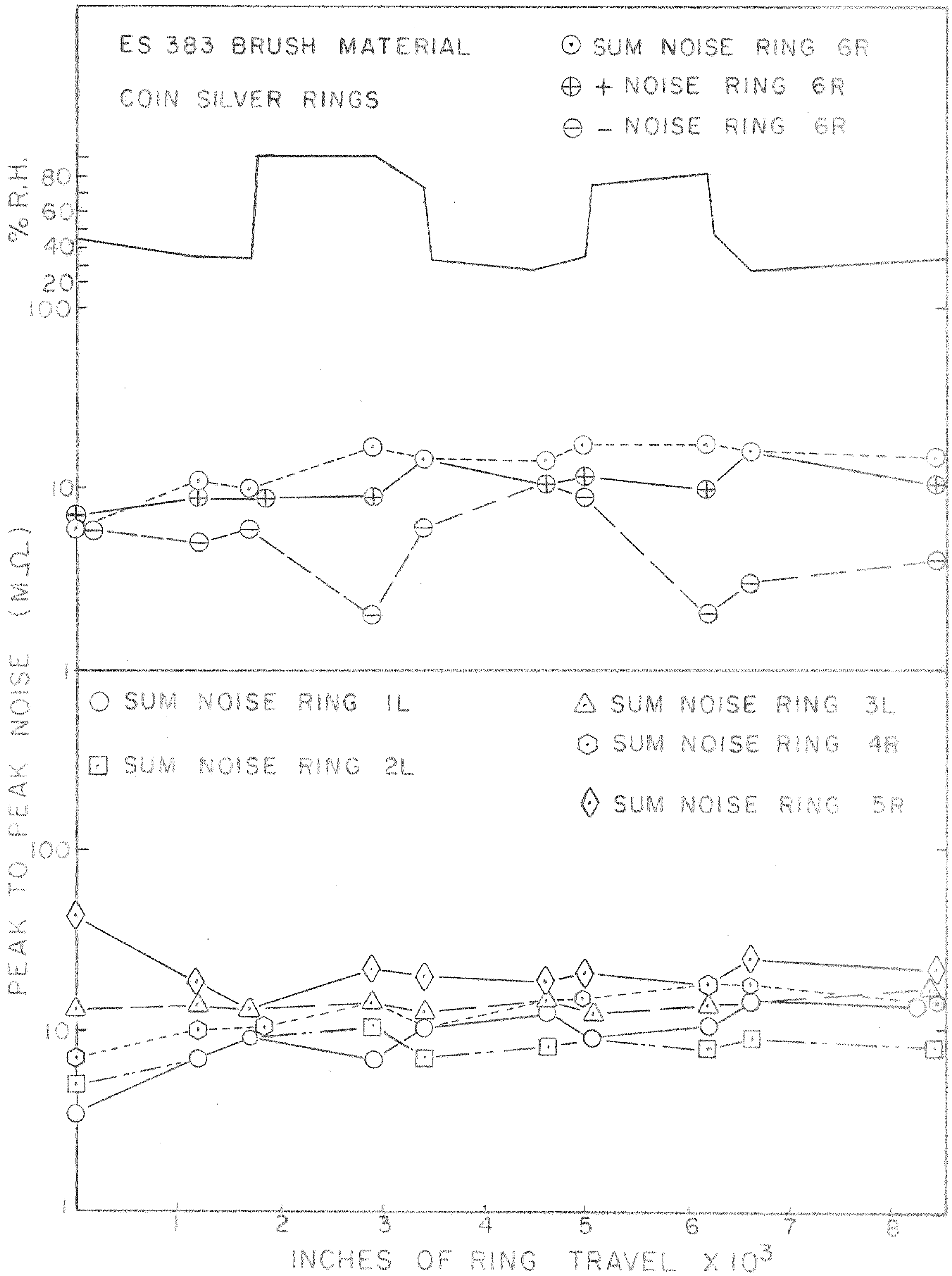

FIGURE 25. NOISE (P-P) DURING HUMIDITY AT 0.1 RPM

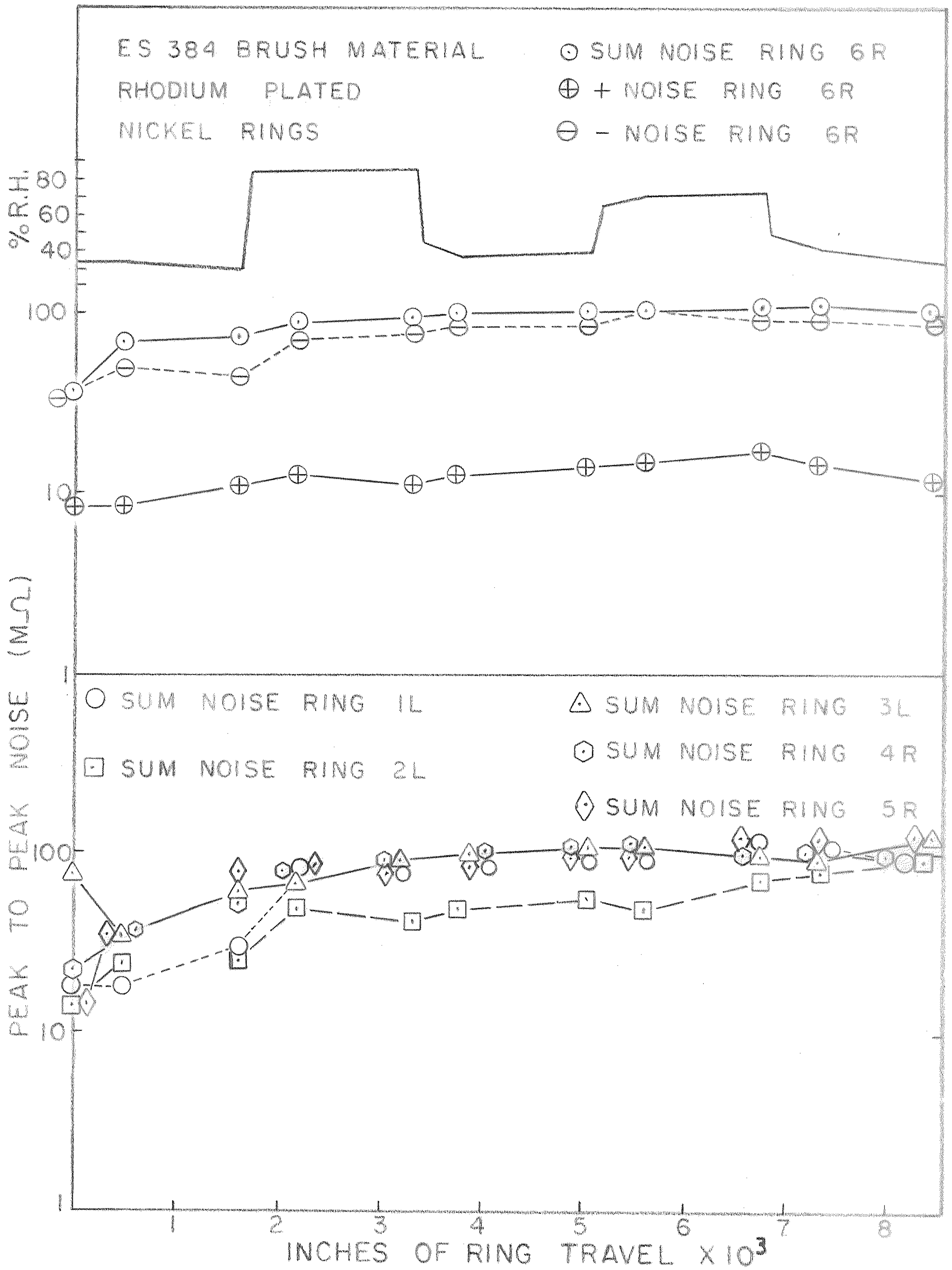

FIGURE 26. NOISE (P-P) DURING HUMIDITY AT 0.1 RPM

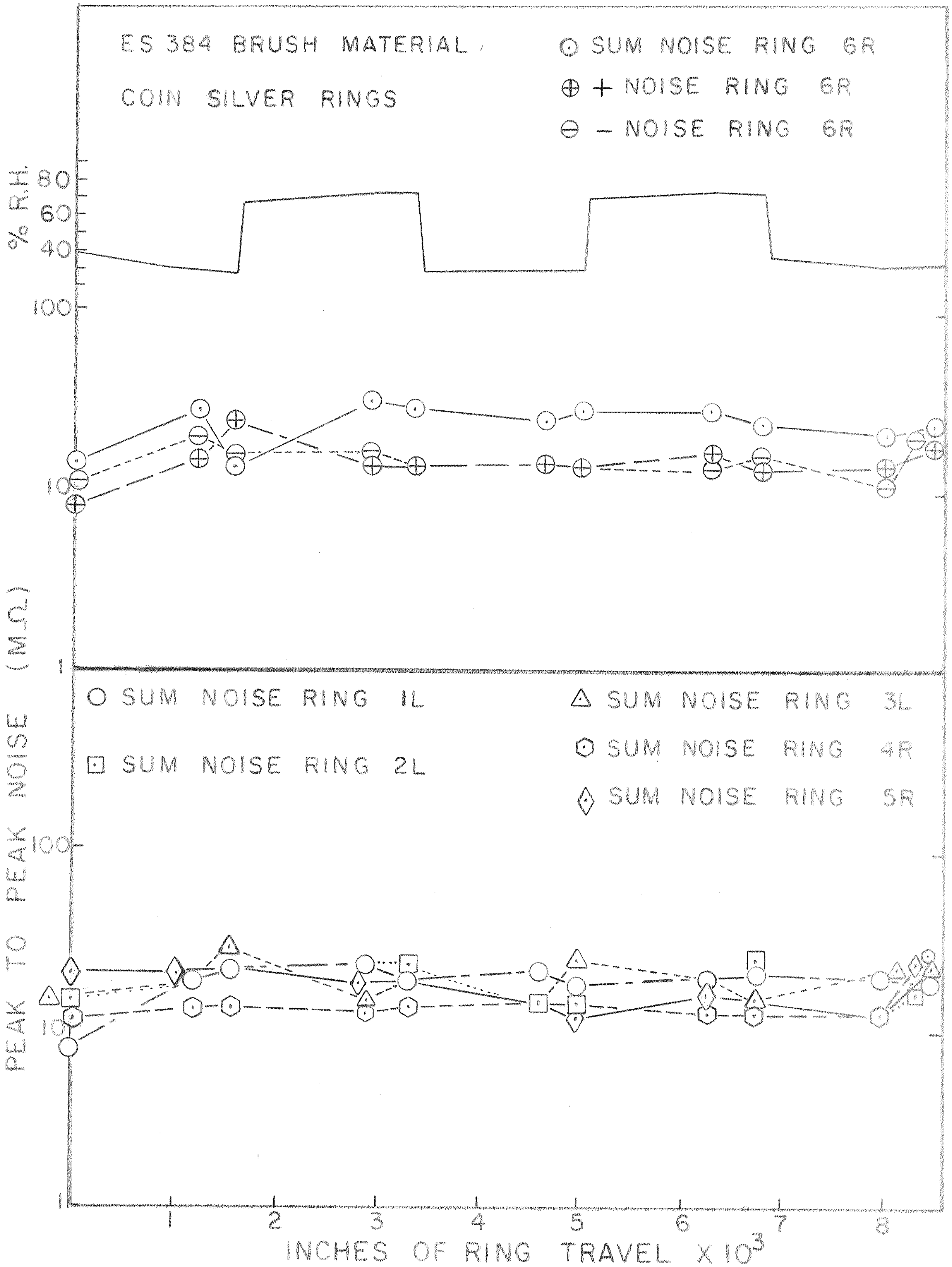

FIGURE 27. NOISE (P-P) DURING HUMIDITY AT 0.1 RPM

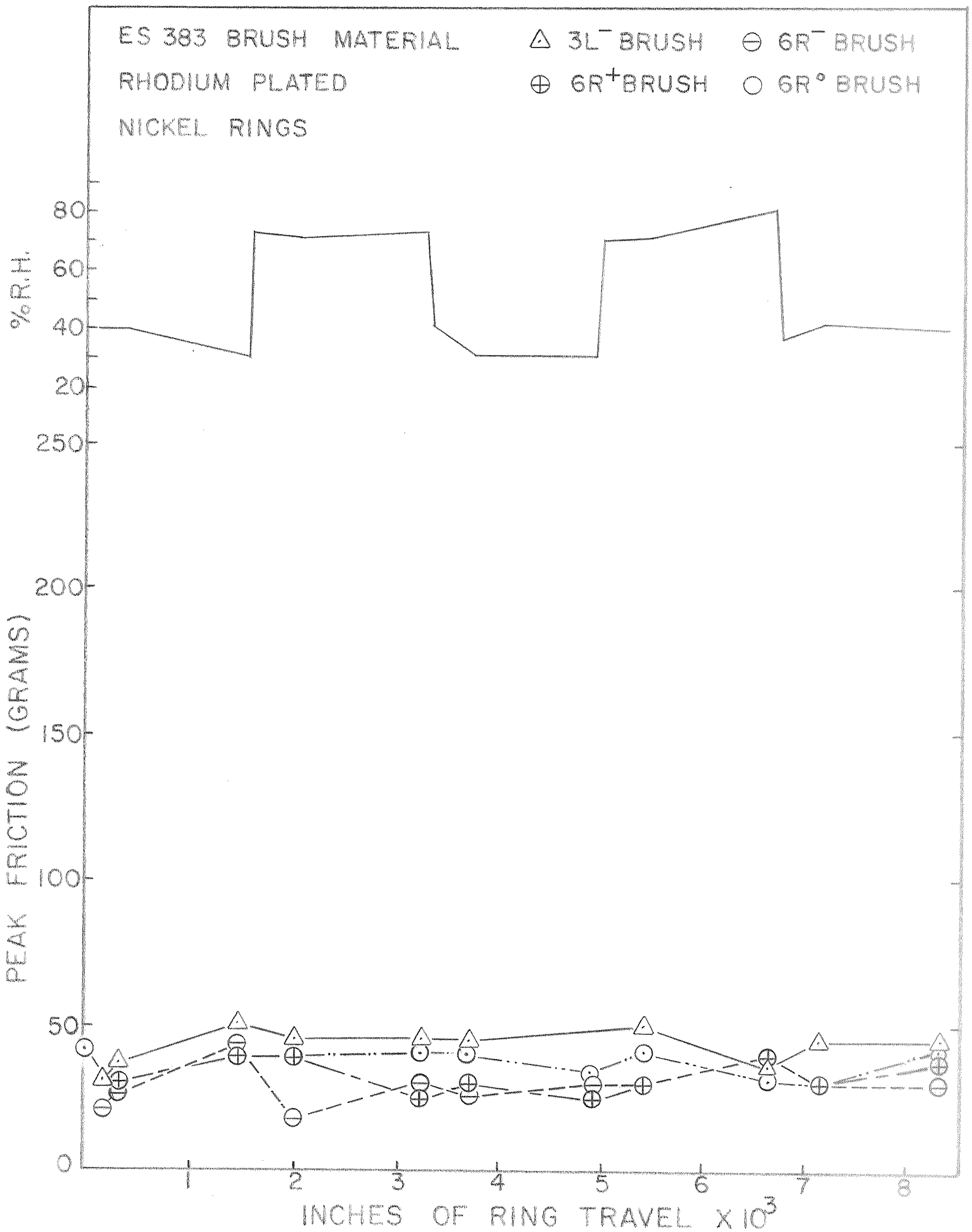

FIGURE 28. PEAK FRICTION DURING HUMIDITY AT 0.1 RPM

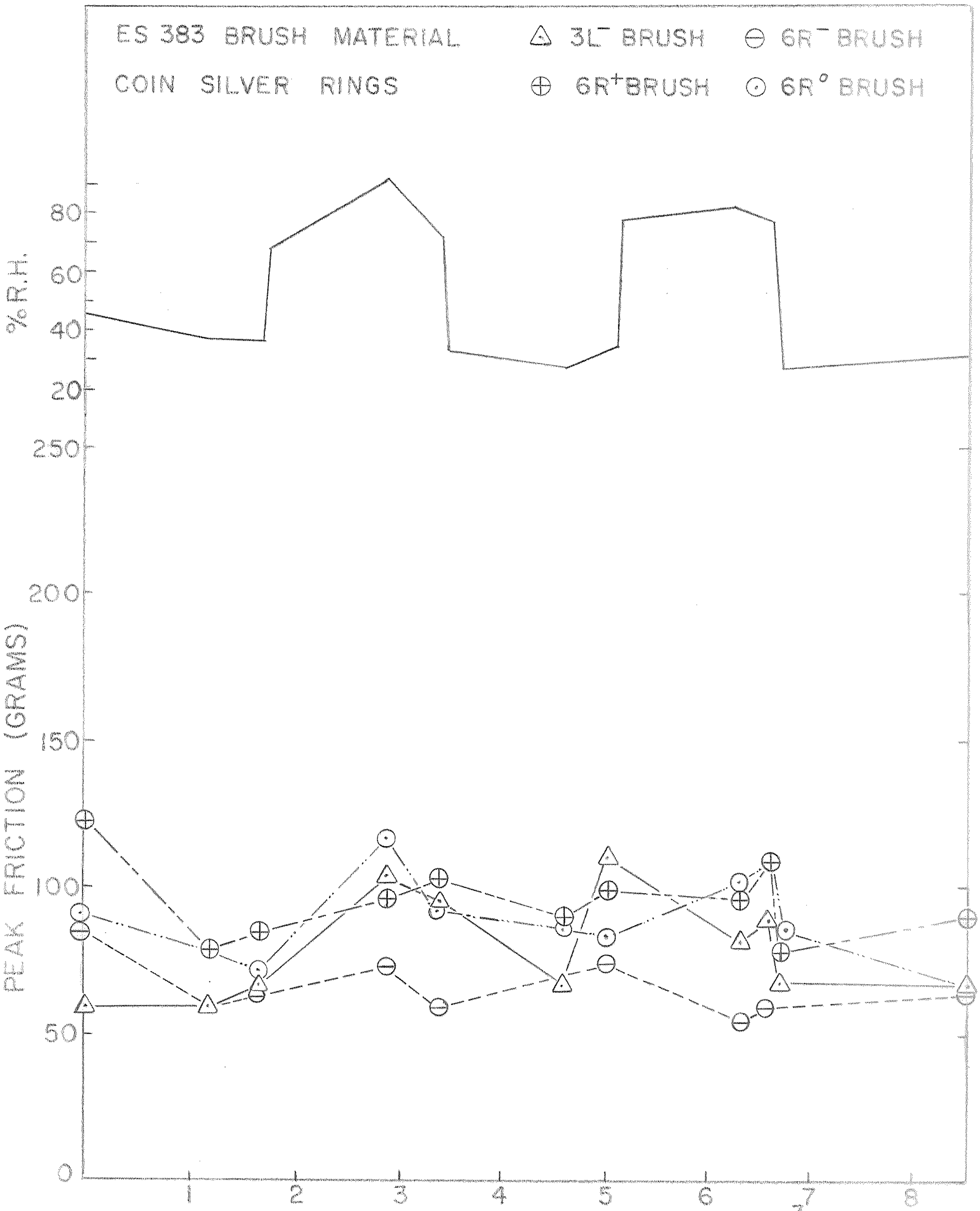

FIGURE 29. PEAK FRICTION DURING HUMIDITY AT 0.1 RPM

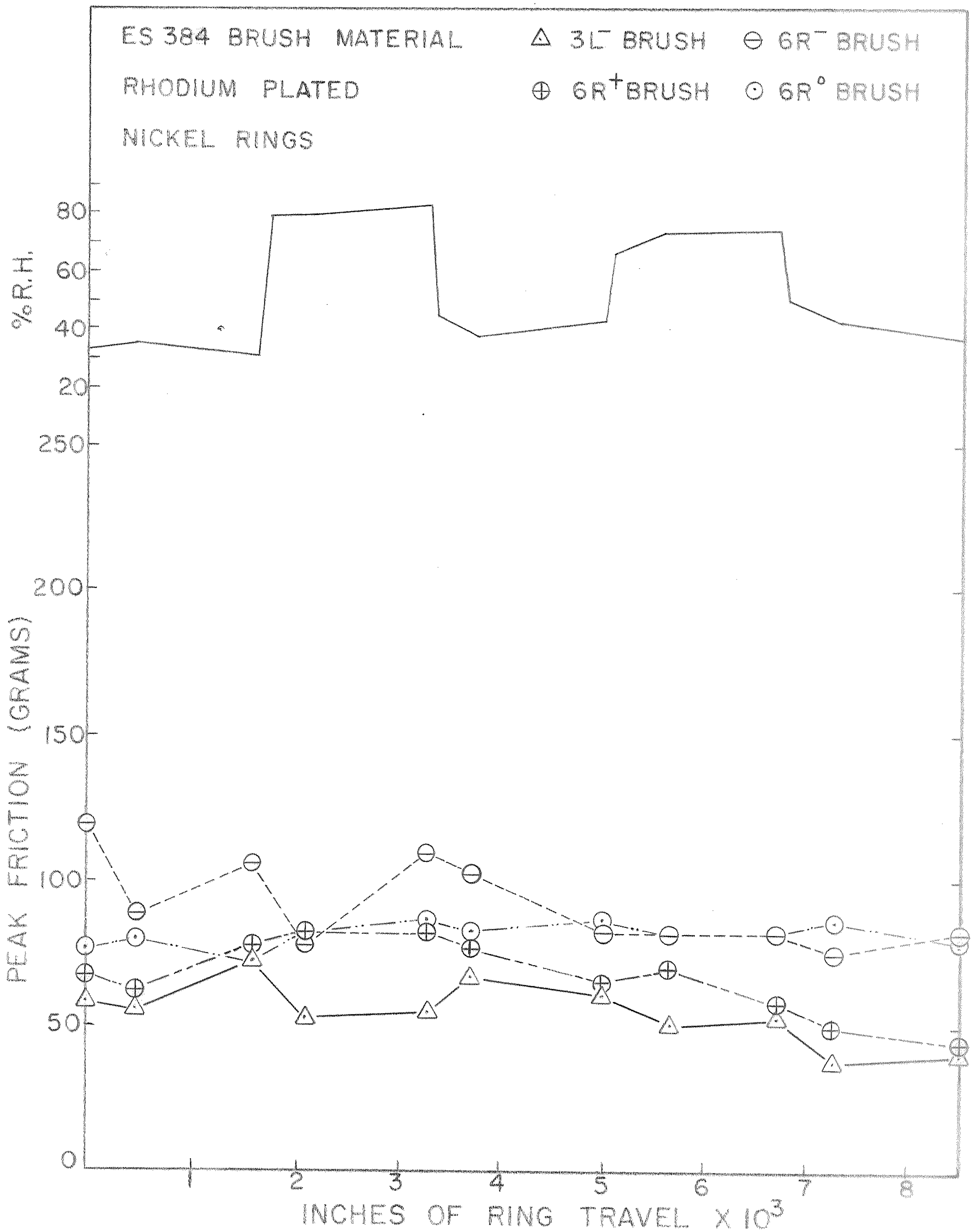

FIGURE 30. PEAK FRICTION DURING HUMIDITY AT 0.1 RPM

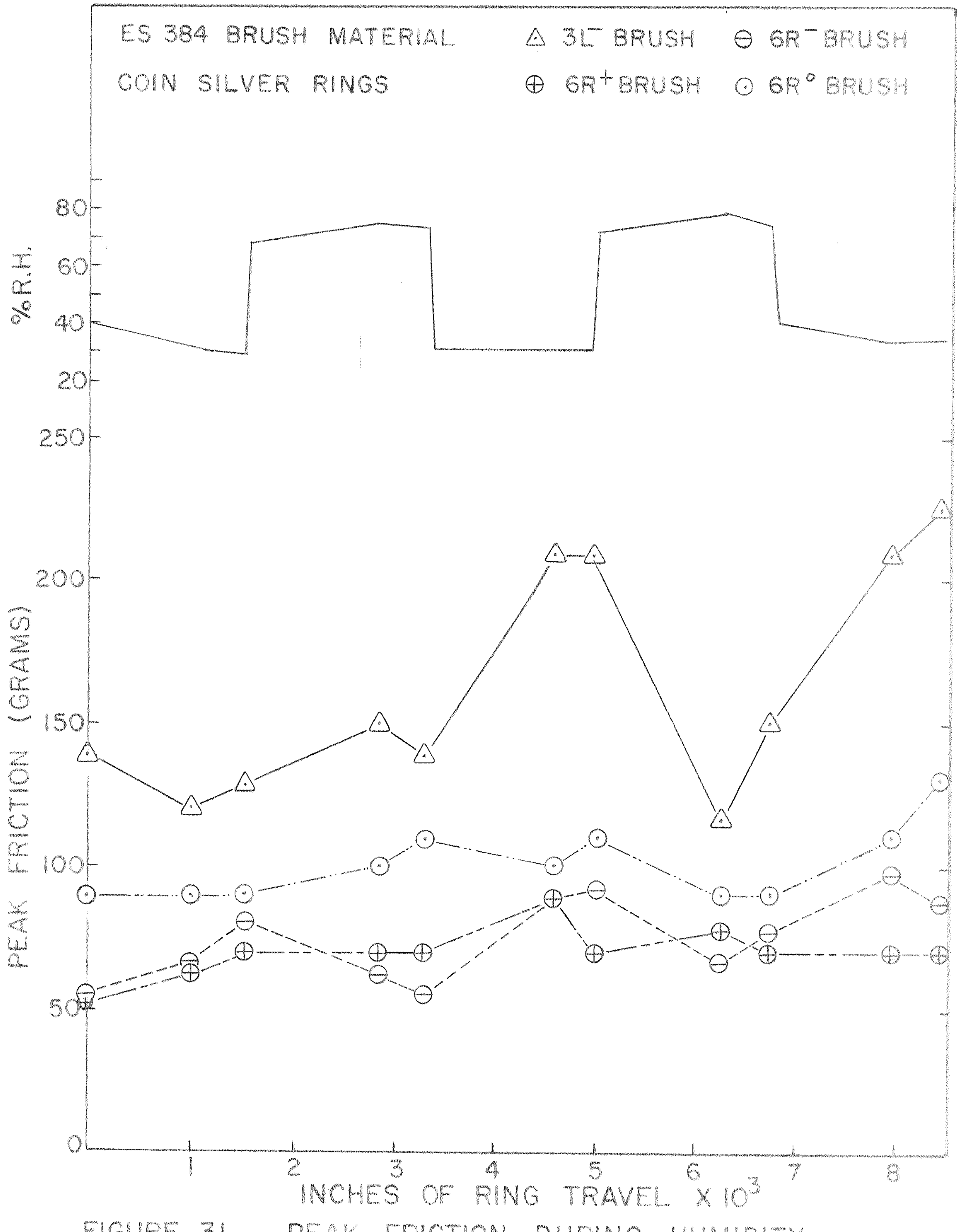

FIGURE 31. PEAK FRICTION DURING HUMIDITY AT 0.1 RPM

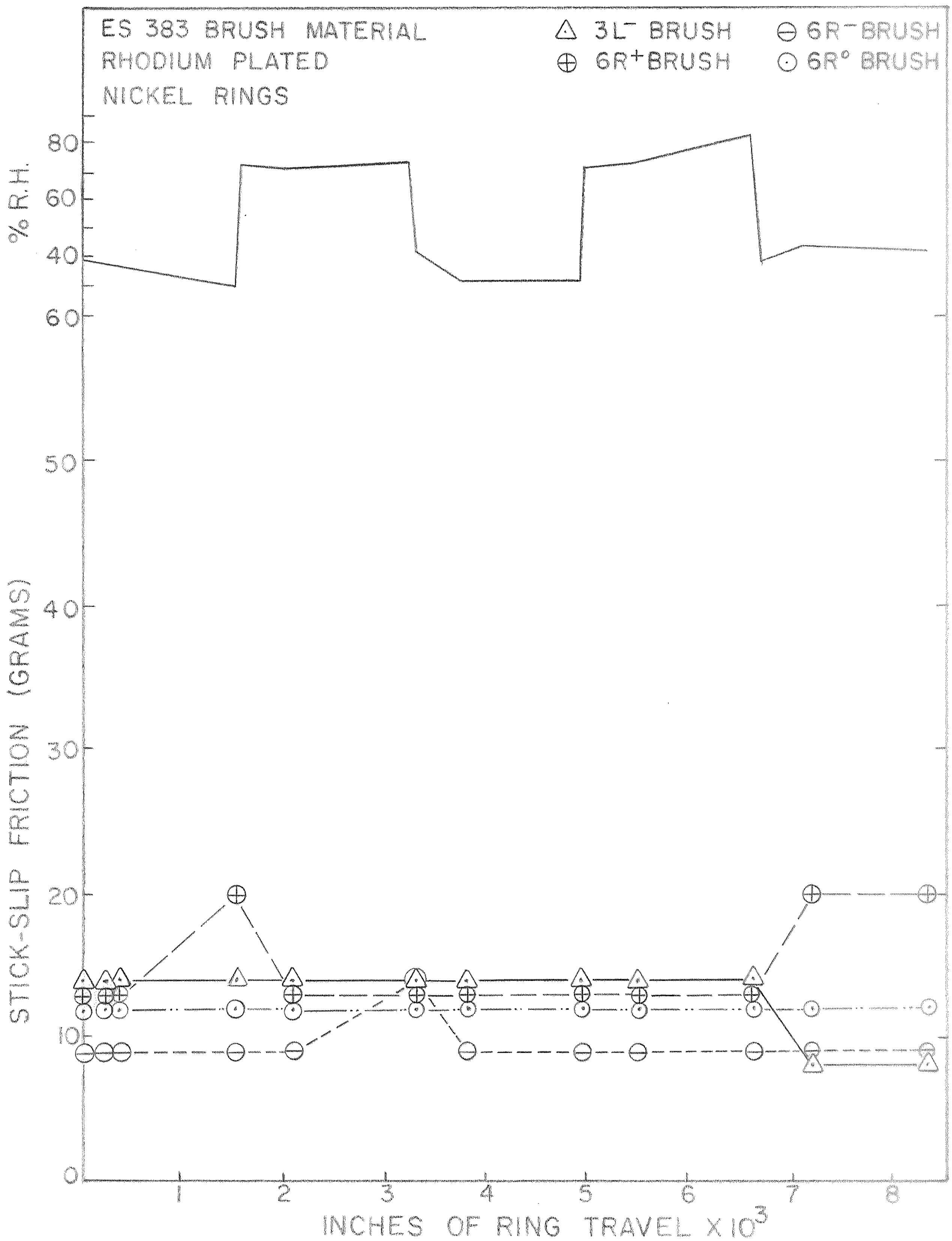

FIGURE 32. STICK-SLIP FRICTION DURING HUMIDITY AT 0.1 RPM

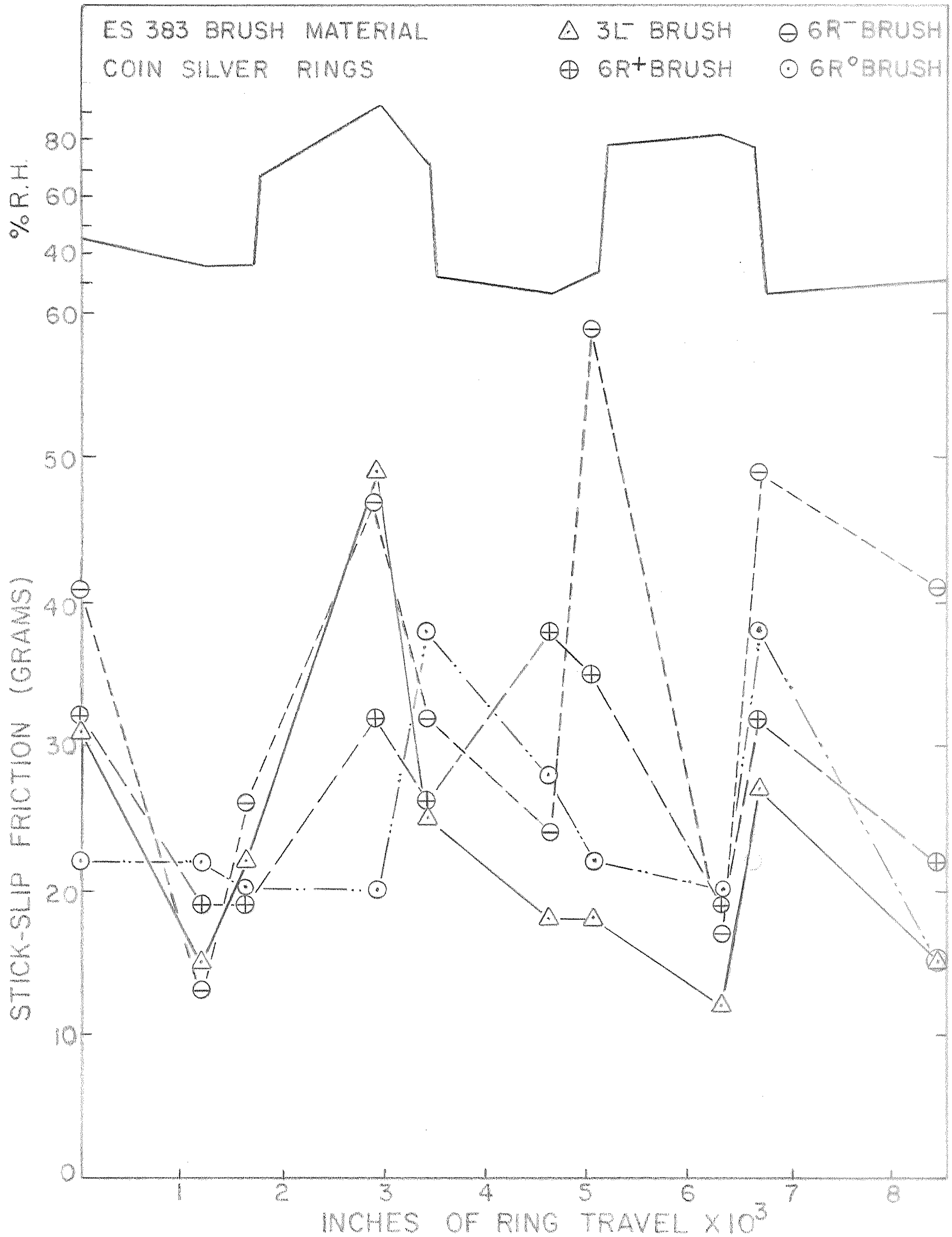

FIGURE 33. STICK-SLIP FRICTION DURING HUMIDITY AT 0.1 RPM

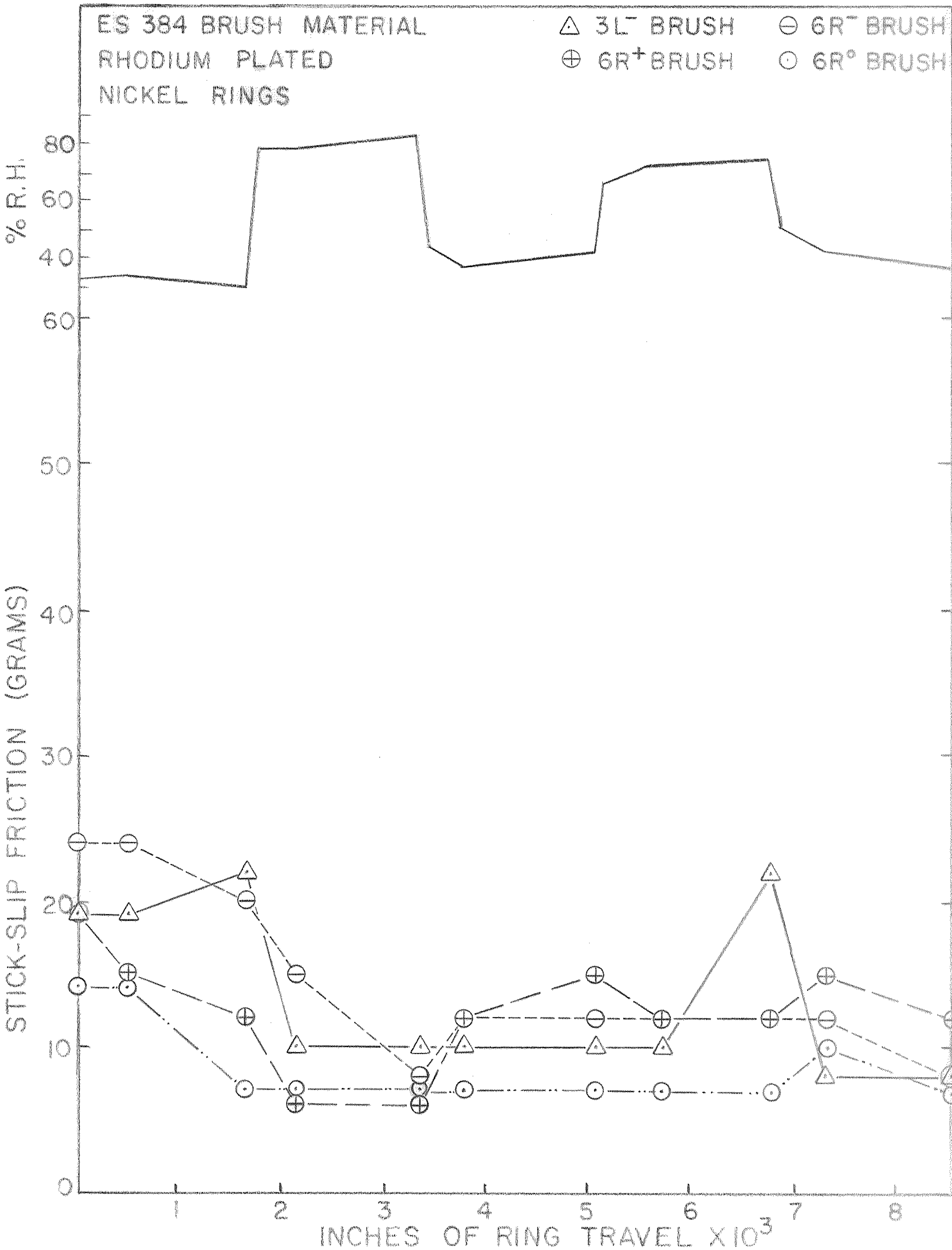

FIGURE 34. STICK-SLIP FRICTION DURING HUMIDITY AT 0.1 RPM

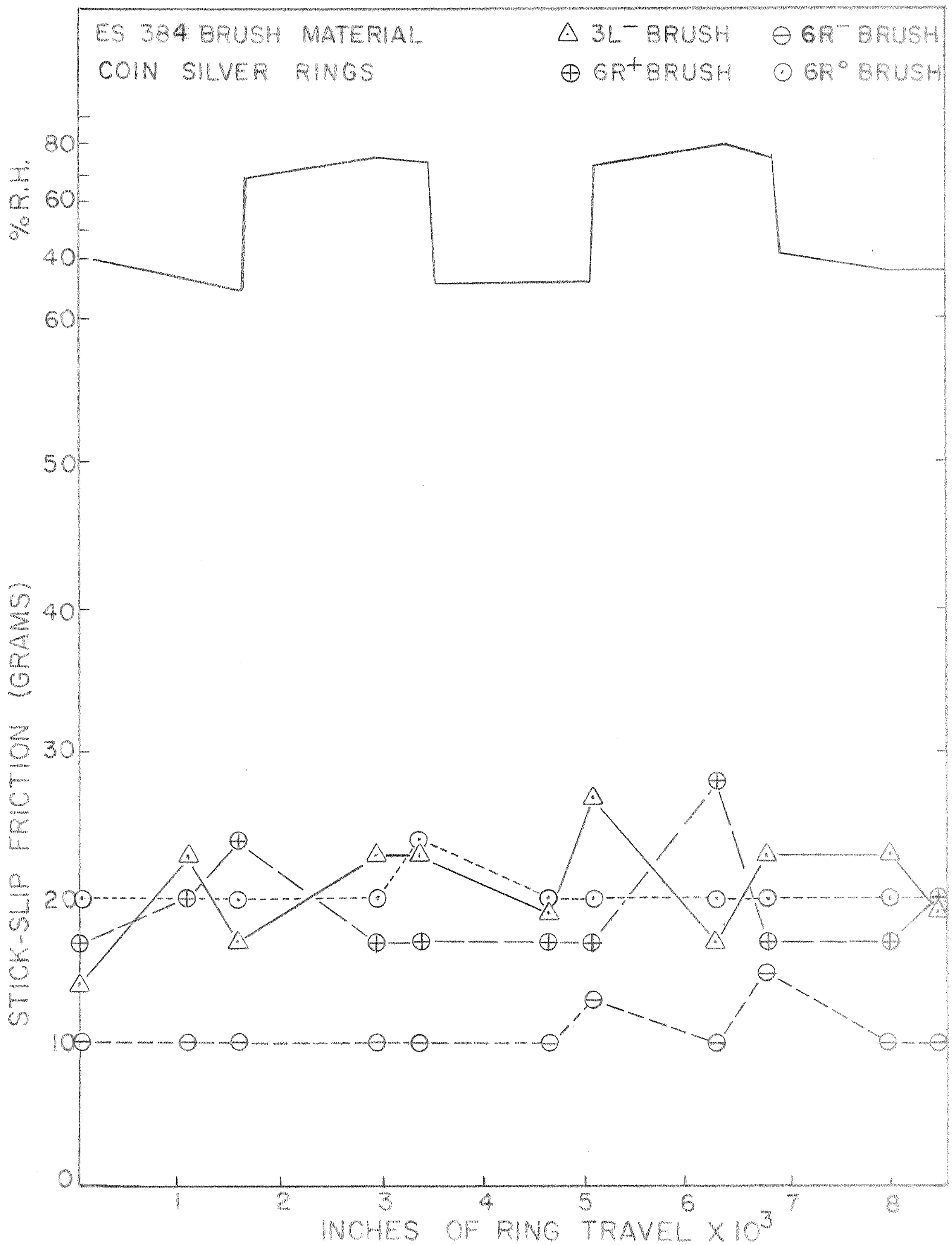

FIGURE 35. STICK-SLIP FRICTION DURING HUMIDITY AT 0.1 RPM

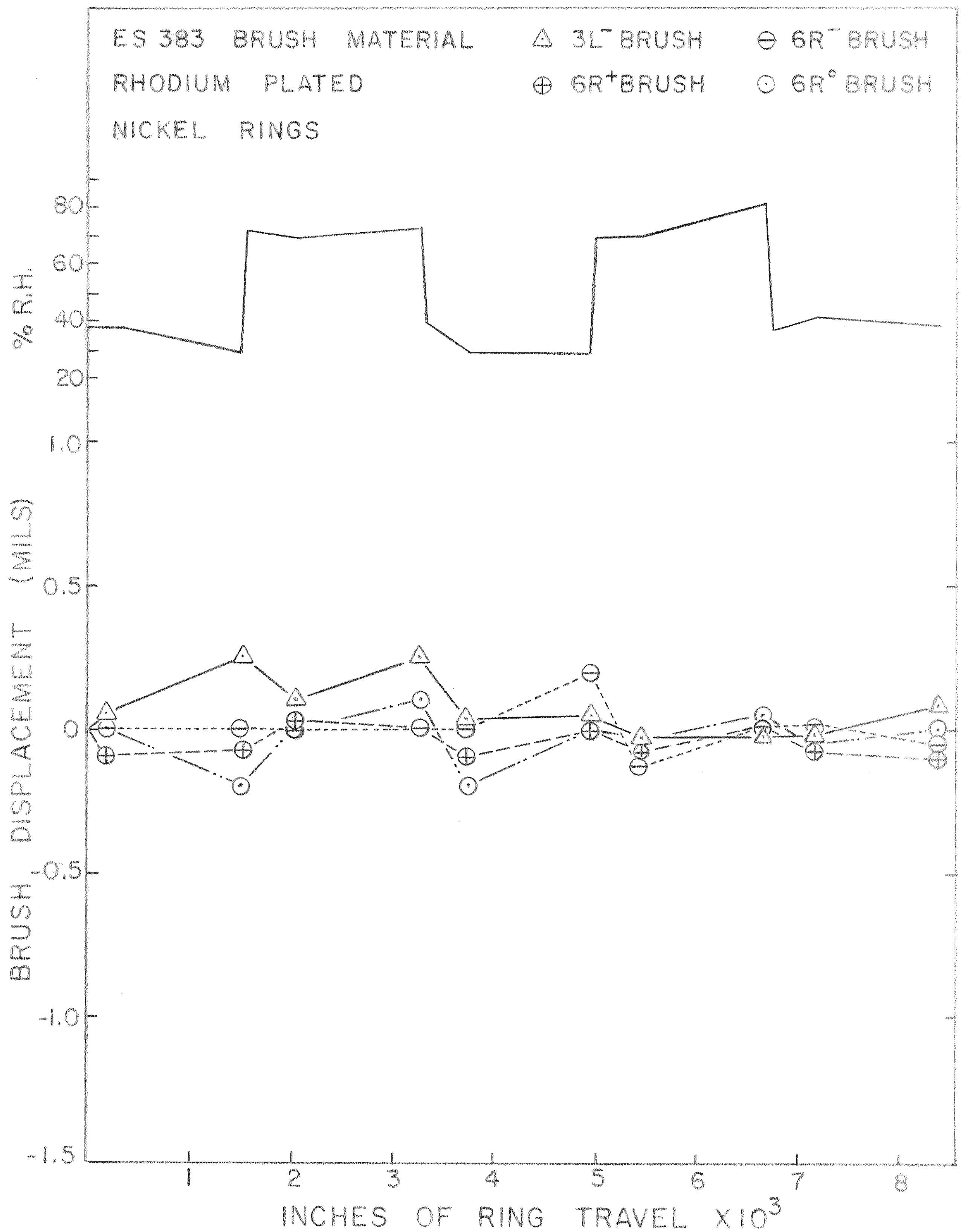

FIGURE 36. BRUSH DISPLACEMENT DURING HUMIDITY AT 0.1 RPM

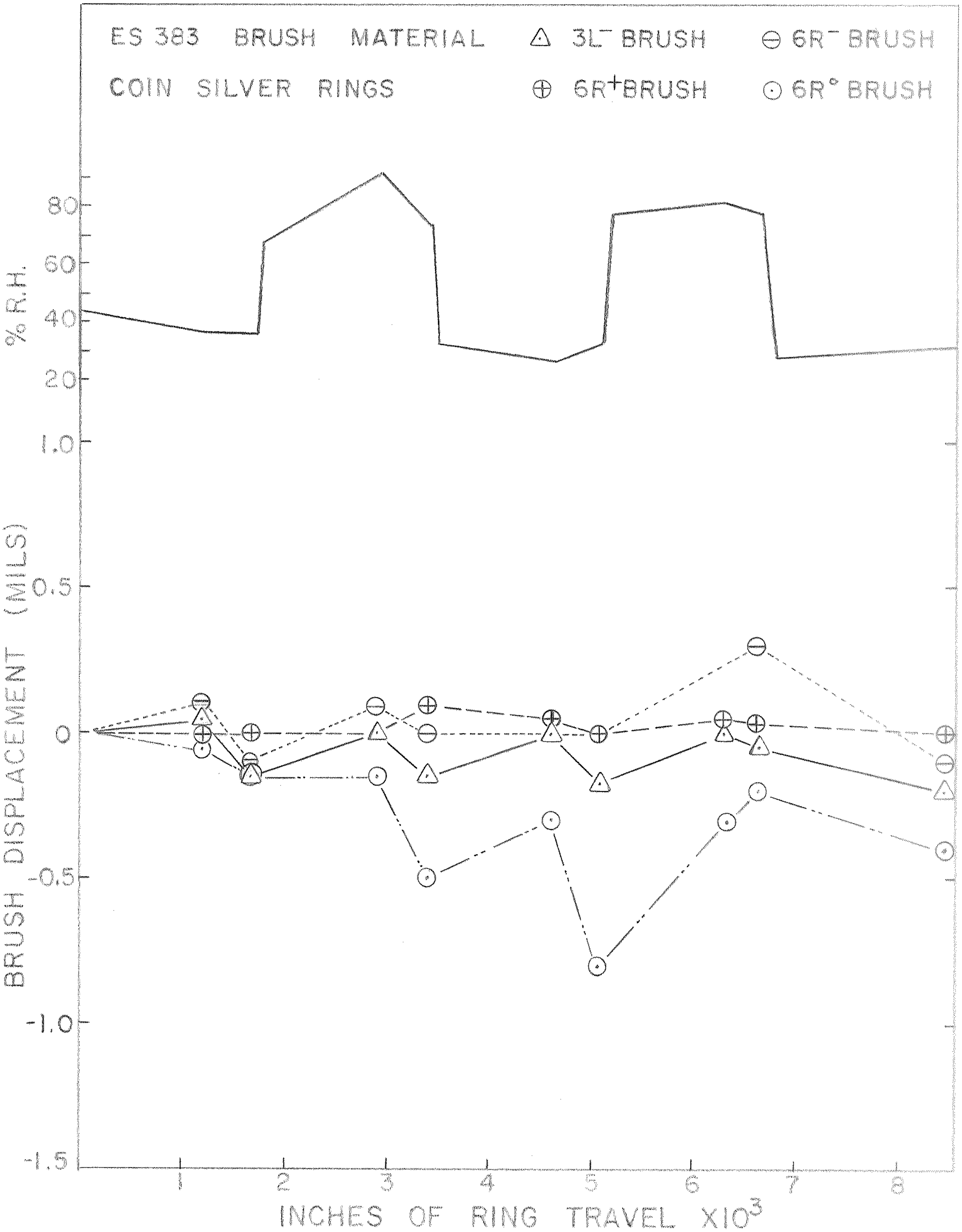

FIGURE 37. BRUSH DISPLACEMENT DURING HUMIDITY AT 0.1 RPM

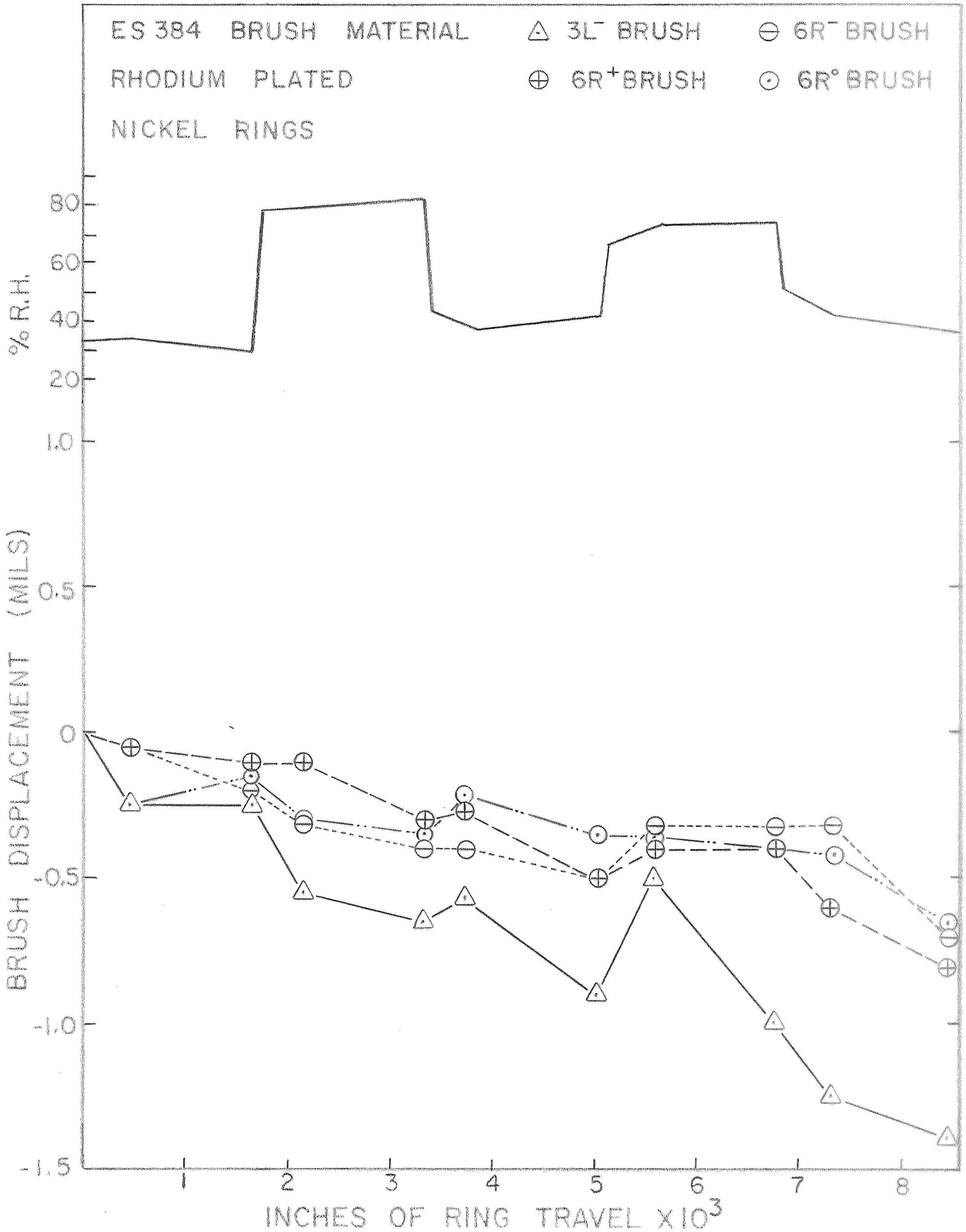

FIGURE 38. BRUSH DISPLACEMENT DURING HUMIDITY AT 0.1 RPM

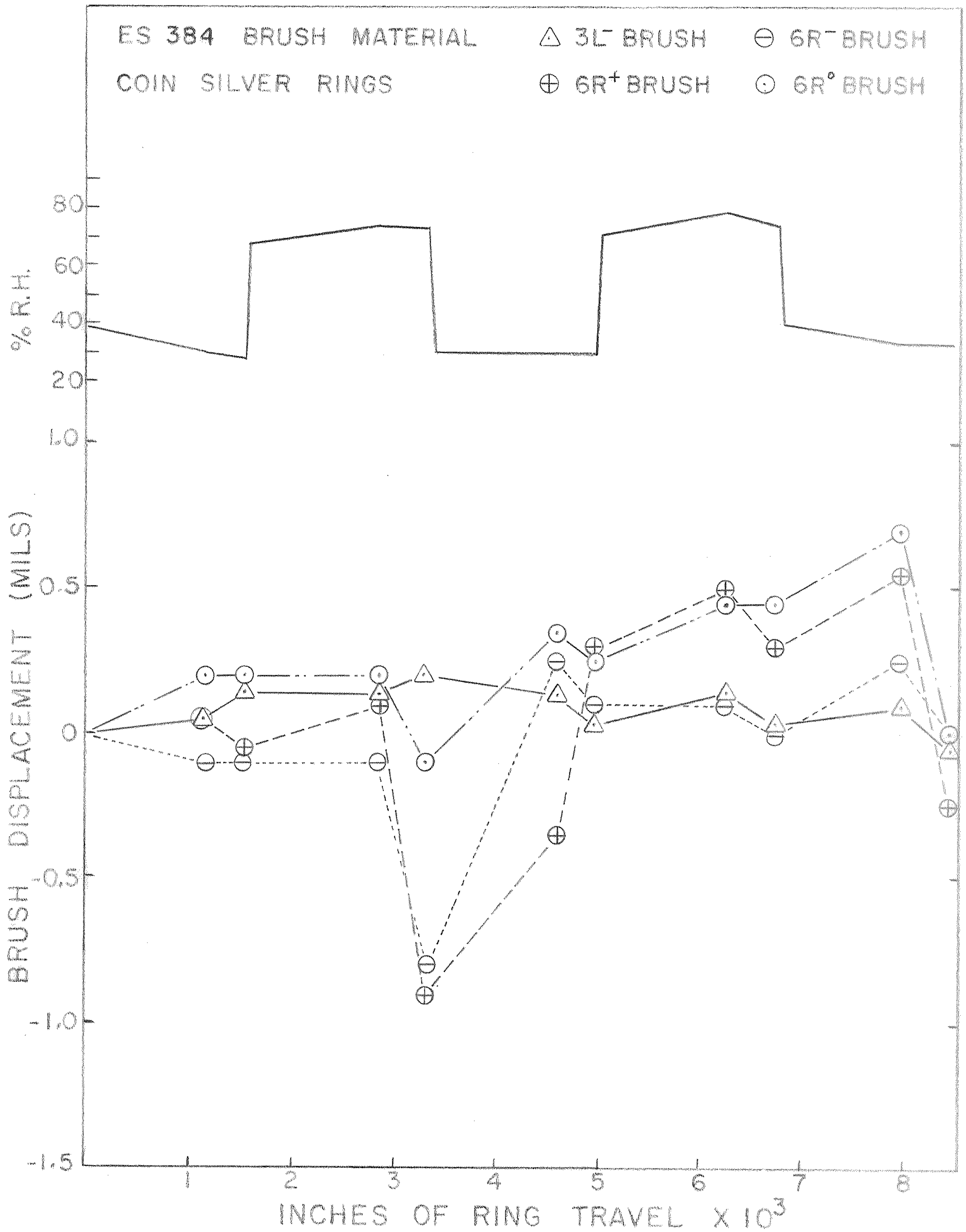

FIGURE 39. BRUSH DISPLACEMENT DURING HUMIDITY AT 0.1 RPM

TABLE I

SIMULTANEOUS DATA COLLECTION SEQUENCE

RECORDER CHANNEL	STEPPING SWITCH POSITION	3	4	5	6	7	8	9	10
	1	N^{S}_{A1}	N^{S}_{A4}	N^{S}_{B1}	N^{S}_{B4}	N^{S}_{C1}	N^{S}_{C4}	N^{S}_{D1}	N^{S}_{D4}
	2	N^{S}_{A2}	N^{S}_{A5}	N^{S}_{B2}	N^{S}_{B5}	N^{S}_{C2}	N^{S}_{C5}	N^{S}_{D2}	N^{S}_{D5}
	3	N^{S}_{A3}	N^{S}_{A6}	N^{S}_{B3}	N^{S}_{B6}	N^{S}_{C3}	N^{S}_{C6}	N^{S}_{D3}	N^{S}_{D6}
	4	N^{+}_{A6}	N^{-}_{A6}	N^{+}_{B6}	N^{-}_{B6}	N^{+}_{C6}	N^{-}_{C6}	N^{+}_{D6}	N^{-}_{D6}
	5	F^{o}_{A6}	F^{+}_{A6}	F^{o}_{B6}	F^{+}_{B6}	F^{o}_{C6}	F^{+}_{C6}	F^{o}_{D6}	F^{+}_{D6}
	6	F^{-}_{A3}	F^{-}_{A6}	F^{-}_{B3}	F^{-}_{B6}	F^{-}_{C3}	F^{-}_{C6}	F^{-}_{D3}	F^{-}_{D6}
	7	W^{o}_{A6}	W^{+}_{A6}	W^{o}_{B6}	W^{+}_{B6}	W^{o}_{C6}	W^{+}_{C6}	W^{o}_{D6}	W^{+}_{D6}
	8	W^{-}_{A3}	W^{-}_{A6}	W^{-}_{B3}	W^{-}_{B6}	W^{-}_{C3}	W^{-}_{C6}	W^{-}_{D3}	W^{-}_{D6}

NOISE – $N^{\text{SUM OR POLARITY}}_{\text{MAT'L. COMB.} \quad \text{RING NO.}}$

FRICTION – $F^{\text{BRUSH POLARITY}}_{\text{MAT'L. COMB.} \quad \text{RING NO.}}$

WEAR – $W^{\text{BRUSH POLARITY}}_{\text{MAT'L. COMB.} \quad \text{RING NO.}}$

TABLE II

DATA FROM 12% MoS_2, 3% GRAPHITE, 85% Ag COMPOSITES
(E S 383)

Shear Strengths, PSI

	Transverse	Normal	Long.
SAMPLE A	7330	5782	2742
	6700	5088	2971
	6700	4857	3200
	6660	5181	2732
	7170	4940	2732
	6910	5185	2846
	7010	5157	3713
	7350	6188	3713
	7270	4240	3713
	(7010)	(5180)	(3150)
SAMPLE B	7010	5501	2572
	7260	5663	2805
	7880	5501	2650
	(7380)	(5560)	(2680)
AVG	[7100]	[5270]	[3030]

Density (Percent Theoretical)

SAMPLE A		SAMPLE B
92		93
89		86
90		91
(90)		(90)
	[90]	

Resistivity (ohm inches X 10^{-6})

Transverse	2.5
Normal	2.2
Longitudinal	6.9
	[3.9]

( ) Sample Mean

[ ] Lot Mean

TABLE III

DATA FROM 15% $NbSe_2$, 3% GRAPHITE, 82% Ag COMPOSITES (E S 384)

Shear Strengths, PSI

	Transverse		Normal		Longitudinal	
	Lot #1	Lot #2	Lot #1	Lot #2	Lot #1	Lot #2
SAMPLE A	8470	8880	8090	9830	6330	6990
	7410	8300	7850	8770	6000	7230
	8000	8760	7380	9360	5830	6600
	8360	(8650)	7380	(9320)	6160	(6940)
	7650		7450		7090	
	7300		7740		5830	
	(7870)		(7650)		(6210)	
SAMPLE B	7720	6510	7550	8190	5570	5570
	7840	7210	7430	7490	5900	5650
	7960	7090	6940	7730	5410	4840
	8080	6740	7180	8430	5240	5730
	7480	7330	6450	7840	5410	5080
	7960	6510	6820	7840	5490	5360
	(7840)	7090	(7060)	8080	(5500)	5320
		6860		7490		5000
	[7850]	6510	[7360]	7490	[5860]	5760
		(6870)		(7840)		(5370)
		[7320]		[8210]		[5760]

Density (Percent Theoretical)

Lot #1			Lot #2	
Sample A	Sample B		Sample A	Sample B
87%	88%		91%	86%
85%	90%		92%	90%
91%	92%		92%	92%
(88%)	(90%)		(92%)	(89%)
[89%]			[91%]	

Resistivity (ohm inches X 10^{-6})

	Transverse		Normal		Longitudinal	
	Lot #1	Lot #2	Lot #1	Lot #2	Lot #1	Lot #2
SAMPLE A	---	3.1	9.6	4.4	13.3	7.1
SAMPLE B	6.8	9.7	4.5	7.3	9.1	10.9
	[6.8]	[6.4]	[7.1]	[5.9]	[11.2]	[9.0]

( ) - Sample Mean

[ ] - Lot Mean

TABLE IV

SUMMARY OF PHYSICAL DATA FOR COMPOSITE BRUSH MATERIALS

12% MoS_2, 3% Graphite, 85% Ag (ES383)			
	Average Strengths, PSI	Resistivity (Ohm-In. X 10^{-6})	Density
Transverse	7100	2.5	
Normal	5270	2.2	90
Longitudinal	3030	6.9	
Grade Mean	[5130]	[3.9]	[90]

15% $NbSe_2$, 3% Graphite, 82% Ag (ES384)						
	Average Strengths, PSI		Resistivity (Ohm-In. X 10^{-6})		Density, % Theoretical	
	Lot #1	Lot #2	Lot #1	Lot #2	Lot #1	Lot #2
Transverse	7850	7320	6.8	6.4		
Normal	7360	8210	7.1	5.9		
Longitudinal	5860	5760	11.2	9.0		
Lot Mean	(7020)	(7100)	(8.4)	(7.1)	(89)	(91)
Grade Mean	[7060]		[7.8]		[90]	

( ) - Lot Mean   [ ] - Grade Mean

APPENDIX A

COMPOSITE BRUSH FOR SPACE ENVIRONMENTS ES383

1.0 Scope:

1.1 This specification establishes the requirements for a composite brush that must be self lubricating in both space and ground environments. It is intended for power or instrument grade brushes with volumes less than 1 in^3.

1.2 All material furnished under this specification must conform to the standards herein described unless otherwise stated on the drawing or in the Purchase Order.

2.0 Applicable Specifications:

2.1 ANSI C 64.1-1970 (NEMBA CB1-1970) forms a part of this specification where applicable and non-conflicting.

2.2 ANSI Z 23.1-1961 (ASTM E11)

3.0 Requirements:

3.1 Chemical Composition (wt.%) - Best commercial grade materials shall be used.

12.0 $\pm$ 1% MoS_2

3.0 $\pm$ 0.5% Graphite (Natural, Ceylon or Madagascar Origin).

Balance - fine silver

3.2 Particle Size

3.2.1 MoS_2 - 100% of the particles shall pass through a 325 mesh (44μ) screen.

3.2.2 Graphite - 100% of the particles shall pass through a 100 mesh (149μ) screen and 50% shall pass through a 325 mesh (44μ) screen.

3.2.3 Silver-Maximum of 12% (wt.) shall remain on 325 mesh screen; maximum of 1% (wt.) shall remain on a 200 mesh screen; 100% must pass through a 100 mesh screen.

3.3 Density:

Composite shall be at least as dense as 85% - 95% of the theoretical density, i.e., greater than 7.12 $gram/cm^3$.

3.4 Backing:

When required by drawing, a metallic backing shall be incorporated into the brush so that it may be soldered. The backing cannot be formed by electroplating. There shall be no apparent cracks or separation of the composite and backing when the interface is viewed at 50X.

3.5 Workmanship:

Brushes shall be structurally sound. All brushes shall be free from cracks, seams, voids, inclusions, segregation and other defects upon examination of a sample at 30X. The composite shall be free of visible corrosion products at 30X.

3.6 Microstructure:

Constituents of the composite shall be uniformly distributed when a polished section is viewed at 75X. Particles shall not have been dislodged from edges of the composites as a result of handling after the forming operations. Metallic particles shall not have been dislodged by normal metallographic grinding and polishing operations. Bonding shall be evident between metal particles.

3.7 Crystalline Structure:

The lamellar structure of the MoS_2 or graphite shall not have been destroyed by the manufacturing process.

3.8 Composite Strength:

3.8.1 Normal, longitudinal and transverse shear planes shall be as defined in Figure A-1.

3.8.2 The shear strength in the transverse plane shall be 6500 psi, minimum.

3.8.3 The shear strength in the normal plane shall be 4500 psi, minimum.

3.8.4 The shear strength in the longitudinal plane shall be 2700 psi, minimum.

3.9 Processing:

3.9.1 Lubricants

No lubricants shall be applied to powders that are not part of the desired composite (i.e., MoS_2 and graphite). No sulfurized lubricants may be used on the forming dies.

3.9.2 Scrap material shall not be used in the manufacture of this product.

3.9.3 No binders shall be used.

3.9.4 Processing shall be such as to prevent decomposition of lubricants.

3.10 Specific Resistance: $9X10^{-6}$ Ohm-Inches (maximum)

4.0 Inspection and Testing:

4.1 The vendor shall perform, or have performed at least these minimum tests to insure conformity to this standard.

4.1.1 Visual inspection at 30X to insure compliance with Paragraph 3.5 of this standard.

4.1.2 Check of dimensions as defined on Engineering Drawing.

4.1.3 Determination of density, g/cm^3. Backing material shall not be included in density computation.

4.2 Poly-Scientific may perform any or all of the following tests upon receipt of material furnished to this specification.

4.2.1 Spectrographic Analysis (Paragraph 3.1)

4.2.2 Dimensional check (Engineering Drawing).

4.2.3 Microscopic examination (Paragraph 3.4 and 3.5)

4.2.4 Metallographic examination (Paragraph 3.4 and 3.6)

4.2.5 Measurement of Density (Paragraph 3.3)

4.2.6 Measurement of composite strength (Paragraph 3.8)

4.2.7 X-ray diffraction analysis (Paragraph 3.7)

5.0 Package and Delivery:

5.1 The material furnished under this specification shall be packed in such a way as to insure conformity to the standards herein described upon arrival at Poly-Scientific.

5.2 Packing should be such that danger of damaging upon unpacking is a minimum.

5.3 Deliveries shall be made with due precaution to insure safe, rapid and economic transfer.

6.0 Ordering:

6.1 An order for material under this specification shall include a Poly-Scientific Engineering Drawing with all tolerances defined and a copy of this specification.

6.2 Orders shall specify applicable revision of specification.

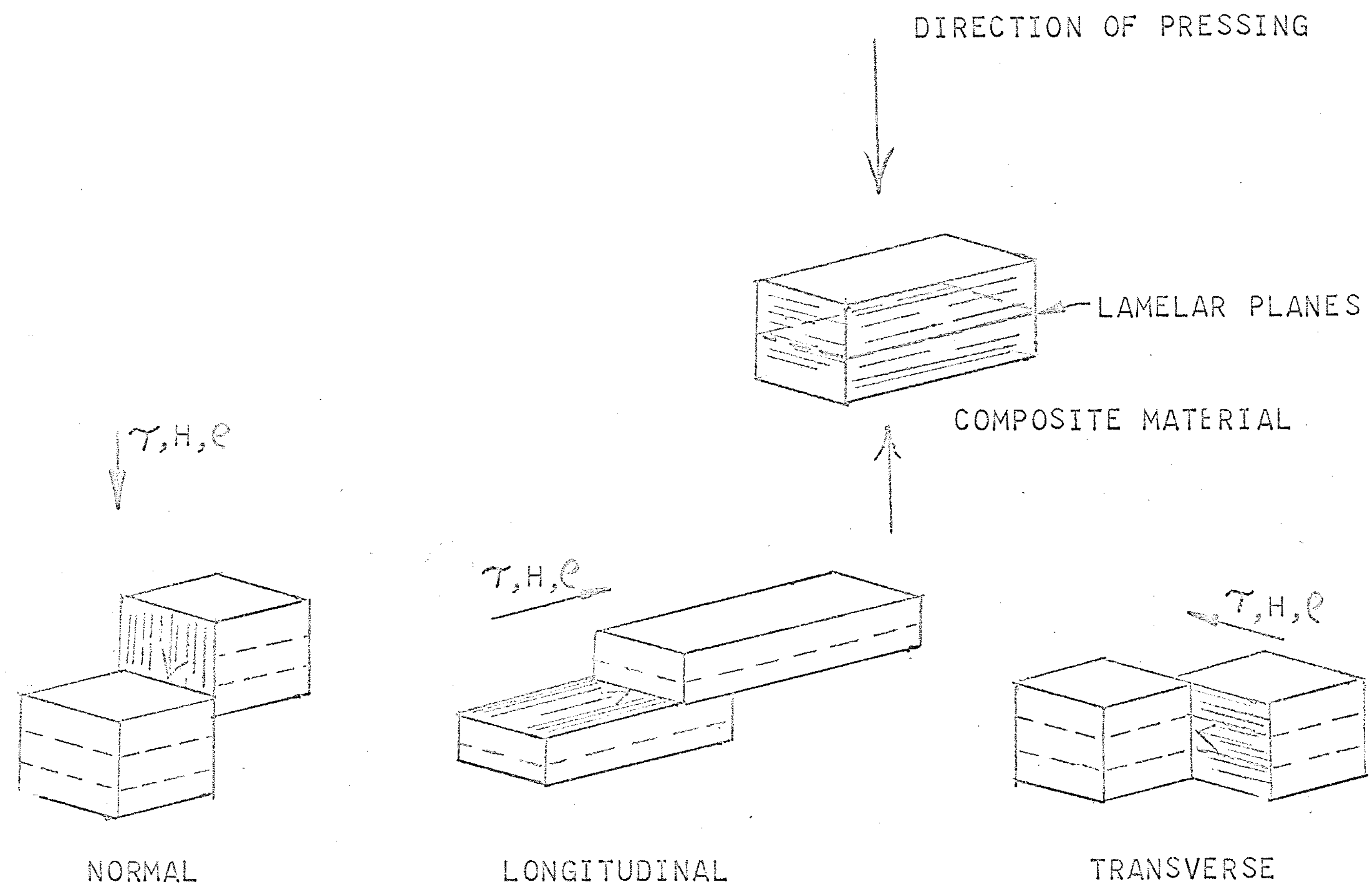

FIGURE A-1. DEFINITION OF TEST PLANES AND DIRECTIONS

APPENDIX B

COMPOSITE BRUSH FOR SPACE ENVIRONMENTS ES384

1.0 Scope:

1.1 This specification establishes the requirements for a composite brush that must be self lubricating in both space and ground environments. It is intended for power or instrument grade brushes with volumes less than 1 in^3.

1.2 All material furnished under this specification must conform to the standards herein described unless otherwise stated on the drawing or in the Purchase Order.

2.0 Applicable Specifications:

2.1 ANSI C 64.1-1970 (NEMBA CB1-1970) forms a part of this specification where applicable and non-conflicting.

2.2 ANSI Z 23.1-1961 (ASTM E11)

3.0 Requirements:

3.1 Chemical Composition (wt.%) - Best commercial grade materials shall be used.

$15.0 \pm 1\%$ $NbSe_2$

$3.0 \pm 0.5\%$ Graphite (Natural Ceylon or Madagascar Origin).

Balance - fine silver

3.2 Particle Size

3.2.1 $NbSe_2$ - 100% of the particles shall pass through a 325 mesh (44μ) screen.

3.2.2 Graphite - 100% of the particles shall pass through a 100 mesh (149μ) screen and 50% shall pass through a 325 mesh (44μ) screen.

3.2.3 Silver - Maximum of 12% (wt.) shall remain on 325 mesh screen; maximum of 1% (wt.) shall remain on a 200 mesh screen; 100% must pass through a 100 mesh screen.

3.3 Density

Composite shall be at least as dense as 85% - 95% of the theoretical density, i.e., greater than 7.18 gram/cm^3.

3.4 Backing

When required by drawing a metallic backing shall be incorporated into the brush so that it may be soldered. The backing cannot be formed by electroplating. There shall be no apparent cracks or separation of the composite and backing when the interface is viewed at 50X.

3.5 Workmanship

Brushes shall be structurally sound. All brushes shall be free from cracks, seams, voids, inclusions, segregation and other defects upon examination of a sample at 30X. The composite shall be free of visible corrosion products at 30X.

3.6 Microstructure

Constituents of the composite shall be uniformly distributed when a polished section is viewed at 75X. Particles shall not have been dislodged from edges of the composites as a result of handling after the forming operations. Bonding shall be evident between metal particles.

3.7 Crystalline Structure

The lamellar structure of the $NbSe_2$ or graphite shall not have been destroyed by the manufacturing process.

3.8 Composite Strength

3.8.1 Normal, longitudinal and transverse shear planes shall be as defined in Figure B-1.

3.8.2 The shear strength in the transverse plane shall be 7000 psi, minimum

3.8.3 The shear strength in the normal plane shall be 6600 psi, minimum.

3.8.4 The shear strength in the longitudinal plane shall be 5200 psi, minimum.

3.9 Processing

3.9.1 Lubricants

No lubricants shall be applied to powders that are not part of the desired composite (i.e., $NbSe_2$ and graphite). No sulfurized lubricants may be used on the forming dies.

3.9.2 Scrap material shall not be used in the manufacture of this product.

3.9.3 No binders shall be used.

3.9.4 Processing shall be such as to prevent decomposition of lubricants.

3.10 Specific Resistance: $12X10^{-6}$ Ohm-Inches (Maximum)

4.0 Inspection and Testing

4.1 The vendor shall perform, or have performed at least these minimum tests to insure conformity to this standard.

4.1.1 Visual inspection at 30X to insure compliance with Paragraph 3.5 of this standard.

4.1.2 Check of dimensions as defined on Engineering Drawing.

4.1.3 Determination of density, g/cm^3. Backing material shall not be included in density computation.

4.2 Poly-Scientific may perform any or all of the following tests upon receipt of material furnished to this specification.

4.2.1 Spectrographic Analysis (Paragraph 3.1)

4.2.2 Dimensional check (Engineering Drawing)

4.2.3 Microscopic examination (Paragraph 3.4 and 3.5)

4.2.4 Metallographic examination (Paragraph 3.4 and 3.6)

4.2.5 Measurement of density (Paragraph 3.3)

4.2.6 Measurement of composite strength (Paragraph 3.8)

4.2.7 X-ray diffraction analysis (Paragraph 3.7)

5.0 Package and Delivery:

5.1 The material furnished under this specification shall be packed in such a way as to insure conformity to the standards herein described upon arrival at Poly-Scientific.

5.2 Deliveries shall be made with due precaution to insure safe, rapid and economic transfer.

6.0 Ordering:

6.1 An order for material under this specification shall include a Poly-Scientific Engineering Drawing with all tolerances defined and a copy of this specification.

6.2 Orders shall specify applicable revision of specification.

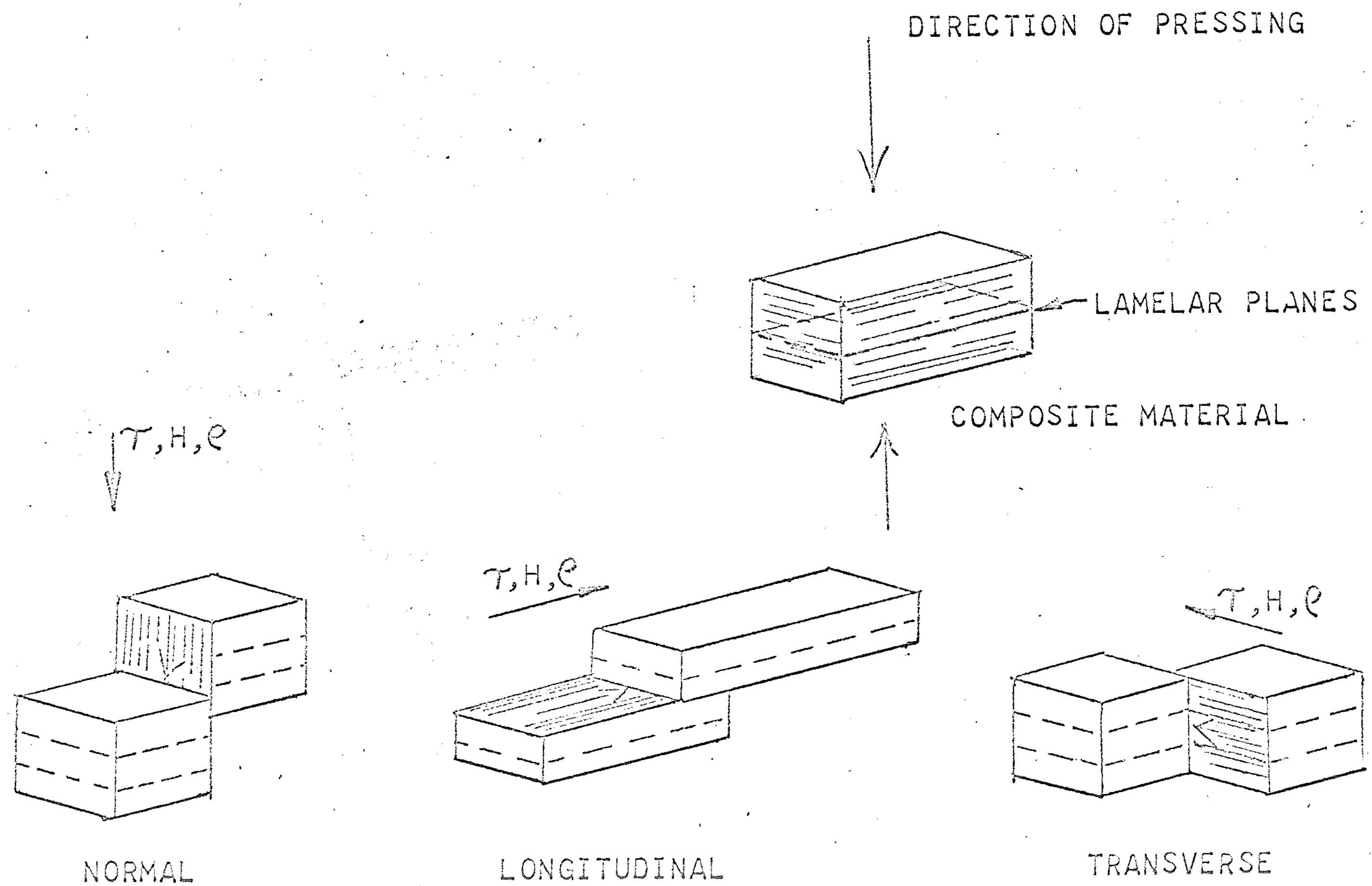

FIGURE B-1. DEFINITION OF TEST PLANES AND DIRECTIONS

REFERENCES

1. Glossbrenner, E. W., "Slip Ring Assemblies for Spacecraft Devices", Proceedings From Seminar on Sliding Electrical Contacts In Vacuum And Space, Sponsored by Virginia Polytechnic Institute and Poly-Scientific Division, Litton Industries, October 1, 1969.

2. Mayer, R. W., "Evaluation of Slip Rings for Communication Satellite Applications", Ball Brothers Research Corporation, Report #F69-07, December 23, 1969.

3. Pentlicki, C. J. and Glossbrenner, E. W., "The Testing of Contact Materials for Slip Ring And Brushes For Space Application" to be presented at the Seventeenth Annual Holm Seminar on Electric Contact Phenomena.