Institute of Paper Science and Technology

PHYSICAL PROPERTIES OF PRINTED BANK NOTES SUBJECTED TO CRUMPLE TESTING

PROJECT 3721

by

Maclin S. Hall and Pierre H. Brodeur

May 20, 1991

Atlanta, Georgia

THE INSTITUTE OF PAPER SCIENCE AND TECHNOLOGY

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Report Submitted to

OFFICE OF RESEARCH AND TECHNOLOGY DEVELOPMENT

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ABSTRACT

Physical properties of uncirculated printed bank notes subjected to the BEP crumple test for ink adhesion have been evaluated. In order to do so, non-destructive and destructive measurements were collected at various stages during the test. Since no database on physical properties of crisp and used bills was available for comparison, measurements were performed as well on crisp bills and bills withdrawn from circulation and sorted by a reconciler machine. Also, the study was extended to the analysis of crisp bills subjected to machine and cross-machine direction flex testing.

It is found that major changes in the physical properties of crumpled bills occur during the first 8 stages of the crumple test. Properties either remain constant or slowly vary thereafter and up to the last stage. Dimensional changes are significant. Since there are no equivalent dimensional changes for used or flexed bills, physical properties cannot easily be compared. Nevertheless, it appears that the crumple test can predict the thickness direction elastic properties of used bills.

Flex testing provides a technique for causing more gradual changes in the physical properties of bills than provided by the crumple test. However, flex testing with the NBS Flex Tester is difficult and inconvenient with cut bills and in some cases provides questionable results. Uncut bills would be more convenient and provide more accurate results.

INTRODUCTION

The Department of the Treasury, Bureau of Engraving and Printing (BEP), Office of Research and Technology Development, has requested the Institute of Paper Science and Technology (IPST) to investigate physical properties of printed bank notes. The main interest of this study lies in the quantitative evaluation of the BEP crumple durability test for ink adhesion in the portrait area of uncirculated one-dollar notes. In order to follow the progression of damage in the bills during the testing procedure, non-destructive and destructive physical measurements were collected on 10 of the 32 stages required for completion of the test. Measurements were also obtained on crisp and used bills, and crisp bills flexed with the NBS Flex Tester. Selected notes for the study are first introduced in Section A. Then, the research program is presented in Section B. Non-destructive and destructive results are next described and interpreted in Section C.

A. CLASSIFICATION OF THE BILLS AVAILABLE FOR TESTING

The BEP has provided IPST with a total of 500 one-dollar notes. These were initially divided into 3 categories:

- A Series: 100 crisp uncirculated notes.
- B Series: 300 notes withdrawn from circulation by cashiers.
- C Series: 100 notes withdrawn from circulation by a reconciler machine (CVCS).

For the purpose of the study, the C-Series bills were not used, as information on soil level was not available. Thirty-eight bills from the B Series have been discarded for four reasons: excess weight, missing parts, too dirty and use for experimentation. The remaining 262 B-Series bills were sorted by a reconciler machine at the Atlanta Federal Reserve. The classification is:

- Soil level ≥ 9 "fit":	117
- 5 ≤ Soil level ≤ 8 "unfit":	100
- Soil level < 5 "unfit":	20
- Miscellaneous defects:	13
- Crumpled in CVCS	12
Total	262

200 of these bills were selected for testing. They are described as follows:

- D Series: 100 bills (5 ≤ soil level ≤ 8)
- E Series: 100 bills (soil level ≥ 9)

In summary, 300 of the 500 available bills were used in this study. They are identified as the A Series (crisp bills), E Series (soil level ≥ 9) and D Series (5 ≤ soil level ≤ 8).

B. RESEARCH PROGRAM

The research program is divided into four distinct phases. The first phase involve non-destructive and destructive physical measurements on A-, E- and D-Series bills. The purpose of such measurements is to establish a database on physical properties of crisp and used bills. The second and third phases involve crumple and flex testing of crisp bills, respectively. The last phase involves exploratory observations with advanced techniques such as image analysis and scanning electron microscopy analysis. When necessary, experimental procedures are briefly described.

1. Non-Destructive and Destructive Measurements on Crisp and Used Bills

1.1 Optical Properties

Optical measurements were performed on crisp bills only. Properties such as opacity, brightness, fluorescence and light scattering were evaluated. While opacity, brightness and fluorescence were analyzed at three different areas as depicted in Figure 1, light scattering was analyzed in the portrait area only. All measurements were performed in agreement with TAPPI standard procedures.

1.1.1 Opacity (40 "A" Series bills tested: A-40)

1.1.2 Brightness (A-50)

1.1.3 Fluorescence (A-50)

1.1.4 Light scattering (A-10)

1.2 Basic Physical Properties

Weight, soft-platen caliper, surface roughness and porosity were measured for all A-, D- and E-Series bills. Basis weight (grammage) and density were not evaluated, as dimensions of used bills vary and cannot easily be measured.

1.2.1 Weight (A-100, D-100, E-100)

1.2.2 Soft-Platen Caliper (A-100, D-100, E-100; portrait area only)

The soft-platen caliper was determined with the IPST thickness direction (ZD) longitudinal sound velocity instrument (see below). Soft-rubber covered transducers are used in this apparatus to overcome surface roughness of paper. Hence, the soft-platen caliper is less sensitive to surface roughness than the hard-platen caliper.

1.2.3 Surface Roughness (A-100, D-100, E-100; portrait area only)

1.2.4 Porosity (A-100, D-100, E-100; portrait area only)

The Parker Print Surf instrument was used to measure surface roughness and porosity (settings: roughness [5 KGF/cm^2]; porosity [20 KGF/cm^2]). Measurements were repeated three times on each bill to improve accuracy.

1.3 Sound Velocity Measurements (Elastic Stiffness Properties)

Elastic stiffness properties of paper can be determined from non-destructive sound velocity measurements of ultrasonic waves propagating through paper. Elastic stiffness properties correlate well with destructively obtained strength properties such as tensile strength. Due to the restrictive dimensions of dollar bills, measurements were gathered along cross-machine and thickness directions only.

1.3.1 ZD Longitudinal Sound Velocity (A-100, D-100, E-100; portrait area only)

1.3.2 CD Longitudinal Sound Velocity (A-10, D-100, E-100; portrait area)

1.3.3 CD Shear Sound Velocity (A-10, D-100, E-100; portrait area)

1.4 Tensile Strength

Due to the limited number of specimens available for crumple and flex testing (see below), tensile strength measurements were limited to three measurements in MD and CD directions. Preliminary measurements were performed on one crisp bill only (enough paper to get three 15 mm wide strips per direction). Since MD tensile strength is large for bank note paper, serrated surface clamps were used as clamping devices to avoid breaking at clamp locations.

1.4.1 MD Tensile Strength (3 measurements)

1.4.2 CD Tensile Strength (3 measurements)

1.5 Short-Span Compressive Strength (STFI)

1.5.1 MD Compressive Strength (10 measurements)

1.5.2 CD Compressive Strength (10 measurements)

2. Crumple Testing

Forty crisp bills from A Series were used in the crumple test. The test was conducted in such a way as to collect data for 10 of the 32 stages. Thus, four bills per stage were available for analysis. Selected stages are: 1X, 2X, 4X, 8X, 12X, 16X, 20X, 24X, 28X and 32X. Since dimensional changes occur during the test (see Figure 2), optical properties were not determined because a comparative analysis with crisp bill data would be meaningless. No attempt was made to mechanically stretch or level out the bills. Also, cross-machine sound velocity measurements were not done because the tested portrait area is smaller than the minimum area required in the measurement procedure.

2.1 Non-Destructive Measurements (4 specimens available per stage)

2.1.1 Soft-Platen Caliper

2.1.2 Surface Roughness

2.1.3 Porosity

2.1.4 ZD Longitudinal Sound Velocity

2.2 Destructive Measurements

2.2.1 MD and CD Tensile Strength (3 measurements per stage)

2.2.2 MD and CD Short-Span Compressive Strength (10 measurements per stage)

3. MD and CD Flex Testing

As mentioned in the Introduction, the NBS Flex Tester was used in this test. Experiments were conducted in both machine and cross-machine directions. 22 crisp specimens were used in each case. In order to follow the progression of damage in the bills, measurements were recorded for 100, 200, 400, 800, 1200, 1600, 2000, 2400, 2800 and 3200 flexes.

3.1 Non-Destructive Measurements

3.1.1 Opacity (4 specimens; portrait area)

3.1.2 Brightness with UV (4 specimens; portrait area)

3.1.3 Light Scattering (1 specimen; portrait area)

3.1.4 Surface Roughness (4 specimens; portrait area)

3.1.5 Porosity (4 specimens; portrait area)

3.1.6 ZD Longitudinal Sound Velocity (4 specimens; portrait area)

3.1.7 CD Longitudinal Sound Velocity (4 specimens)

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3.2.2 MD and CD Short-Span Compressive Strength (10 measurements per stage)

4. Exploratory Observations

4.1 Image Analysis

4.2 Scanning Electron Microscopy Analysis

C. RESULTS

1. Non-Destructive Measurements on Crisp and Used Bills

1.1 Optical Properties

Opacity measurements for three different areas (see Figure 1) of crisp bills are presented in Figures 3, 4 and 5). Although great care was taken to gather measurements over the same areas for different bills, the distributions are not normal. This is an indication that such measurements on printed bank notes are position sensitive. Best results are obtained with area #2, i.e., an area without black ink and minimum green ink. If these measurements were to be repeated to study printing variations, a sample holder would be required to achieve excellent positioning of the bills. Additional measurements on used bills would require a large number of bills to get meaningful statistics.

Brightness measurements with UV included and UV excluded (fluorescence) for all three areas tested are displayed in Figures 6 and 7 (area 1), 8 and 9 (area 2) and 10 and 11 (area 3), respectively. Brightness measurements appear to be less sensitive to position than opacity measurements. UV filtering does not significantly affect brightness for any given area, suggesting that fluorescence is weak and constant.

1.2 Basic Physical Properties

Weight for crisp bills and bills sorted with soil level ≥ 9 and with soil level ≥ 5 are depicted in Figure 12, 13 and 14, respectively. While the crisp bill distribution is sharp, distributions for used bills are wider. Results indicate that weight is independent of the soil level. This suggests that original material is replaced by foreign material in approximately equal weight amounts. Additional measurements as a function of the soil level would be required to further assess this observation.

Soft-platen caliper results are shown in Figures 15, 16 and 17. We can observe that there is a net caliper increase for used bills (up by 25 %). The distribution for bills sorted with soil level ≥ 9 appears to be an intermediate distribution between crisp and dirty bill distributions. We should remember here that soft-platen caliper is less sensitive to surface roughness than hard-platen caliper.

Surface roughness distributions for A, E and D Series bills are presented in Figures 18, 19 and 20, respectively. As one should expect, roughness increases for sorted bills still acceptable for circulation (E Series). This is a consequence of wrinkling and crumpling effects. However, for bills declared unfit for circulation (D Series), roughness decreases because crumpling is extensive and foreign material smooths out thickness variations.

Porosity measurements are shown in Figures 21, 22 and 23. They indicate that porosity decreases for used bills. Also, porosity does not change significantly as a function of the soil level. This suggests that porosity could decrease rapidly as crisp bills are being used and would remain constant thereafter. When comparing weight and porosity for crisp and used bills, it is observed that weight and porosity are inversely related: an increase in weight means a decrease in porosity. Porosity data as a function of roughness data for bills sorted with soil level ≥9 and with soil level ≥5 are shown in Figure 24 and 25, respectively. It appears that there is a good correlation for bills sorted with soil level ≥9 only.

1.3 Sound Velocity Measurements (Elastic Stiffness Properties)

Thickness direction (ZD) sound velocity measurements are presented in Figures 26, 27 and 28. We can observe that there is a net decrease in ZD velocity for used bills. This means that thickness direction elastic stiffness properties decrease for used bills. Since there is a slight change for bills sorted with soil level ≥ 9 and with soil level ≥ 5, it is suggested that ZD stiffness changes are due to early wrinkling and crumpling effects. Additional measurements for CD longitudinal and shear velocities are shown in Figures 29, 30 and 31, and 32, 33 and 34, respectively. As for Z-direction measurements, in-plane elastic stiffness properties are sharply reduced for used bills. Available data do not permit establishing a correlation between elastic properties (ZD and CD) and the soil level. Since porosity decreases for used bills, we can postulate that porosity level and elastic stiffness properties are related. This is indeed shown in Figure 35 for soil level ≥ 9.

2. Crumple Testing

Photographs of crumpled notes for the 10 stages analyzed in this study were presented earlier in Figure 2. As seen in this Figure, significant dimensional changes occur during the test.

2.1 Non-Destructive Measurements

Caliper, surface roughness, porosity and ZD longitudinal sound velocity were measured as a function of crumple stage. Results are shown in Figures 36, 37, 38 and 39, respectively. Average data for crisp notes are represented by an empty circle at stage "0". Error bars represent standard deviations. An overall analysis of these results shows that major physical property changes occur during the first 8 stages: While caliper, roughness and porosity increase, ZD sound velocity decreases.

When compared to measurements available for soil level, caliper increases for crumpled and used bills but for different reasons: dimensional changes (wrinkle effects) in the first case and accumulation of foreign material in the second case (see Figures 12, 13, 14 and 36). Thus, there is also no correlation for caliper.

There is good agreement between surface roughness for soil level ≥9 bills and stage 3 crumple bills (see Figures 15, 16, 17, and 37); in each case, the roughness level is approximately 7.95 micrometer). However, since roughness decreases for bills sorted with soil level ≥ 5 while further increasing in the crumple test, there is no correlation between crumpled and used bills regarding roughness. Porosity does not correlate at all as it increases for crumpled bills but decreases for used bills (see Figures 21, 22, 23 and 38).

A correlation can be established between crumpled and used bills for ZD longitudinal sound velocity only (see Figures 24, 25, 26, and 39). In both cases, velocity decreases from 0.58 km/sec (crisp bills) to 0.35 km/sec (bills sorted with soil level ≥ 9). This shows that a minimum ZD stiffness level is obtained for crumpled and used bills. As ZD elastic stiffness is related to ZD velocity, additional measurements as a function of the soil level are necessary to conclude that the crumple test predicts the ZD elastic stiffness of used bills.

2.2 Destructive Measurements

Tensile strength in machine and cross-machine directions of crumpled bills was analyzed. Results are presented in Figure 40. As one should expect, tensile strength decreases as a function of the number of crumple stages. This is in agreement with ZD sound velocity measurements. No tensile strength measurements collected from used bills are available for comparison.

MD and CD STFI short-span compressive strengths were also evaluated (see Figure 41). Measurements indicate that compressive strength sharply decreases during the first 4 stages. Compressive strength is so weak after the fourth stage (especially CD) that it can no longer be determined. Results correlate to surface roughness and porosity measurements (Figures 37 and 38).

3. MD and CD Flex Testing

In order to evaluate the effects of flexing crisp bills, the NBS Flex Tester was used to flex bills in the top-to-bottom machine direction (MD) or in the end-to-end cross-machine direction (CD). Four bills were evaluated after 100, 200, 400, 800, 1200, 1600, 2000, 2400, 2800, and 3200 double flex cycles for both MD and CD flex directions.

Because we had only cut bills, it was necessary to tape bills together for flexing. Cellophane tape was tried but would soon break due to flexing. A masking tape was selected because it was found to survive extensive flexing and could be peeled off the bills before testing and regrouping. There was some slippage and the possibility of residue on the bills from the adhesive. Flexing in the MD direction was the most difficult because four bills were taped together and the length of new bills slightly exceeded the width of the flex fixture. The 0.32 cm diameter rollers were used. Only the weight of the holder was used for CD flexing, but the two supplied weights were added for the MD flexing.

While using tape on the bills, it was noted that a significant amount of the printing is removed from the bills with the tape. Some exploratory trials indicated that the amount of printing removed increased as the number of flexes increased. A tape test was made on one sample of each of the flex stages. Some increase in ink removal was observed but was less than expected, and smearing of the image was noted. This suggests that gum from the masking tape was smeared onto the bills and ink was removed from the bill during flexing. In fact, some isolated bumps of ink were found on the flex rods during the MD flexing.

The above observations suggest that, provided uncut bills or alternate assembly and flexing techniques are used, a low number of flexes (less than 1000) followed by tape removal of "loose" ink, might be developed into a quantitative test for the probable performance of the printing on bank notes.

3.1 Non-Destructive Measurements (MD and CD Flex Testing)

3.1.1 Opacity (portrait area)

The TAPPI opacity was measured for three samples for each stage of MD flexing and for four samples for each stage of CD flexing. The averages and standard deviations are plotted in Figures 42 and 43, respectively. There is very little change and no clear trend; however, all averages are slightly greater than that measured for crisp bills.

3.1.2 Brightness (portrait area)

The brightness was measured for three samples for each stage of MD flexing and for four samples for each stage of CD flexing. The averages and standard deviations are plotted in Figures 44 and 45, respectively. All points are above that for crisp bills and brightness increases with flexing. This is consistent with loss of ink.

3.1.3 Light Scattering

The light scattering coefficient was measured on ten crisp bills and then measured on one of these bills after each stage of MD flexing. The data are shown in Figure 46. There is no significant change or trend in these data. Four bills in the D series were measured: D33 = 11.69, D43 = 11.45, D45 = 11.37, and D58 = 16.05. A significant change is measured for these "unfit" bills. D58 has a particularly obvious loss of ink.

3.1.4 Surface Roughness (portrait area)

The surface roughness was measured for four samples for each stage of MD and CD flexing. The averages and standard deviations are plotted in Figures 47 and 48, respectively. The plots of roughness are nearly the same for MD and CD flexing. There is an initial increase followed by a gradual increase in roughness with flexing.

3.1.5 Porosity (portrait area)

The porosity was measured for four samples for each stage of MD and CD flexing. The averages and standard deviations are plotted in Figures 49 and 50, respectively. Although the plots for MD and CD flexing appear similar, the variation of the measurements is very large. Tape residue on the flexed bills may have affected these results.

3.1.6 ZD Longitudinal Sound Velocity (portrait area)

One sample from each stage of MD and CD flexing was measured for ZD longitudinal sound velocity and for caliper. No meaningful changes in caliper were observable for these samples. The averages of two velocity measurements of each sample are plotted in Figure 51. There is an initial decrease and then an apparent leveling off with increased flexes. MD flexing causes a greater decrease in the ZD sound velocity than that caused by CD flexing.

3.1.7 CD Longitudinal Sound Velocity

The CD longitudinal sound velocity was measured for four samples for each stage of MD and CD flexing. The averages and standard deviations are plotted in Figures 52 and 53, respectively. The data for CD flexing in Figure 53 show a slight decrease with flexes and very small variation in the readings. However, the MD flex data show very large variations in the readings. This can be attributed to the difficulty in MD flexing of cut bills. Some of the bills showed visible wrinkles. The CD longitudinal velocity is particularly sensitive to wrinkles and fold across the measurement path.

3.1.8 CD Shear Sound Velocity

The CD shear sound velocity was measured for four samples for each stage of MD and CD flexing. The averages and standard deviations are plotted in Figures 54 and 55, respectively. The data for CD flexing in Figure 55 again have less variation than the MD flex data in Figure 54. Both show a decrease in flexes, with a greater decrease for the apparently more damaging MD flexing.

3.2 Destructive Measurements (MD and CD Flex Testing)

3.2.1 MD and CD Flexing - Tensile Strength

One sample from each stage of MD flexing was measured for MD and CD tensile strength. The averages and standard deviations of three measurements for each sample are plotted in Figure 56. There is a decrease with flexing for the MD tensile strength, but very little change in the CD tensile strength.

One sample from each stage of CD flexing was measured for MD and CD tensile strength. The averages and standard deviations of three measurements for each sample are plotted in Figure 57. The MD tensile strength is slightly higher here than for MD flexing shown in Figure 56. The trend is slightly down with increased flexing. Again there is little change in the smaller CD tensile strength values.

3.2.2 MD and CD Flexing - Short-Span Compression

One sample from each stage of MD flexing was measured for MD and CD short-span compressive strength. The averages and standard deviations of ten measurements for each sample are plotted in Figure 58.

One sample from each stage of CD flexing was measured for MD and CD short-span compressive strength. The averages and standard deviations of ten measurements for each sample are plotted in Figure 59. A comparison of Figures 58 and 59 shows that the CD compressive strength is about the same for both MD and CD flexing with a more apparent down trend with flexing for MD flexing. However, the MD compressive strength is decreased much more by MD flexing.

4. Exploratory Observations

4.1 Image Analysis

In order to evaluate the potential for image analysis as a mean to evaluate ink adhesion on dollar bills, one crisp bill and one used bill were tested. In both cases, the same sub-area of the portrait area (shoulder region) was scanned with an image analyzer system. 512 X 512 pixels images with 128 gray levels resolution were recorded. Both images could be displayed on a computer shown in Figure 60. Since the chosen area is printed with black ink, it is not surprising to observe that the crisp bill is darker than the used bill.

It is believed that this technique could be used on crumpled bills, providing that they are uncrumpled (back to original dimensions) before analysis. Pattern recognition techniques could be implemented to evaluate crumpled bills with standards.

4.2 Scanning Electron Microscopy

Scanning electron microscopy was performed on one crisp bill and two crumpled bills (stage 1 and stage 32): "A Z-directional section was cut from each sample and mounted with double-sided sticky tape onto an aluminum SEM stub. The section removed from each currency sample was from the facial region. A freeze fractured cross-section was also taken from each of the three samples. The cross-section for the sample#49 (crisp bill) is in the MD direction and the cross-sections for samples #53 (stage #1) and #89 (stage #32) are both in the CD direction. The cross-sections were mounted such that the 'President side' of the currency is facing the annotation on each SEM micrograph.

"A JEOL 35C scanning electron microscope was used to collect the SEM images. The experimental parameters included a 15 kV primary accelerating voltage and about 500 pA of cup current. Secondary electrons were collected from SEM images. The magnifications used were 100X and 390X. The accelerating voltage, magnification, sample number and a scale bar are given at the bottom of each photomicrograph (Dr. Lisa D. Detter-Hoskin)."

Analysis of the Z-directional sections for the three specimens shows that the black ink pattern for sample #49 (Figure 61) is not as sharply defined for the stage 1 crumpled bill (Figure 62). The pattern disappears completely after 32 stages (Figure 63); ink particles can be seen in the micrograph.

A comparative analysis of the cross-section micrographs (Figures 64, 65 and 66) is not easy because the samples were not mounted in an identical manner. Also, it would have been preferable to stretch the crumpled bills to their original dimensions before the SEM preparation. Nevertheless, we observe what seem to be delamination effects for samples #53 (Figure 65) and #89 (Figure 66).

SUMMARY AND CONCLUSIONS

Crisp and Used Bills

For the purpose of the study, 100 crisp uncirculated bills, 100 bills sorted with soil level ≥9, and 100 bills sorted with soil level ≥5 have been analyzed.

Optical property measurements on crisp bills have shown that opacity is very position sensitive. Brightness does not correlate with opacity. Brightness with UV and without UV (fluorescence) does not change significantly, indicating that fluorescence is constant and weak.

Optical measurements have not been performed on used bills. Since printing variations are important for these bills, accurate positioning of the bills would be necessary in order to get reliable results.

Weight is increasing for used bills. Data show that weight does not correlate with soil level. As a possible explanation, the original material is being replaced by foreign material in approximately equal weights as bills get dirtier.

Soft-platen caliper increases as a function of the soil level (higher for dirtier bills).

Surface roughness increases for bills sorted with soil level ≥ 9 but decreases for bills sorted with soil level ≥ 5. This is most likely a consequence of weaker strength properties for dirtier bills.

Porosity increases as a function of the soil level.

Sound velocity measurements in Z-direction and cross-machine direction show that elastic properties are significantly less for used bills. Correlation with soil level cannot easily be established.

An overall analysis of the measurements on crisp and used bills shows that general trends for physical properties of bills sorted as a function of the soil level cannot easily be determined with only two soil levels.

Crumple Testing

Forty crisp bills were used to assess physical property of crumpled bills during crumple testing. Measurements were performed at stages 1X, 2X, 4X, 8X, 12X, 16X, 20X, 24X, 28X and 32X.

Dimensions of crumpled bills are somewhat operator dependent and no attempt was made to flatten or mechanically stretch the bills to their original dimensions.

Due to significant dimensional changes, optical properties were not measured.

Major changes in physical properties of crumpled bills occur during the first 8 stages.

While caliper, surface roughness and porosity increase as a function of the number of stages, ZD longitudinal sound velocity, tensile strength and short-span compressive strength decrease.

ZD sound velocity measurements are in good agreement with destructive measurements (tensiie strength and compressive strength).

Compressive strength can no longer be measured past the 8th stage, suggesting that compressive strength of crumpled bills weakens very early in the testing procedure.

Data indicate that there is a possible correlation between ZD sound velocity measurements for crumpled and used bills. Additional measurements would be required to assess that crumple testing could be used to predict elastic properties of used bills.

MD and CD Flex Testing

There is very little change in opacity and no clear trend; however, all averages are slightly greater than that measured for crisp bills.

The brightness of flexed bills is greater than that for crisp bills and brightness increases with flexing. This is consistent with loss of ink.

No significant change or trend was observed in the scattering coefficient data (values 7.5 to 8.0) for MD flexed bills. However, four bills from the D series were measured with values ranging from 11 to 16, showing a significant change in these "unfit" bills.

MD flexing causes a greater decrease in the ZD sound velocity than that caused by CD flexing. However, the ZD sound velocity remained in the general range of the measured for crisp bills.

CD Longitudinal Sound Velocity shows a slight decrease with flexes and very small variation in the readings. However, the MD flex data show very large variations in the readings. This can be attributed to the difficulty in MD flexing of cut bills. Some of the bills showed visible wrinkles. The CD longitudinal velocity is particularly sensitive to wrinkles and folds across the measurement path.

The CD shear sound velocity for CD flexing again has less variation than the MD flex data. Both show a decrease with flexes with a greater decrease for the apparently more damaging MD flexing.

A general observation regarding the sound velocity data is that the values of sound velocity measured for the E series of "unfit" bills were all lower than the ZD, CD longitudinal, or CD shear sound velocity for the flexed bills. Many of the D series of "fit" bills were also lower. This suggests that, although the sound velocity measurements determined changes in the flexed bill, the amount of flexing was insufficient to reduce sound velocities or stiffnesses to the extent observed for circulated bills.

Very little change was observed in the CD tensile strength as a result of MD or CD flexing. The MD tensile strength is slightly less for MD flexing than that for CD flexing and the trend is slightly down with increased flexing. Double flexes up to 3200 are apparently insufficient to cause a significant change in tensile strength.

The CD short-span compressive strength is about the same for both MD and CD flexing with a more apparent down trend with flexing for MD flexing. However, the MD short-span compressive strength is decreased significantly more by MD flexing than by CD flexing.

Exploratory trials suggest the possibility of developing a combination of flex testing and tape removal of "loose" ink into a test for predicting the probable performance of the printing on bank notes.

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John Bobalek and Mark Weiss arranged to loan an NBS Crumpling Device and an NBS Flex Tester to us for this project. They visited IPST to discuss the operation of these devices and the project.

John Bobalek obtained 500 one dollar bills from the Atlanta Federal Reserve Bank for this project. He also made arrangements with James Brown and Joe Hassan for us to have some of these bills sorted on the Bank's CVCS machine. Laurie Crossley came in early one morning to do this for us. We appreciated the cooperation and assistance of all.

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FEDERAL RESERVE NOTE
THE UNITED STATES OF AMERICA
F 73269484 E
F
2
1
F 73269484 E
ONE DOLLAR
THE UNITED STATES OF AMERICA
IN GOD WE TRUST
ONE
3
ONE DOLLAR

Figure 1

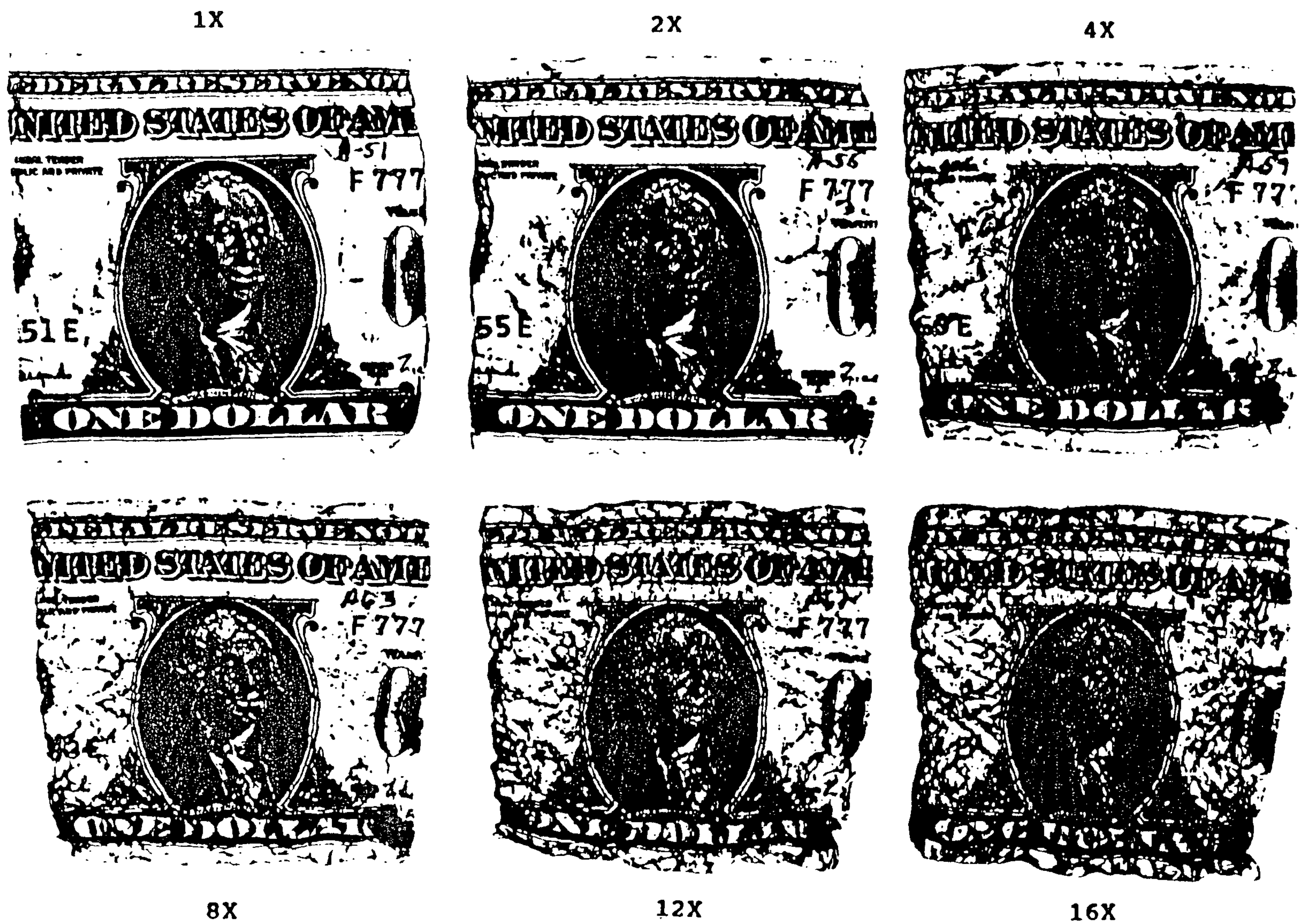


Figure 2

20X 24X 28X

32X

Figure 2

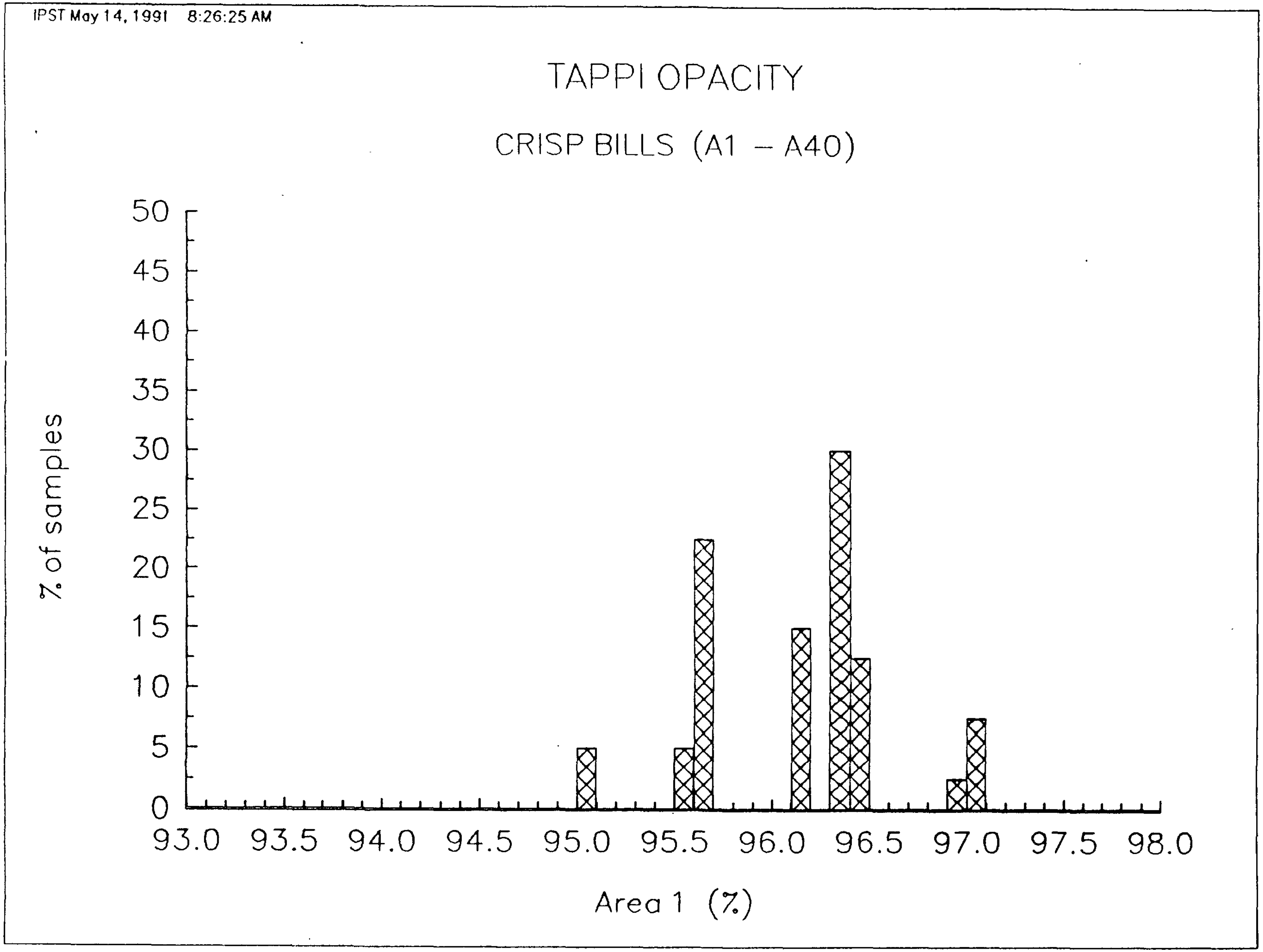

IPST May 14, 1991 8:26:25 AM
TAPPI OPACITY
CRISP BILLS (A1 – A40)
% of samples
50
45
40
35
30
25
20
15
10
5
0
93.0
93.5
94.0
94.5
95.0
95.5
96.0
96.5
97.0
97.5
98.0
Area 1 (%)

Figure 3

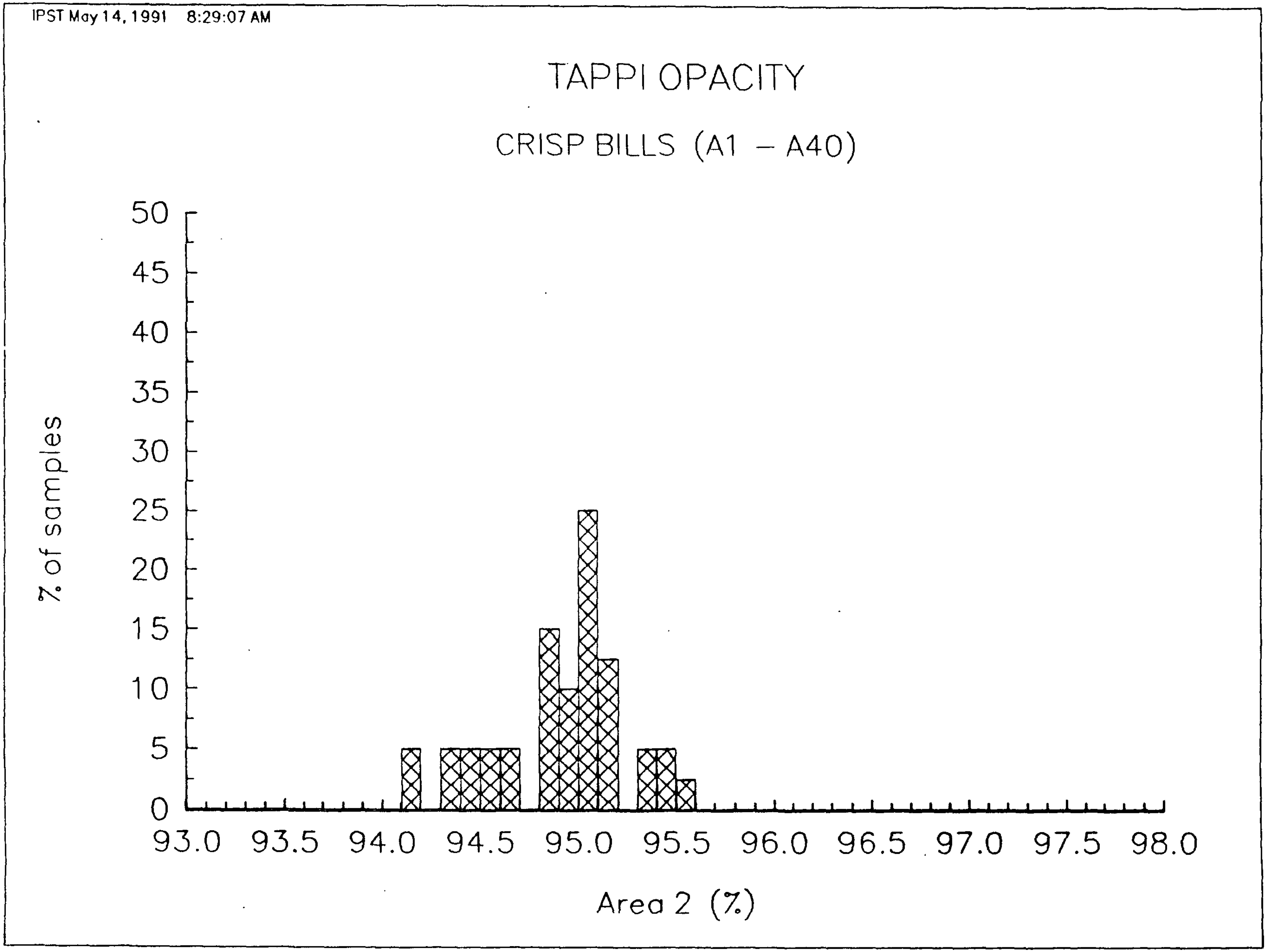

IPST May 14, 1991 8:29:07 AM
TAPPI OPACITY
CRISP BILLS (A1 – A40)
% of samples
0
5
10
15
20
25
30
35
40
45
50
93.0
93.5
94.0
94.5
95.0
95.5
96.0
96.5
97.0
97.5
98.0
Area 2 (%)

Figure 4

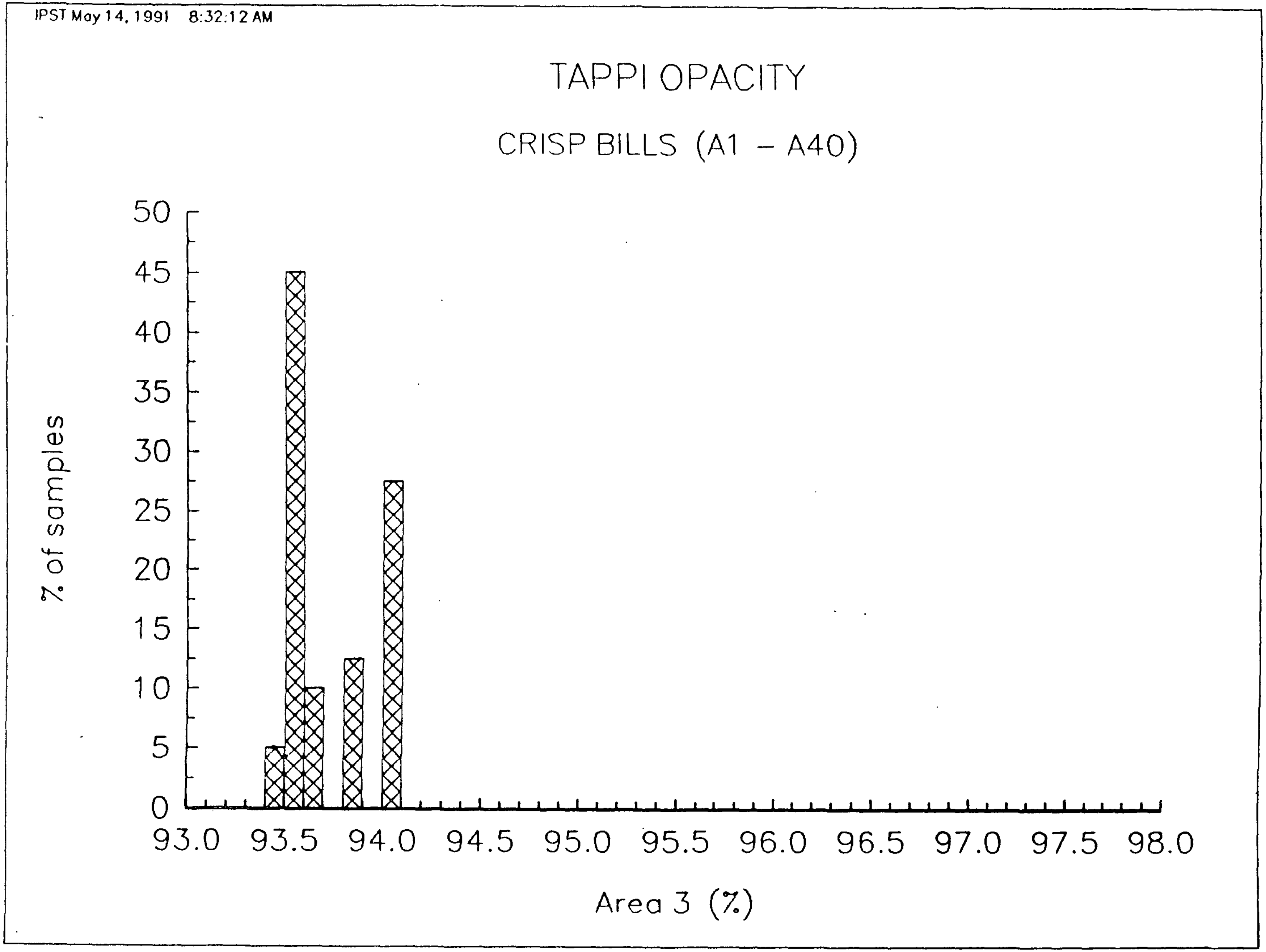

IPST May 14, 1991 8:32:12 AM
TAPPI OPACITY
CRISP BILLS (A1 – A40)
% of samples
50
45
40
35
30
25
20
15
10
5
0
93.0
93.5
94.0
94.5
95.0
95.5
96.0
96.5
97.0
97.5
98.0
Area 3 (%)

Figure 5

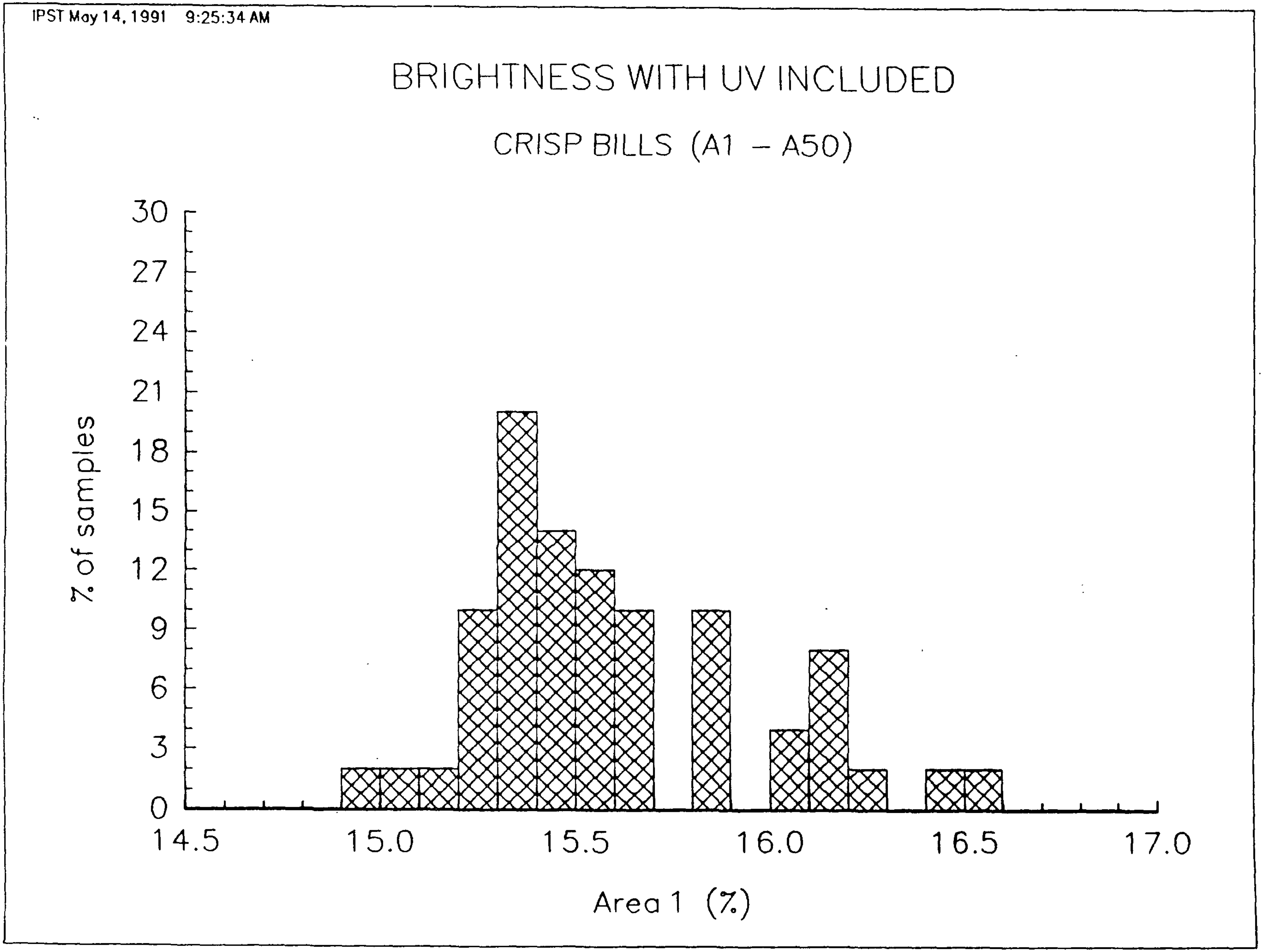
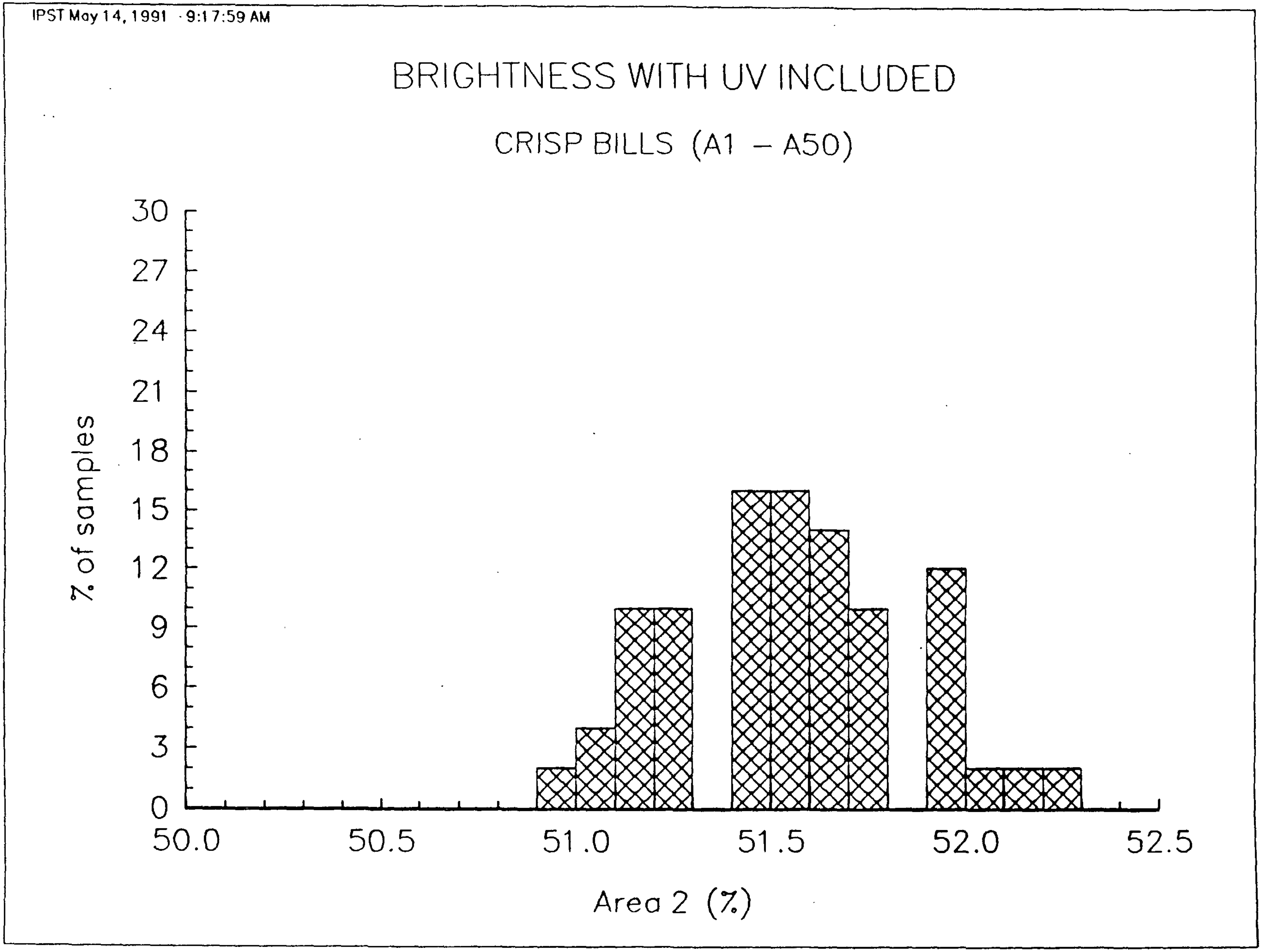

IPST May 14, 1991 9:25:34 AM
BRIGHTNESS WITH UV INCLUDED
CRISP BILLS (A1 – A50)
% of samples
30
27
24
21
18
15
12
9
6
3
0
14.5
15.0
15.5
16.0
16.5
17.0
Area 1 (%)

Figure 6



IPST May 14, 1991 · 9:17:59 AM
BRIGHTNESS WITH UV INCLUDED
CRISP BILLS (A1 – A50)
% of samples
30
27
24
21
18
15
12
9
6
3
0
50.0
50.5
51.0
51.5
52.0
52.5
Area 2 (%)

Figure 7

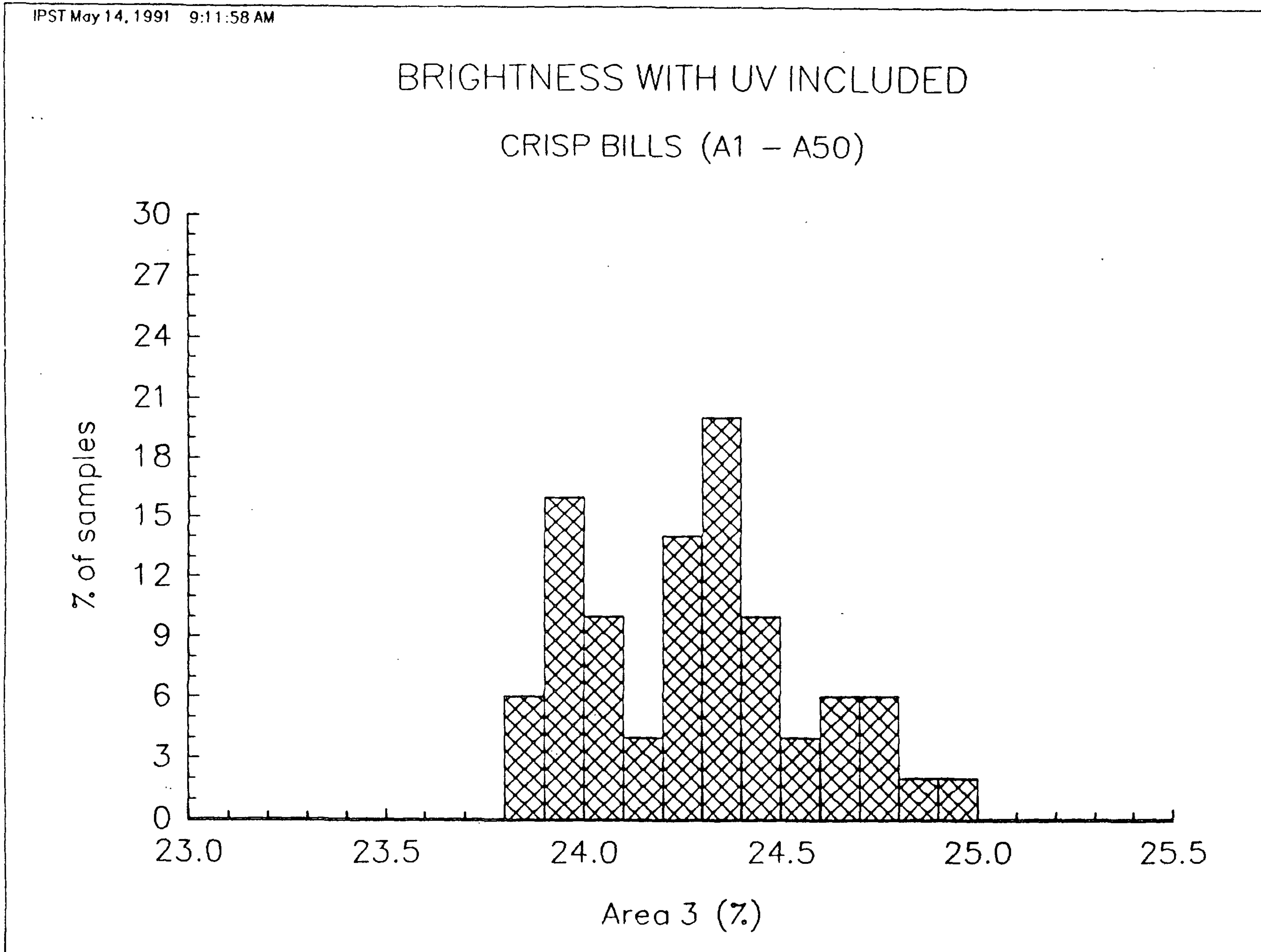

IPST May 14, 1991 9:11:58 AM
BRIGHTNESS WITH UV INCLUDED
CRISP BILLS (A1 – A50)
% of samples
30
27
24
21
18
15
12
9
6
3
0
23.0
23.5
24.0
24.5
25.0
25.5
Area 3 (%)

Figure 8

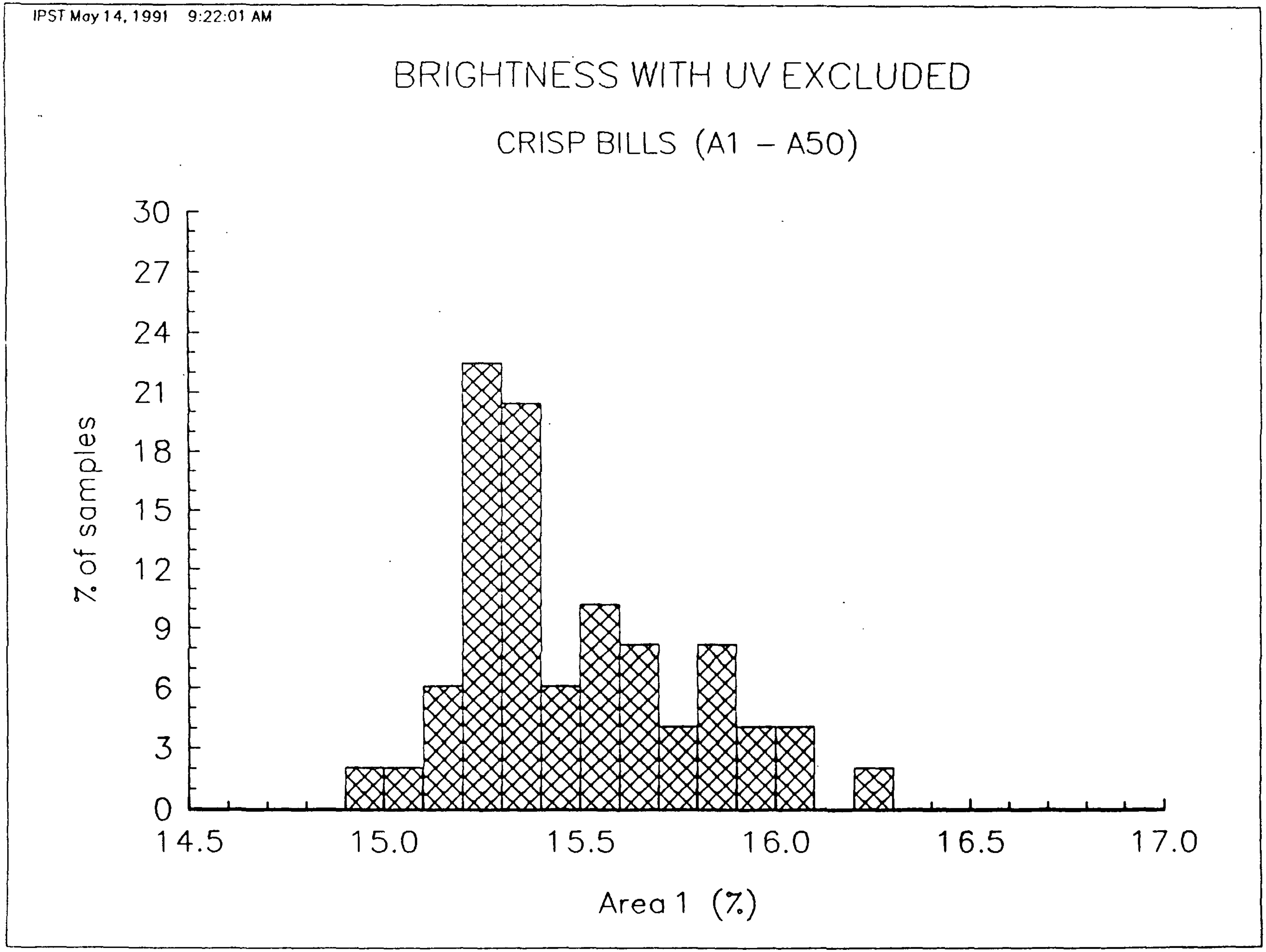

IPST May 14, 1991 9:22:01 AM
BRIGHTNESS WITH UV EXCLUDED
CRISP BILLS (A1 – A50)
% of samples
30
27
24
21
18
15
12
9
6
3
0
14.5
15.0
15.5
16.0
16.5
17.0
Area 1 (%)

Figure 9

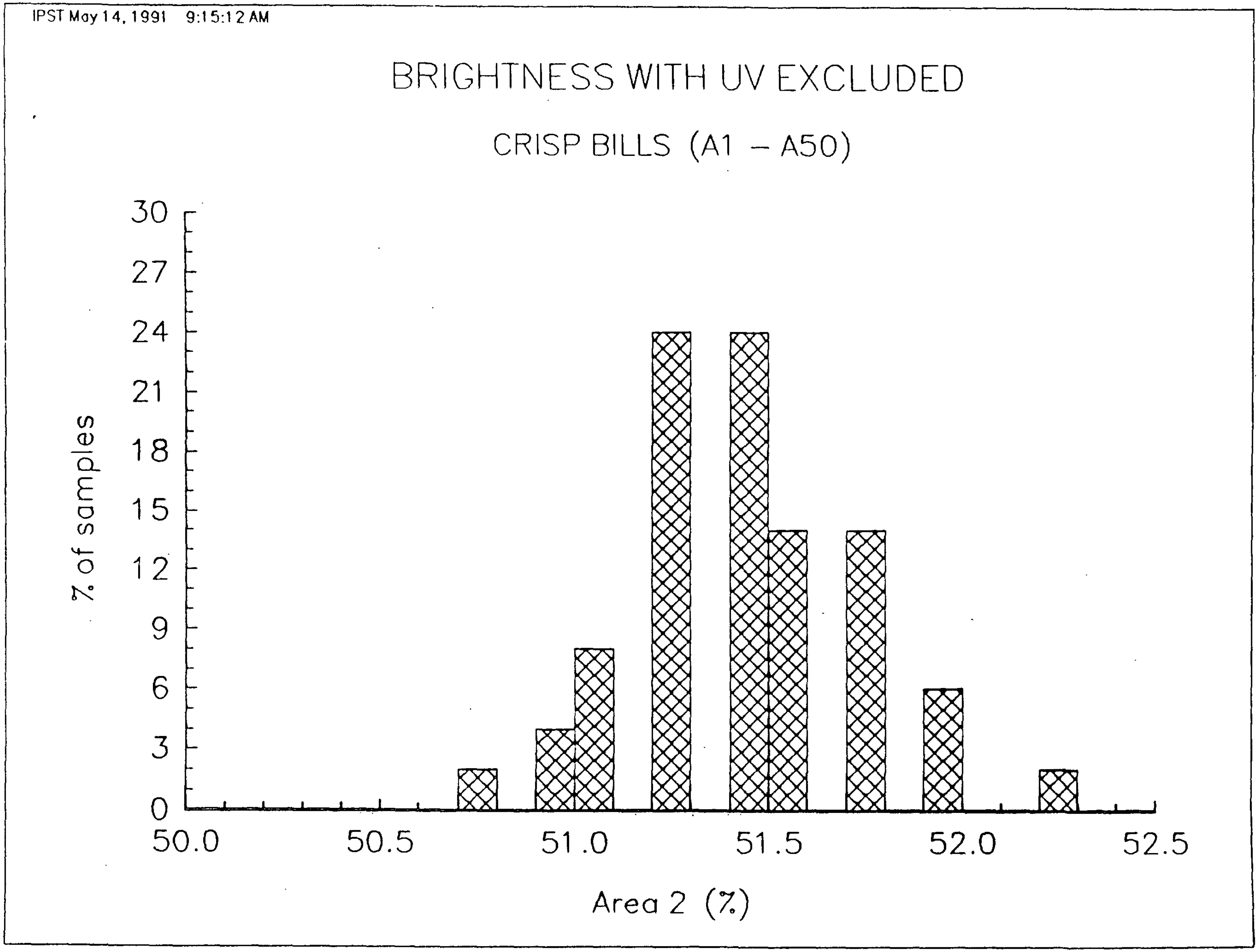

IPST May 14, 1991 9:15:12 AM
BRIGHTNESS WITH UV EXCLUDED
CRISP BILLS (A1 – A50)
% of samples
30
27
24
21
18
15
12
9
6
3
0
50.0
50.5
51.0
51.5
52.0
52.5
Area 2 (%)

Figure 10

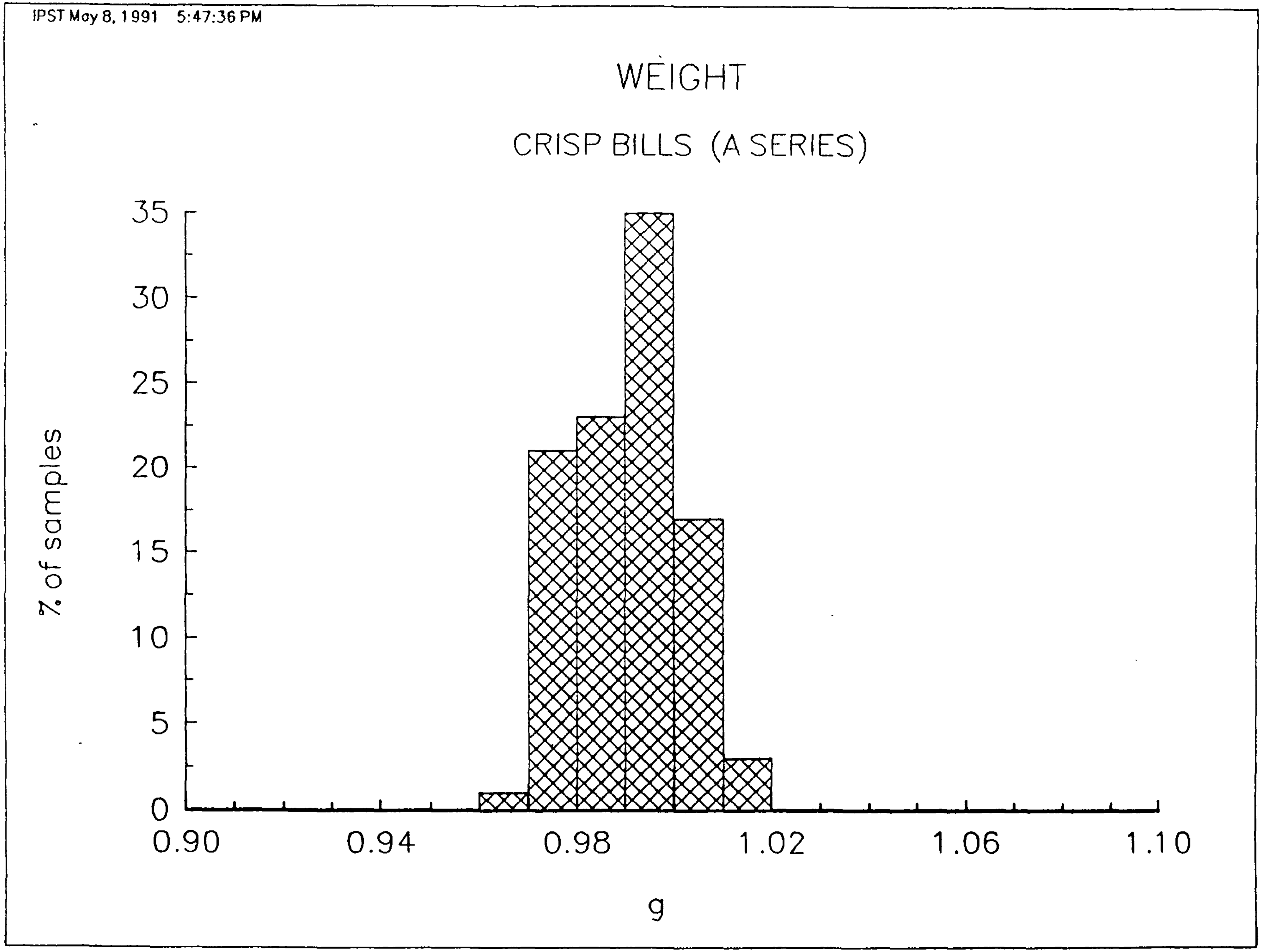

IPST May 8, 1991 5:47:36 PM
WEIGHT
CRISP BILLS (A SERIES)
% of samples
35
30
25
20
15
10
5
0
0.90
0.94
0.98
1.02
1.06
1.10
g

Figure 12

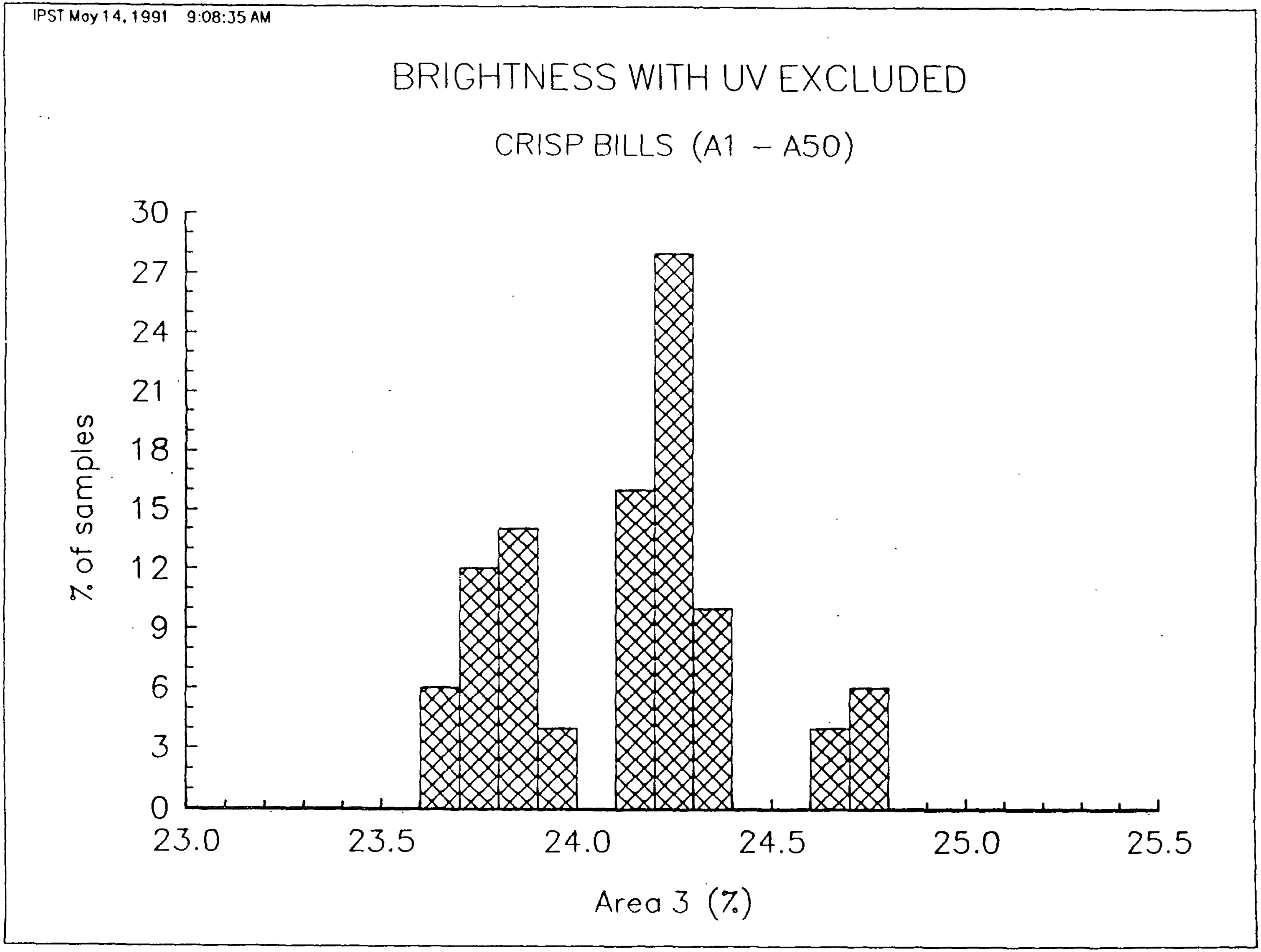

IPST May 14, 1991 9:08:35 AM
BRIGHTNESS WITH UV EXCLUDED
CRISP BILLS (A1 – A50)
% of samples
30
27
24
21
18
15
12
9
6
3
0
23.0
23.5
24.0
24.5
25.0
25.5
Area 3 (%)

Figure 11

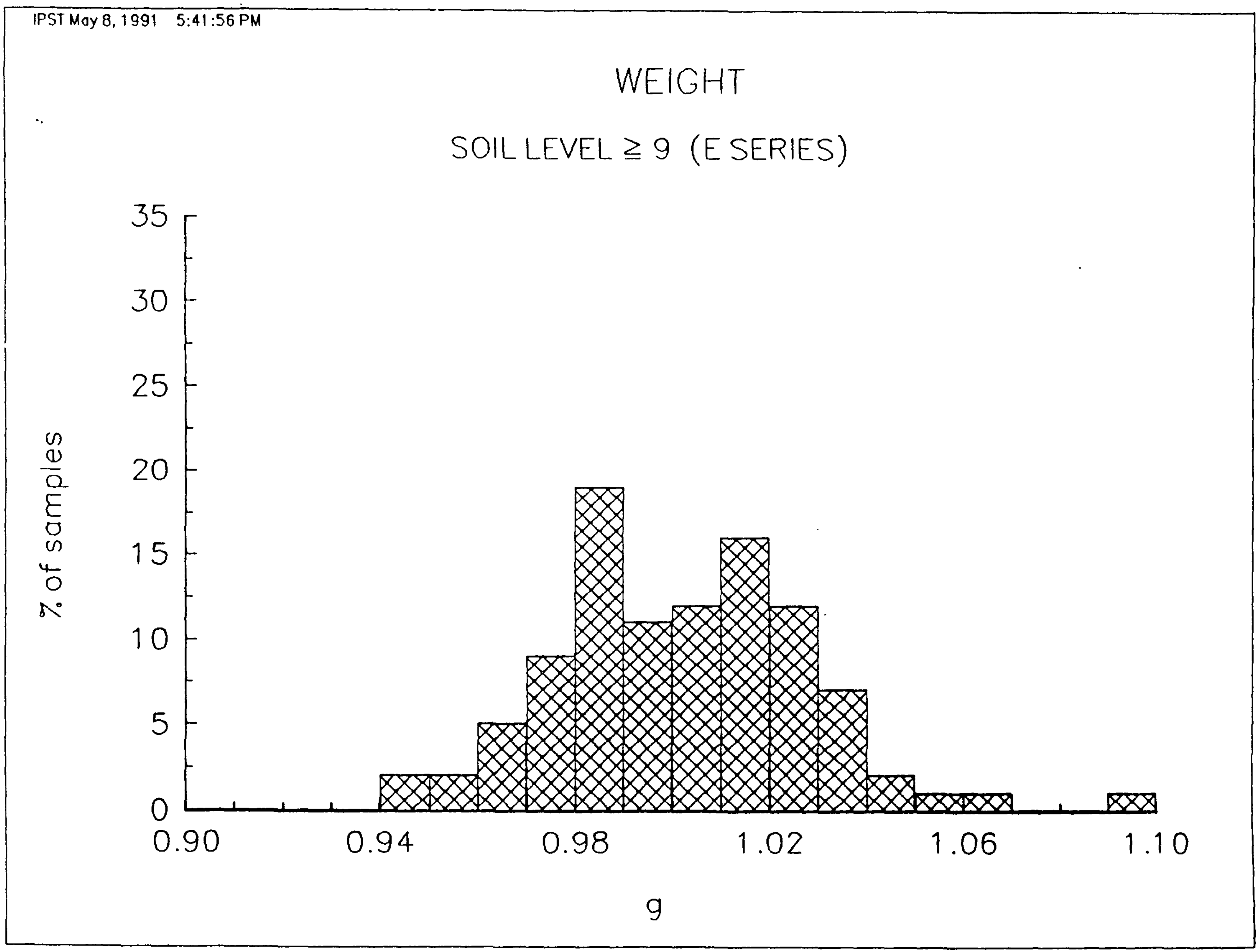

IPST May 8, 1991 5:41:56 PM
WEIGHT
SOIL LEVEL ≧ 9 (E SERIES)
% of samples
35
30
25
20
15
10
5
0
0.90
0.94
0.98
1.02
1.06
1.10
g

Figure 13

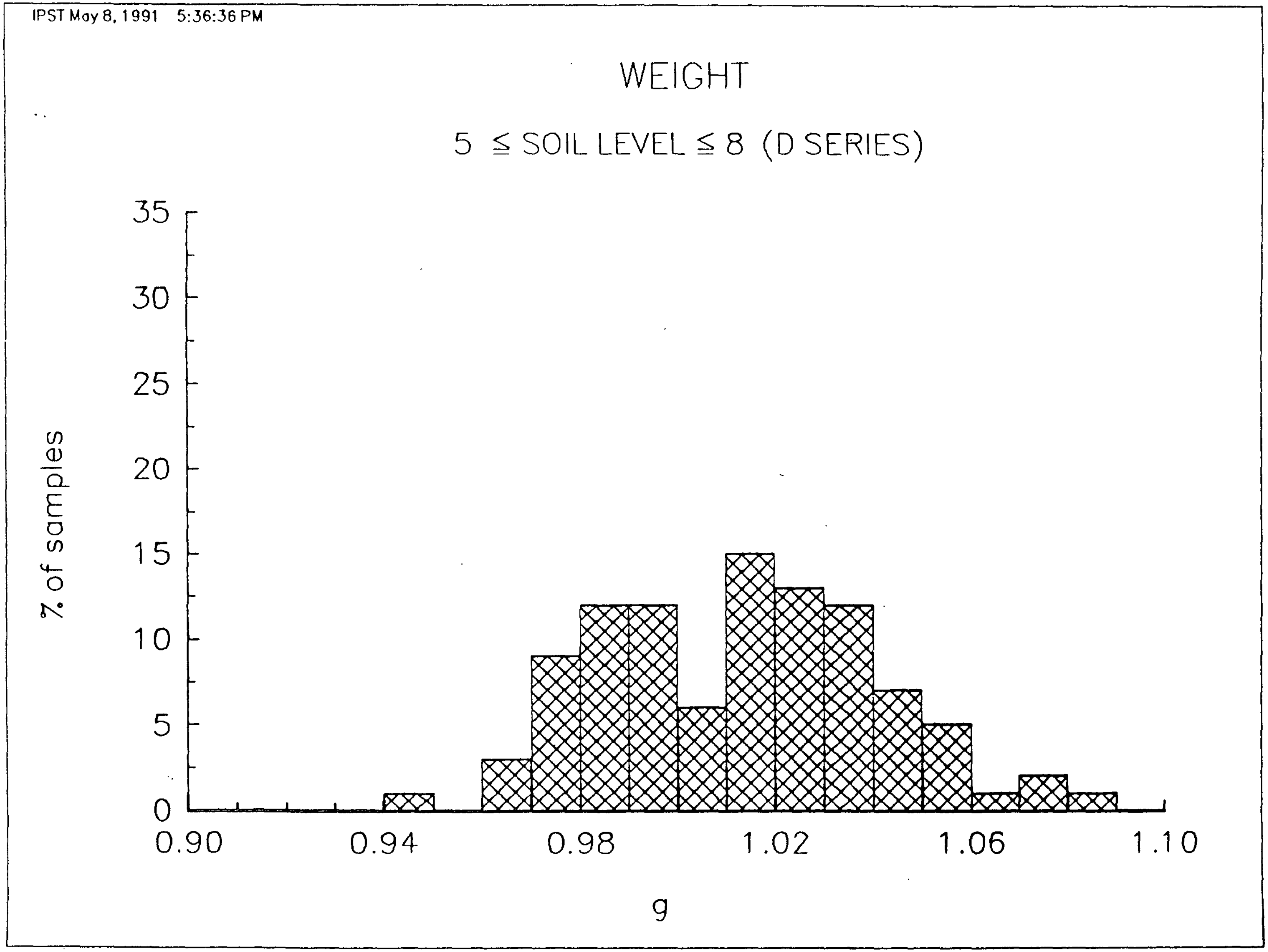

IPST May 8, 1991 5:36:36 PM
WEIGHT
5 ≦ SOIL LEVEL ≦ 8 (D SERIES)
% of samples
35
30
25
20
15
10
5
0
0.90
0.94
0.98
1.02
1.06
1.10
g

Figure 14

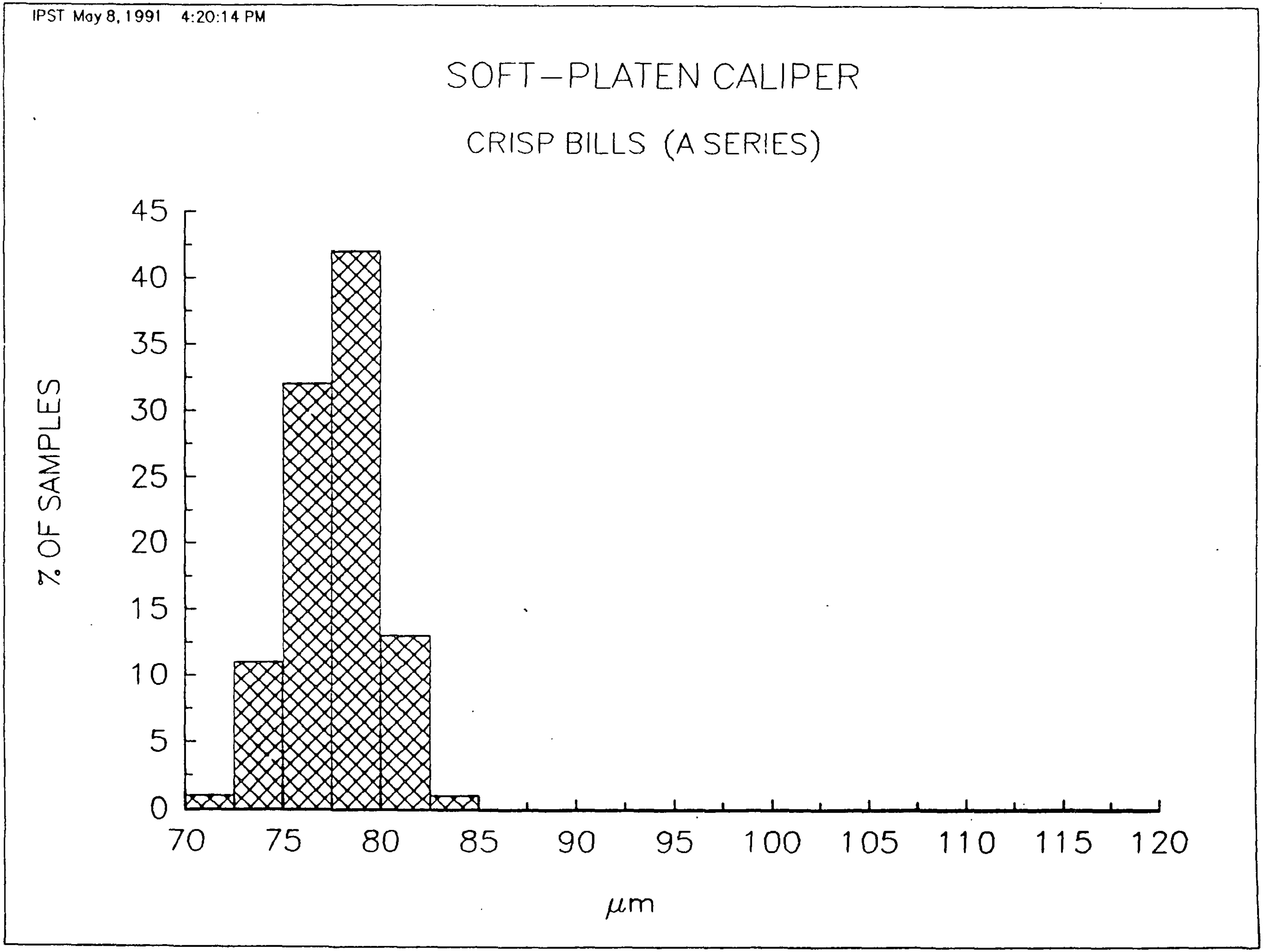

IPST May 8, 1991 4:20:14 PM
SOFT–PLATEN CALIPER
CRISP BILLS (A SERIES)
% OF SAMPLES
0
5
10
15
20
25
30
35
40
45
70
75
80
85
90
95
100
105
110
115
120
μm

Figure 15

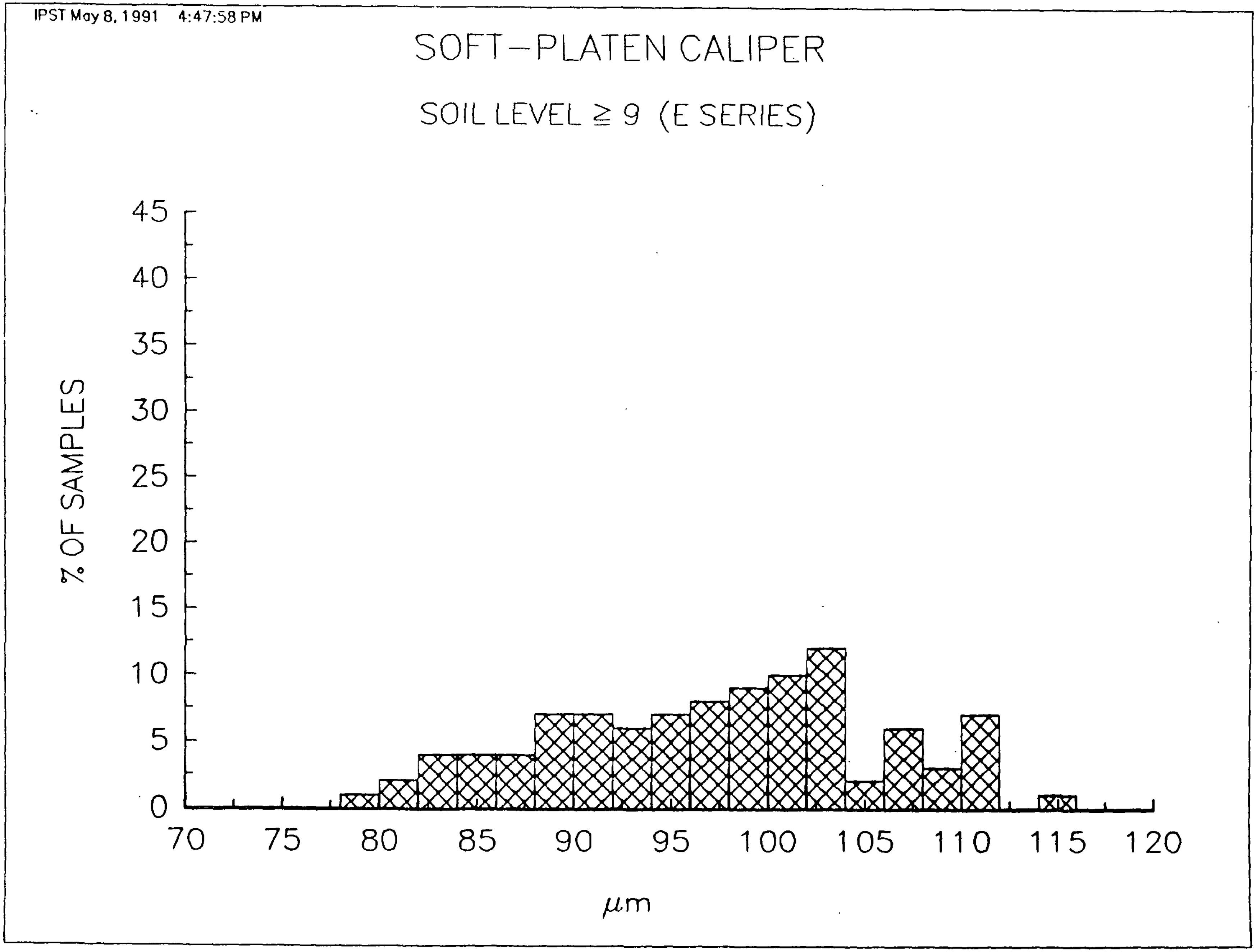

IPST May 8, 1991 4:47:58 PM
SOFT–PLATEN CALIPER
SOIL LEVEL ≧ 9 (E SERIES)
% OF SAMPLES
45
40
35
30
25
20
15
10
5
0
70
75
80
85
90
95
100
105
110
115
120
μm

Figure 16

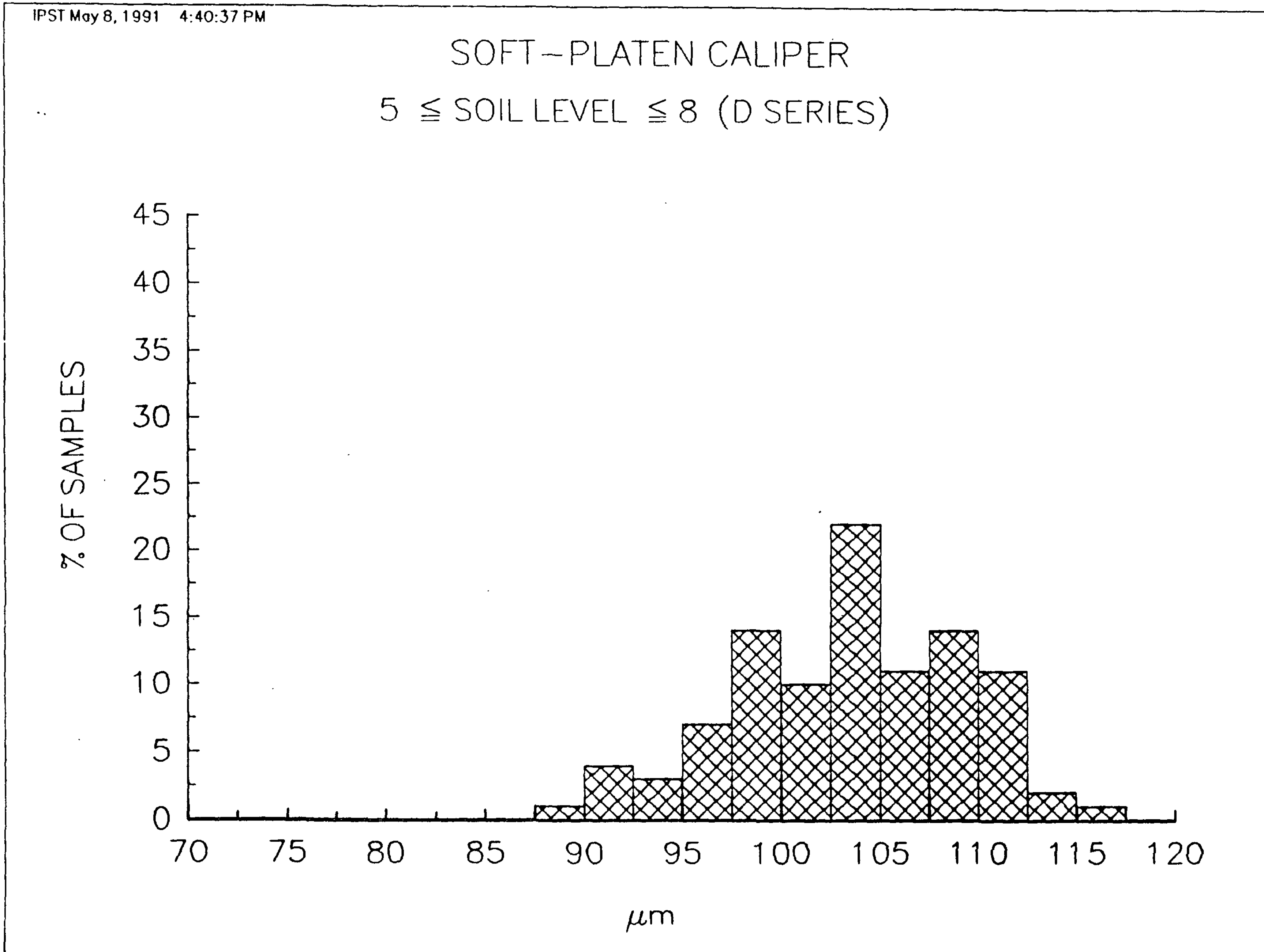

IPST May 8, 1991 4:40:37 PM
SOFT–PLATEN CALIPER
5 ≦ SOIL LEVEL ≦ 8 (D SERIES)
% OF SAMPLES
45
40
35
30
25
20
15
10
5
0
70
75
80
85
90
95
100
105
110
115
120
μm

Figure 17

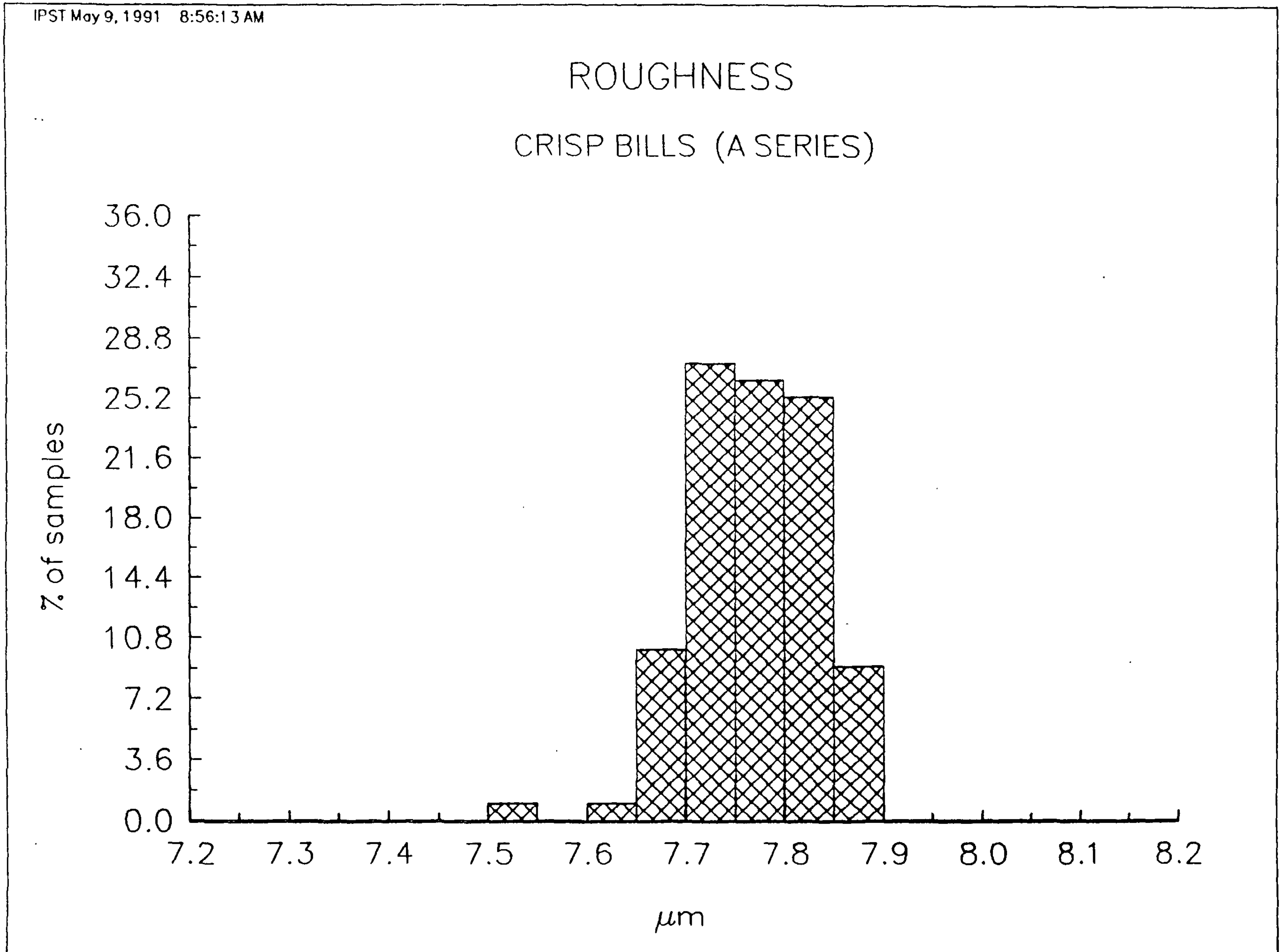

IPST May 9, 1991 8:56:13 AM
ROUGHNESS
CRISP BILLS (A SERIES)
% of samples
36.0
32.4
28.8
25.2
21.6
18.0
14.4
10.8
7.2
3.6
0.0
7.2
7.3
7.4
7.5
7.6
7.7
7.8
7.9
8.0
8.1
8.2
μm

Figure 18

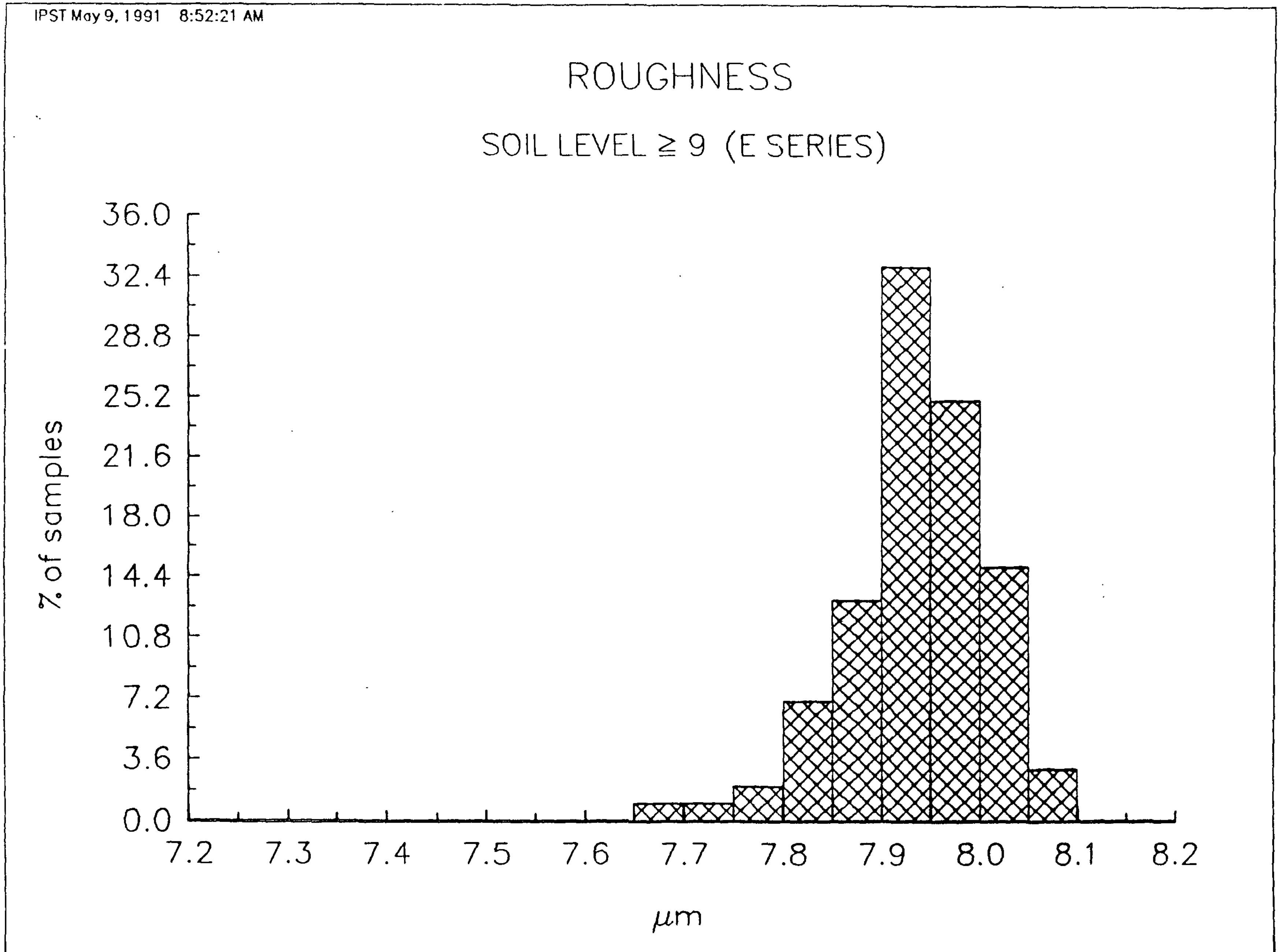

IPST May 9, 1991 8:52:21 AM
ROUGHNESS
SOIL LEVEL ≧ 9 (E SERIES)
% of samples
36.0
32.4
28.8
25.2
21.6
18.0
14.4
10.8
7.2
3.6
0.0
7.2
7.3
7.4
7.5
7.6
7.7
7.8
7.9
8.0
8.1
8.2
μm

Figure 19

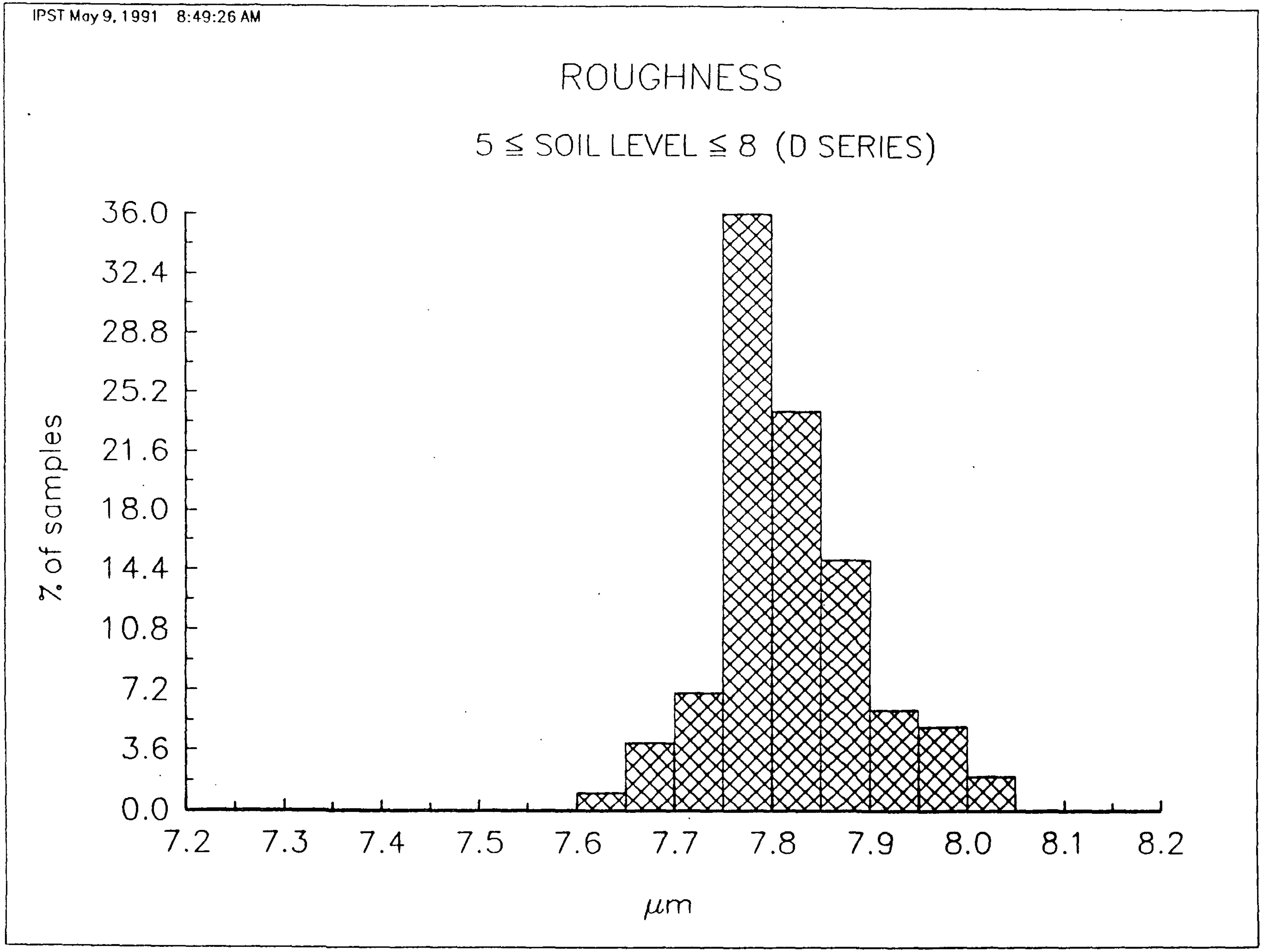

IPST May 9, 1991 8:49:26 AM
ROUGHNESS
5 ≦ SOIL LEVEL ≦ 8 (D SERIES)
% of samples
36.0
32.4
28.8
25.2
21.6
18.0
14.4
10.8
7.2
3.6
0.0
7.2
7.3
7.4
7.5
7.6
7.7
7.8
7.9
8.0
8.1
8.2
μm

Figure 20

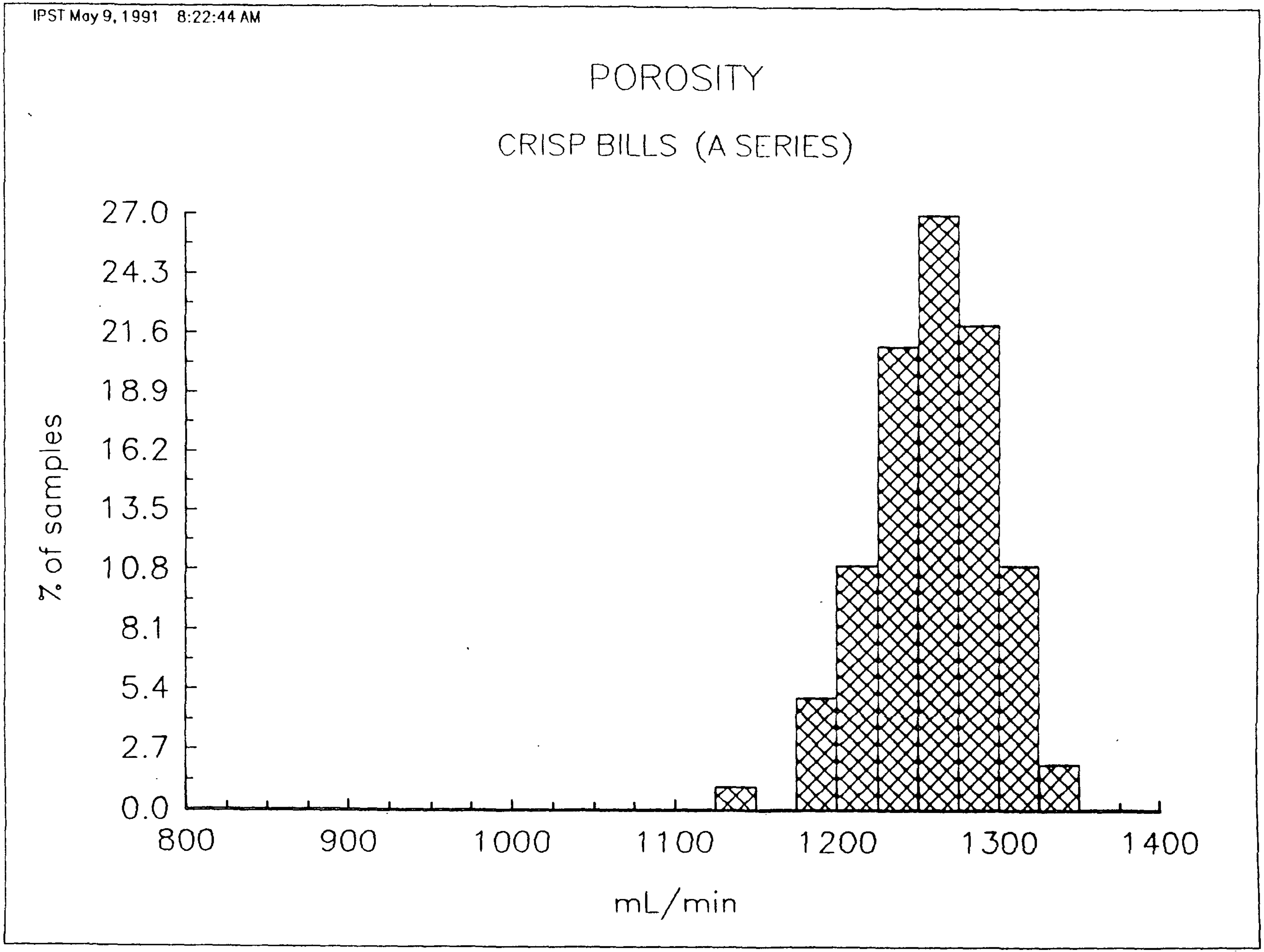

IPST May 9, 1991 8:22:44 AM
POROSITY
CRISP BILLS (A SERIES)
% of samples
27.0
24.3
21.6
18.9
16.2
13.5
10.8
8.1
5.4
2.7
0.0
800
900
1000
1100
1200
1300
1400
mL/min

Figure 21

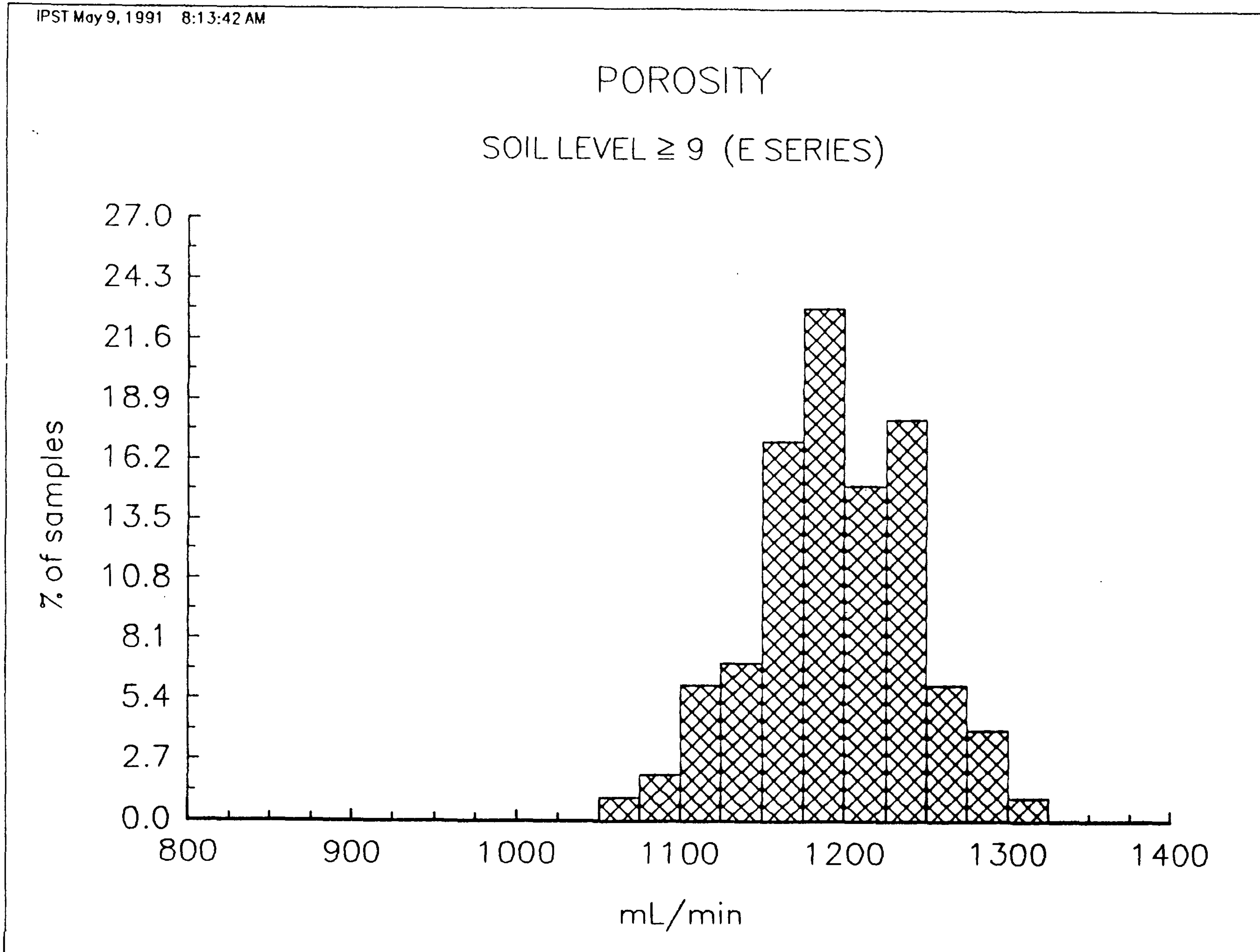

IPST May 9, 1991 8:13:42 AM
POROSITY
SOIL LEVEL ≧ 9 (E SERIES)
% of samples
27.0
24.3
21.6
18.9
16.2
13.5
10.8
8.1
5.4
2.7
0.0
800
900
1000
1100
1200
1300
1400
mL/min

Figure 22

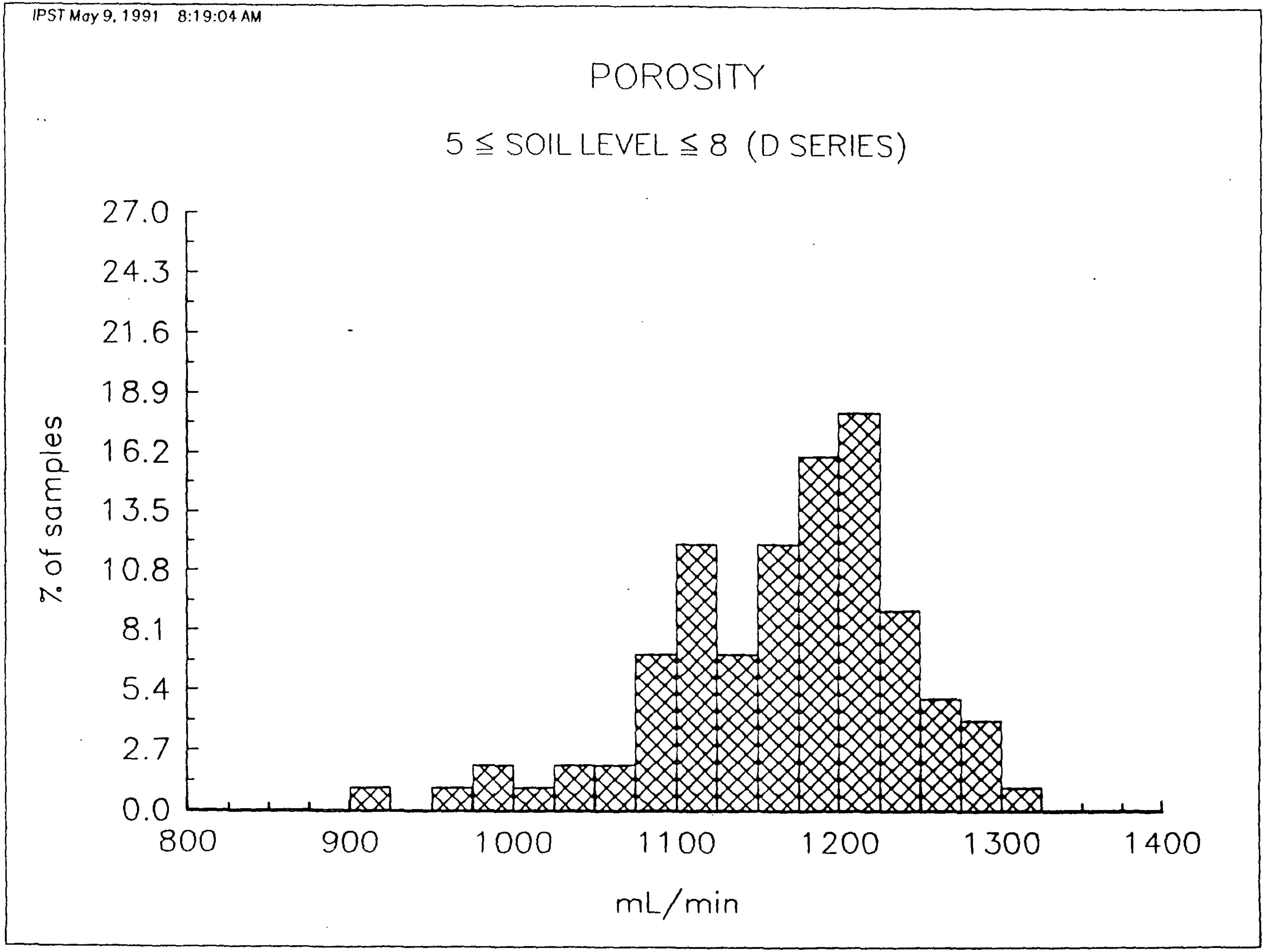

IPST May 9, 1991 8:19:04 AM
POROSITY
5 ≦ SOIL LEVEL ≦ 8 (D SERIES)
% of samples
27.0
24.3
21.6
18.9
16.2
13.5
10.8
8.1
5.4
2.7
0.0
800
900
1000
1100
1200
1300
1400
mL/min

Figure 23

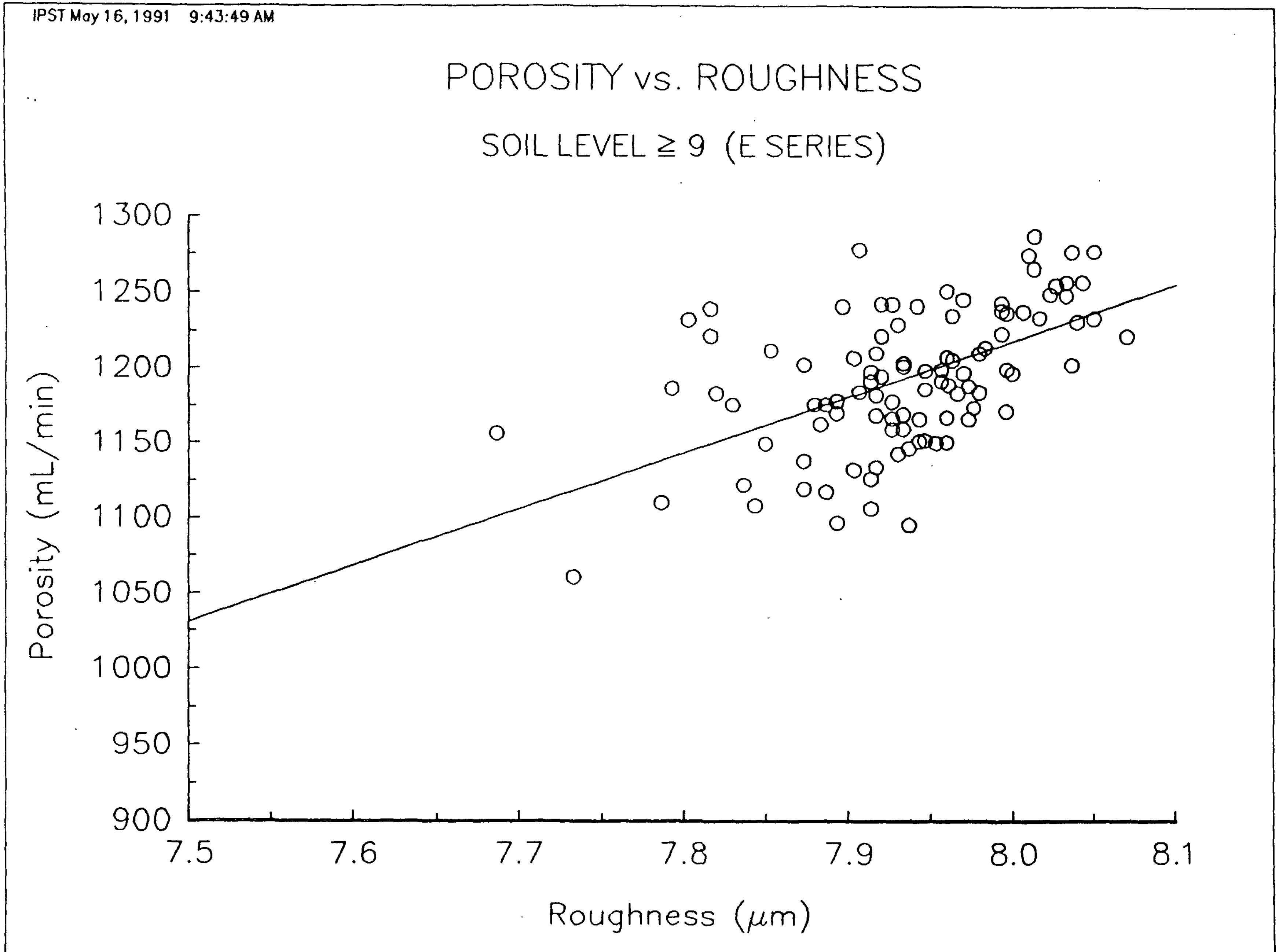

IPST May 16, 1991 9:43:49 AM
POROSITY vs. ROUGHNESS
SOIL LEVEL ≧ 9 (E SERIES)
Porosity (mL/min)
1300
1250
1200
1150
1100
1050
1000
950
900
7.5
7.6
7.7
7.8
7.9
8.0
8.1
Roughness (μm)

Figure 24

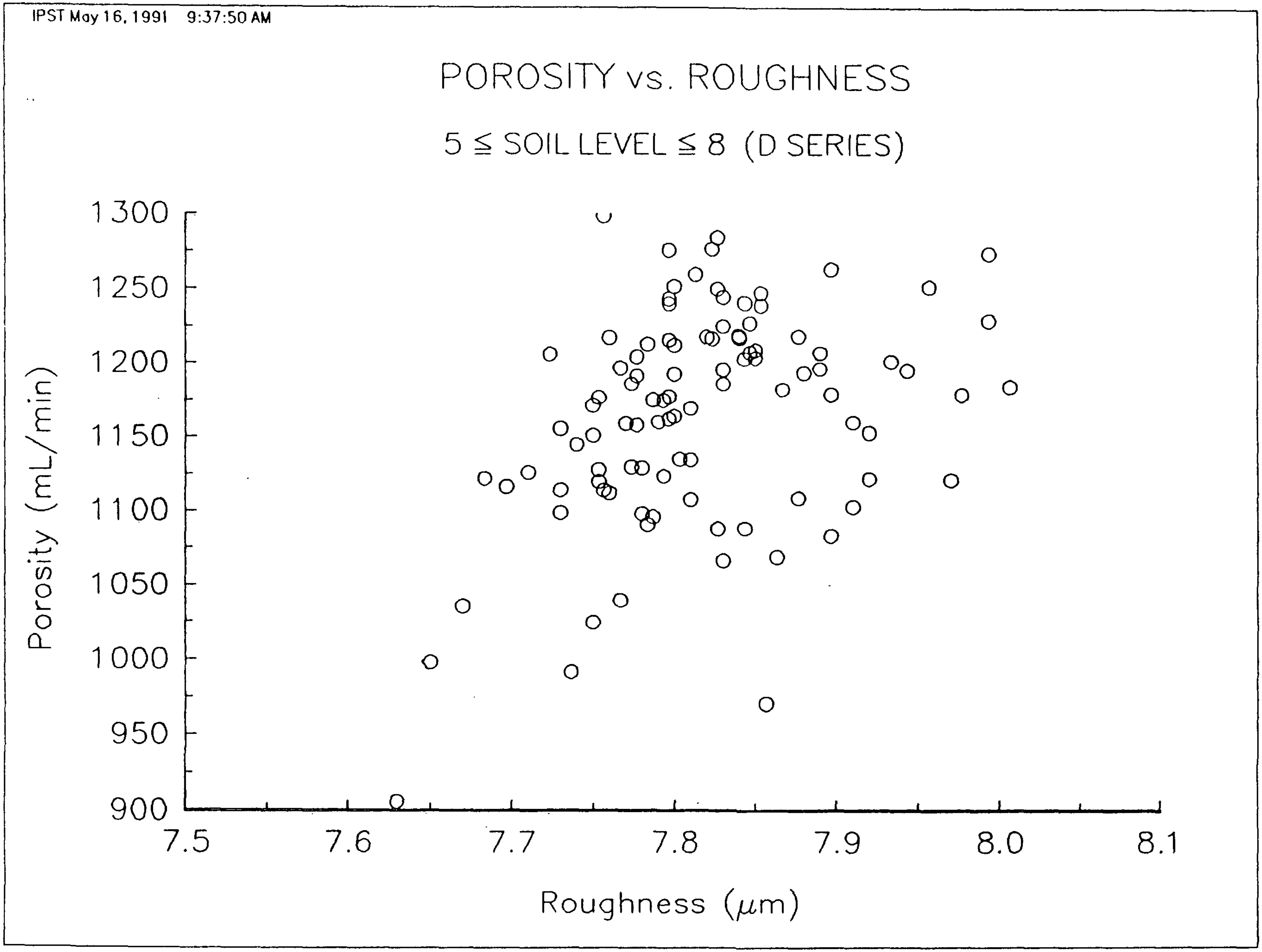

IPST May 16, 1991 9:37:50 AM
POROSITY vs. ROUGHNESS
5 ≦ SOIL LEVEL ≦ 8 (D SERIES)
Porosity (mL/min)
1300
1250
1200
1150
1100
1050
1000
950
900
7.5
7.6
7.7
7.8
7.9
8.0
8.1
Roughness (μm)

Figure 25

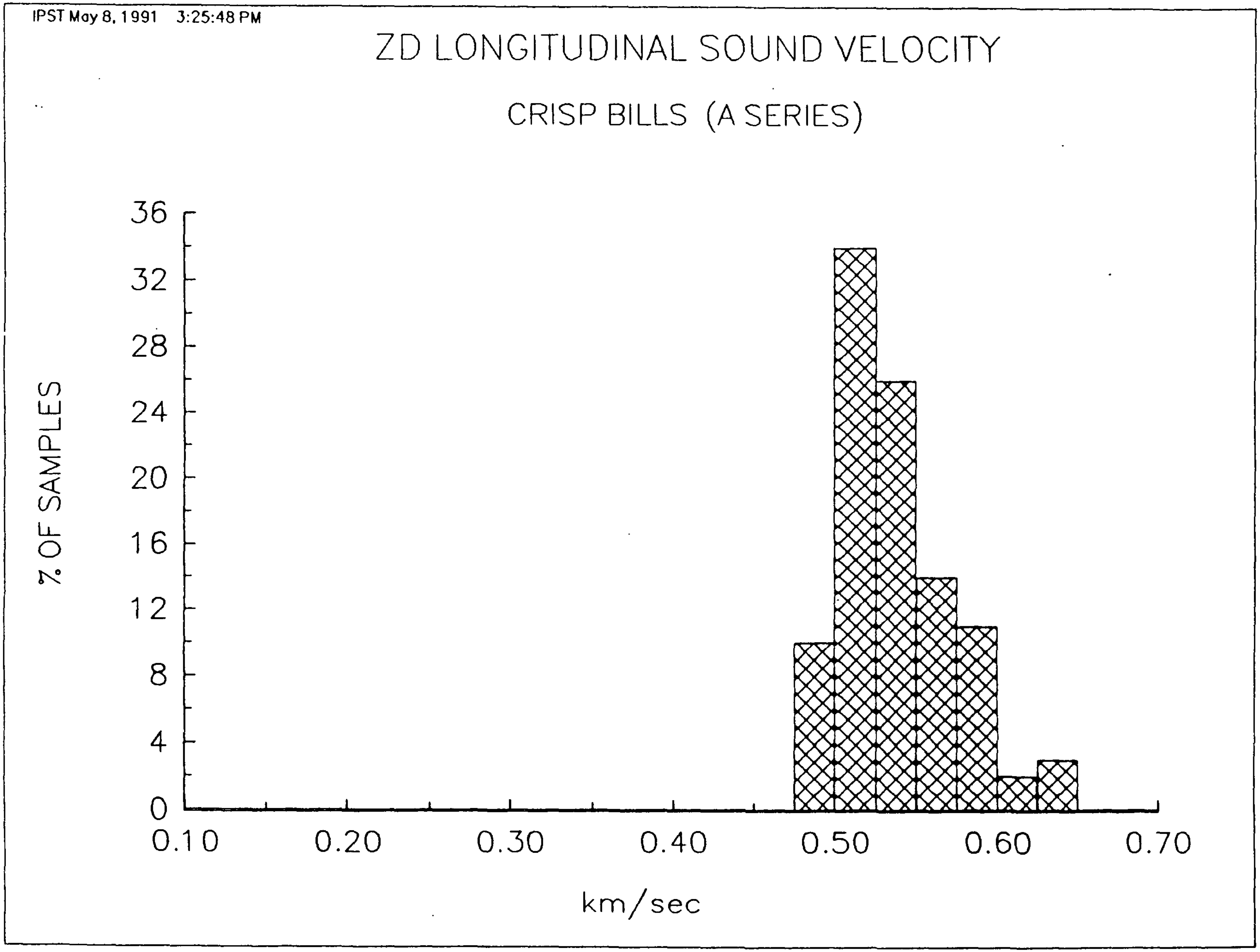

IPST May 8, 1991 3:25:48 PM
ZD LONGITUDINAL SOUND VELOCITY
CRISP BILLS (A SERIES)
% OF SAMPLES
36
32
28
24
20
16
12
8
4
0
0.10
0.20
0.30
0.40
0.50
0.60
0.70
km/sec

Figure 26

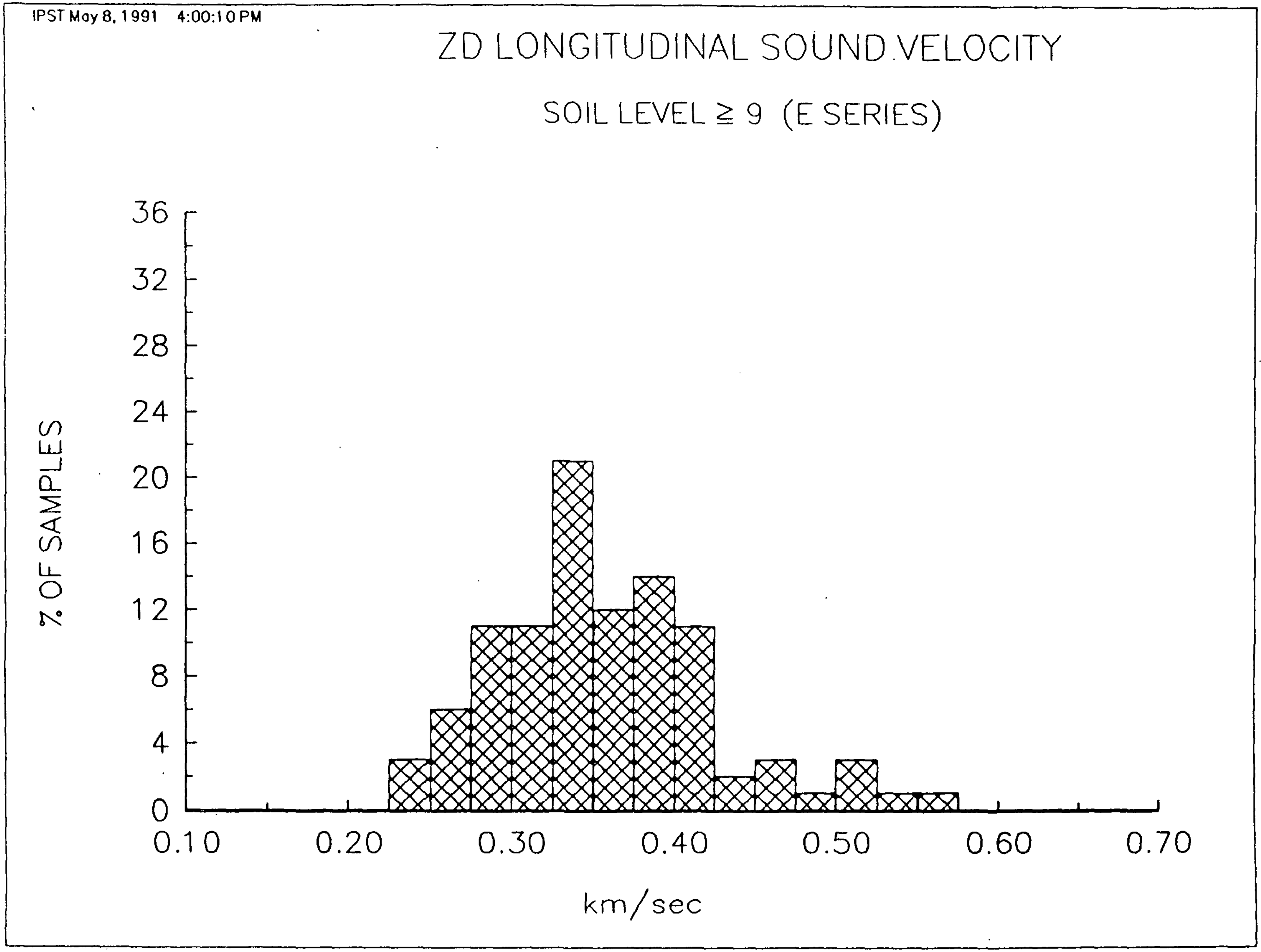

IPST May 8, 1991 4:00:10 PM
ZD LONGITUDINAL SOUND VELOCITY
SOIL LEVEL ≧ 9 (E SERIES)
% OF SAMPLES
0
4
8
12
16
20
24
28
32
36
0.10
0.20
0.30
0.40
0.50
0.60
0.70
km/sec

Figure 27

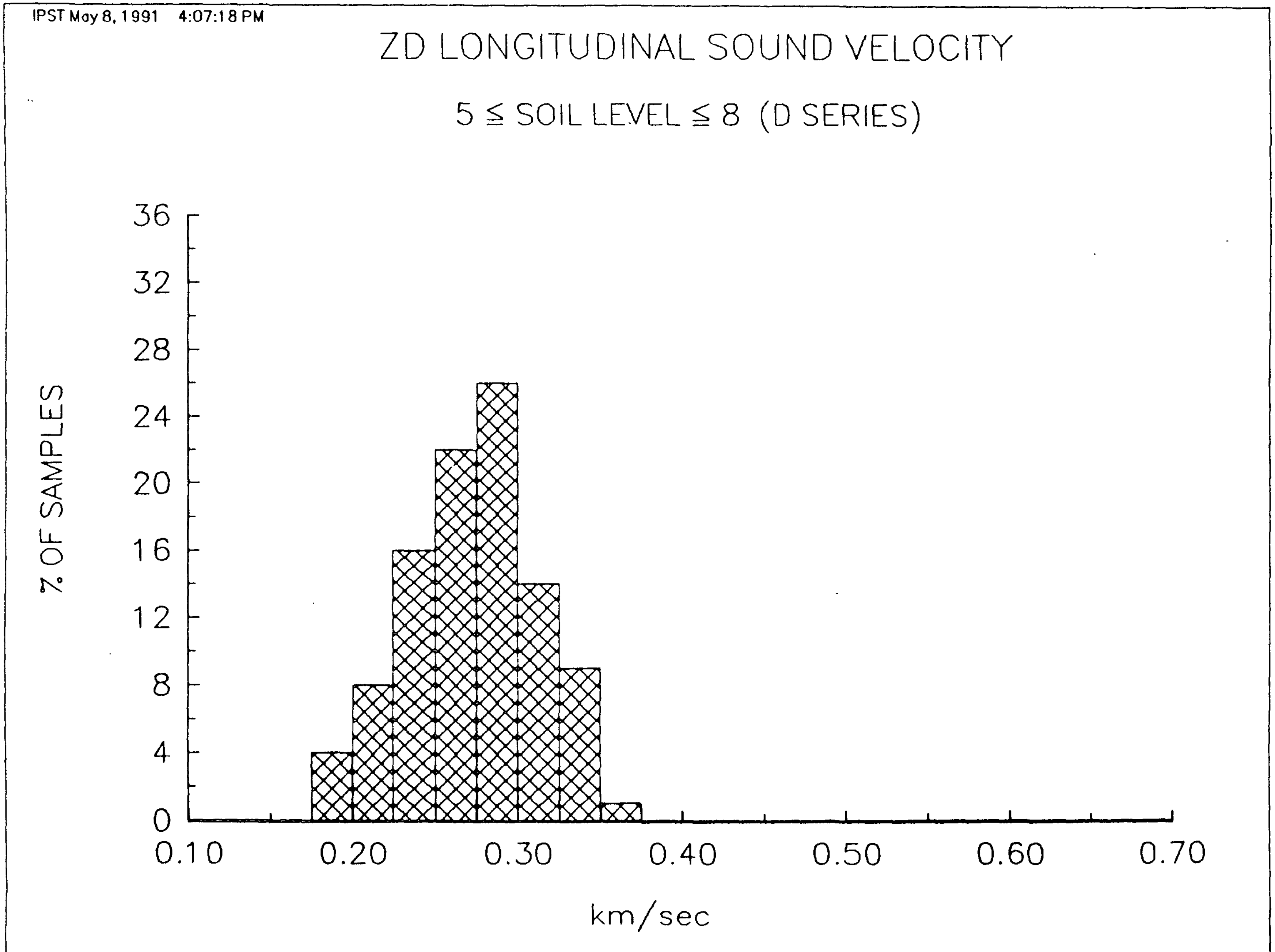
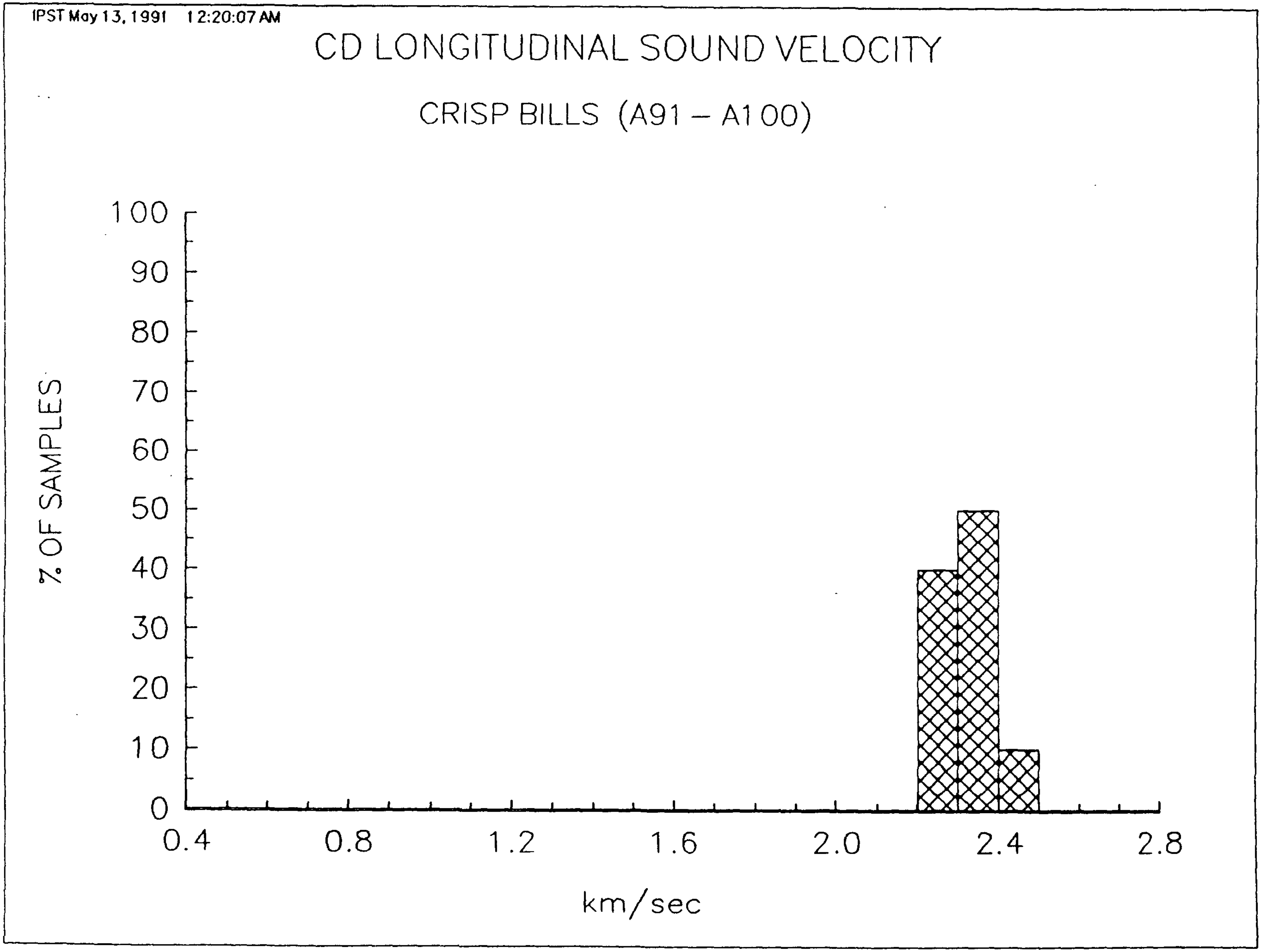

IPST May 8, 1991 4:07:18 PM
ZD LONGITUDINAL SOUND VELOCITY
5 ≦ SOIL LEVEL ≦ 8 (D SERIES)
% OF SAMPLES
36
32
28
24
20
16
12
8
4
0
0.10
0.20
0.30
0.40
0.50
0.60
0.70
km/sec

Figure 28


IPST May 13, 1991 12:20:07 AM
CD LONGITUDINAL SOUND VELOCITY
CRISP BILLS (A91 – A100)
% OF SAMPLES
100
90
80
70
60
50
40
30
20
10
0
0.4
0.8
1.2
1.6
2.0
2.4
2.8
km/sec
Figure 29

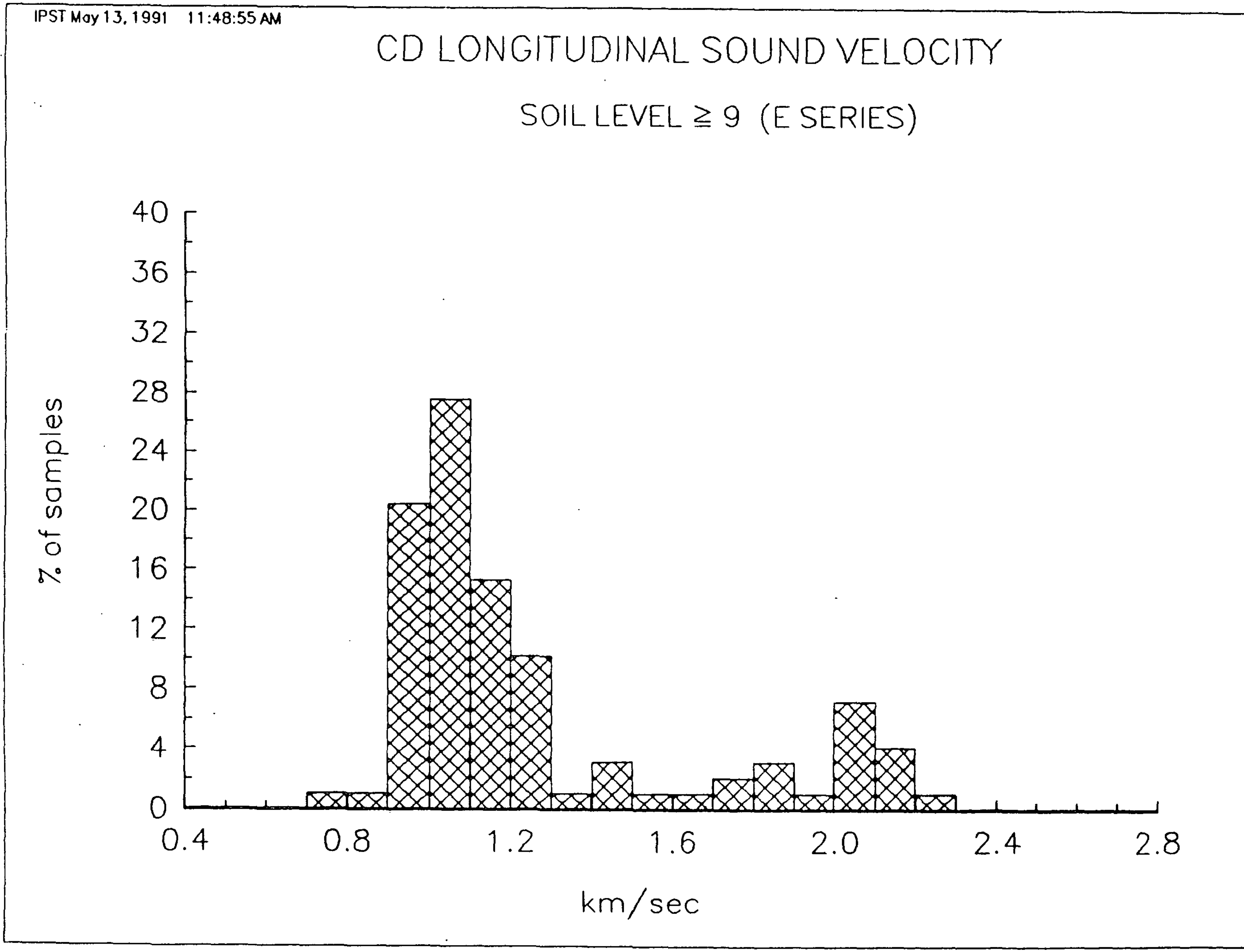

IPST May 13, 1991 11:48:55 AM
CD LONGITUDINAL SOUND VELOCITY
SOIL LEVEL ≧ 9 (E SERIES)
% of samples
40
36
32
28
24
20
16
12
8
4
0
0.4
0.8
1.2
1.6
2.0
2.4
2.8
km/sec

Figure 30

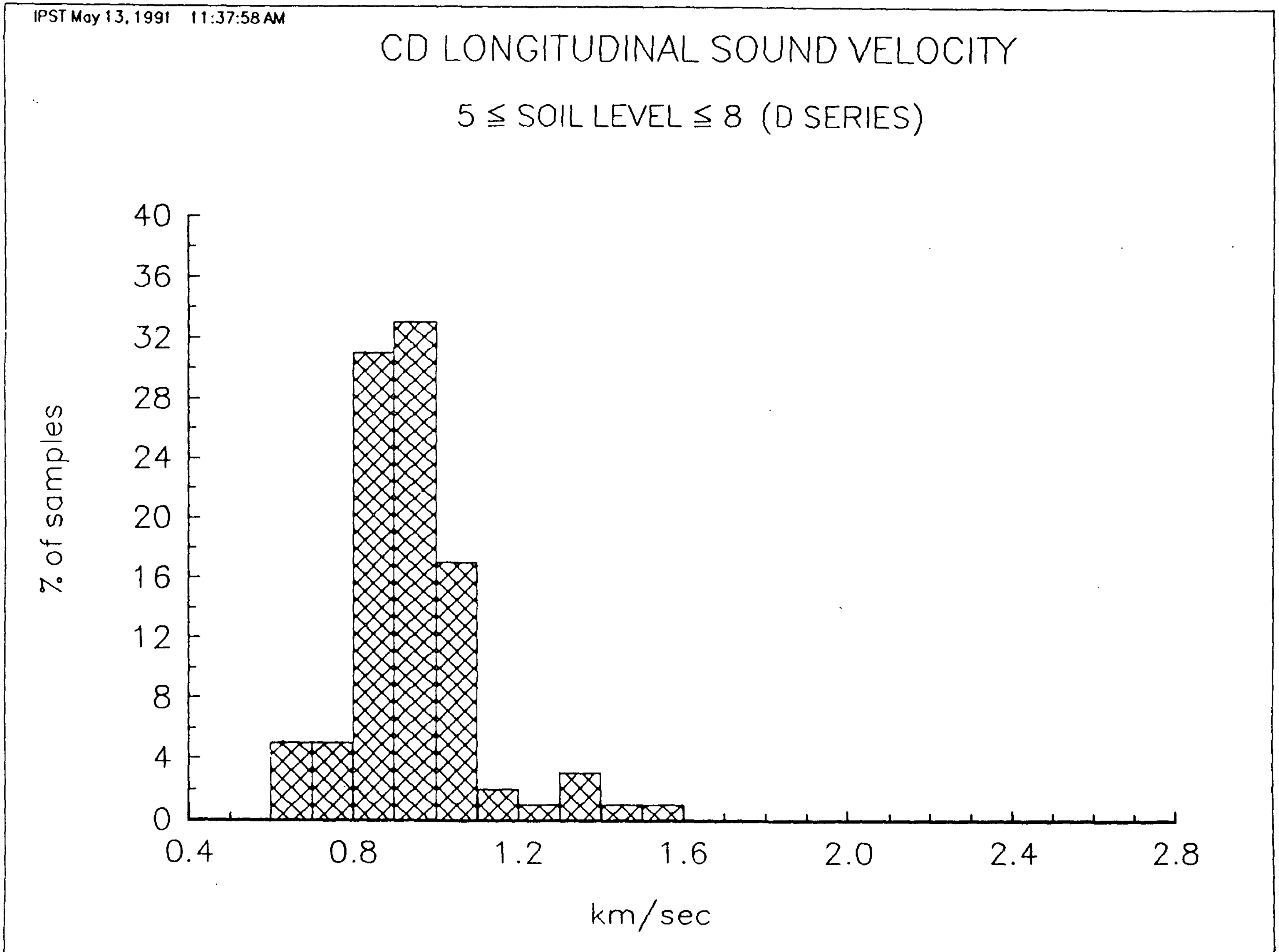

IPST May 13, 1991 11:37:58 AM
CD LONGITUDINAL SOUND VELOCITY
5 ≦ SOIL LEVEL ≦ 8 (D SERIES)
% of samples
0
4
8
12
16
20
24
28
32
36
40
0.4
0.8
1.2
1.6
2.0
2.4
2.8
km/sec

Figure 31

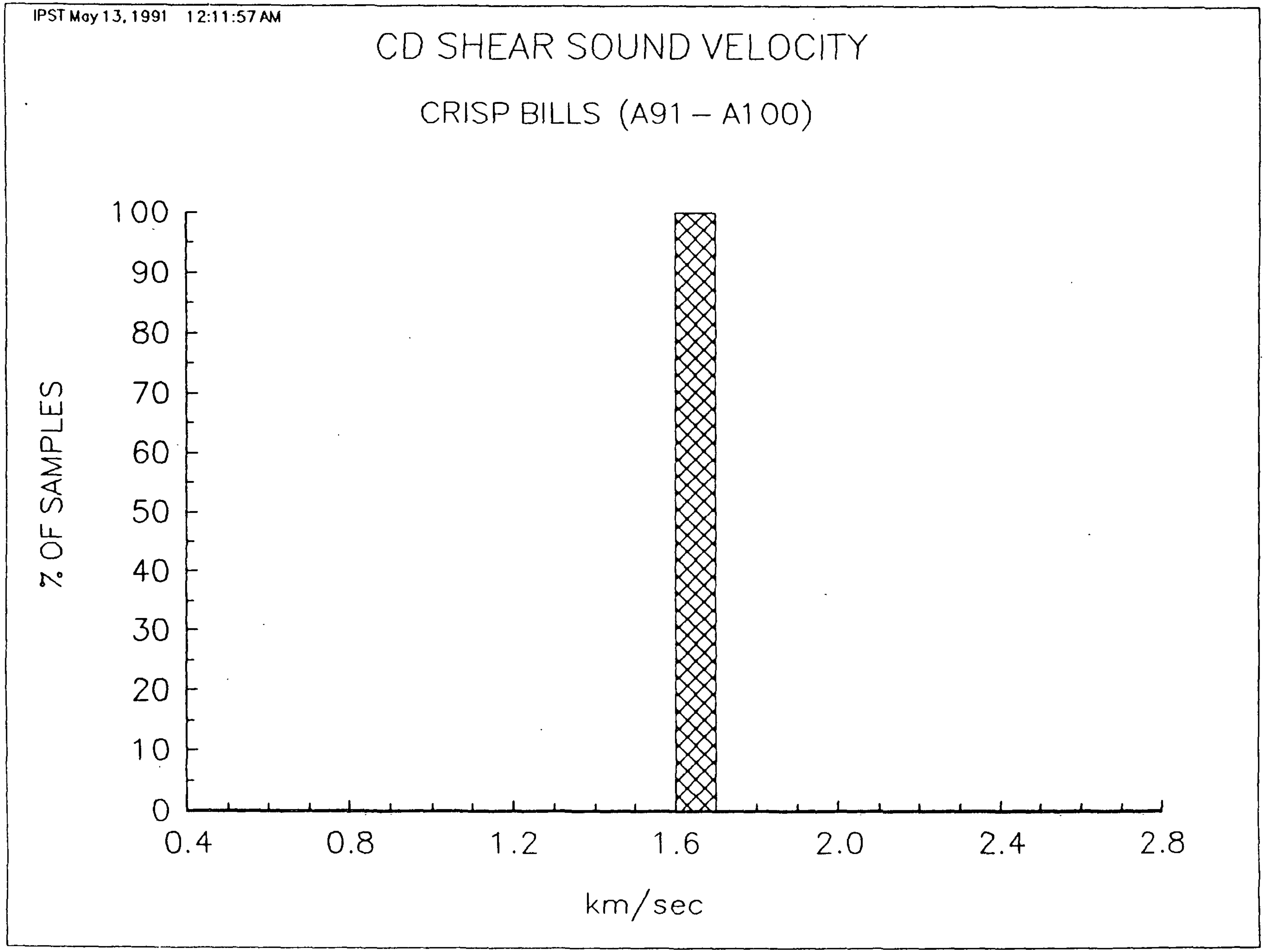
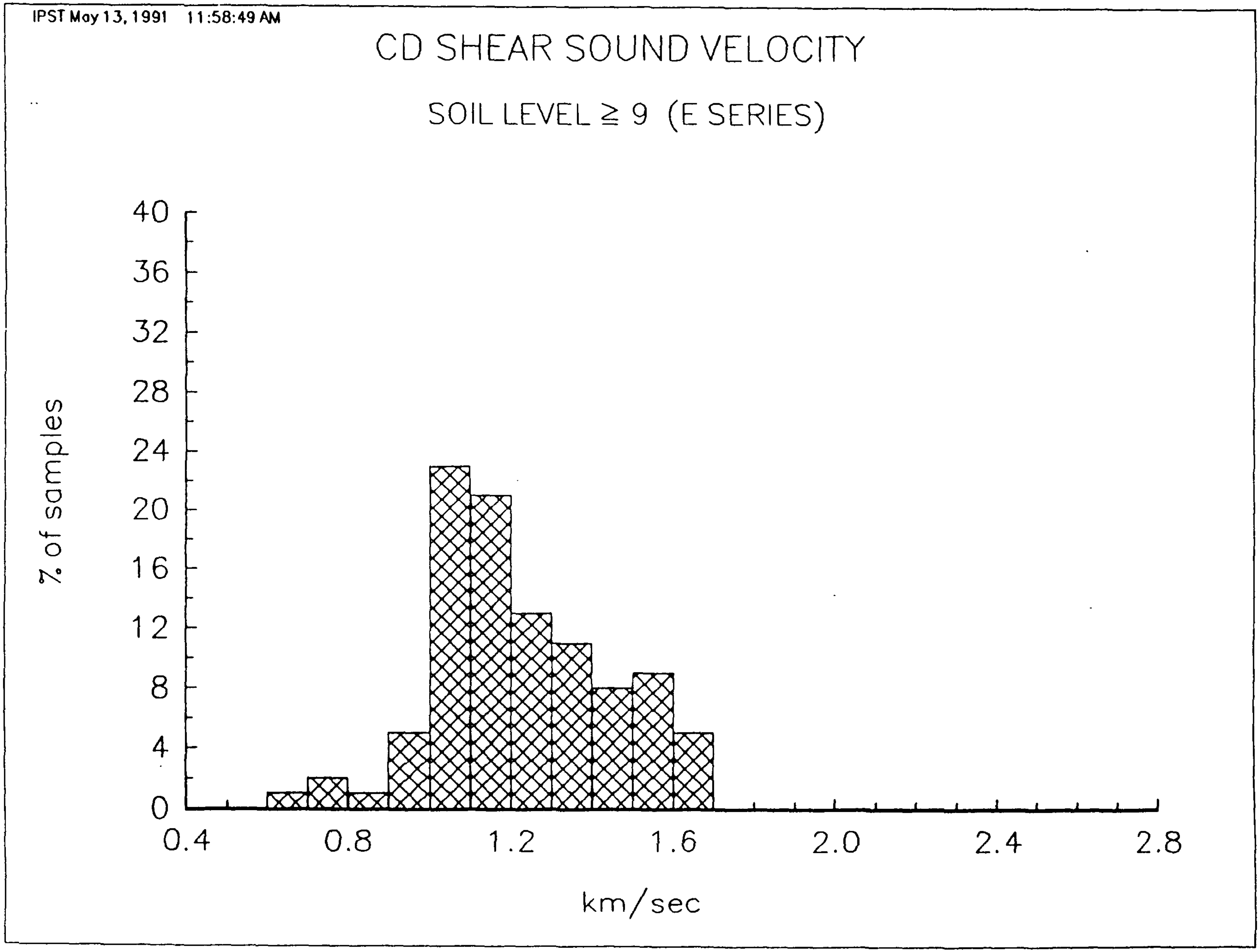

IPST May 13, 1991 12:11:57 AM
CD SHEAR SOUND VELOCITY
CRISP BILLS (A91 – A100)
% OF SAMPLES
100
90
80
70
60
50
40
30
20
10
0
0.4
0.8
1.2
1.6
2.0
2.4
2.8
km/sec

Figure 32



IPST May 13, 1991 11:58:49 AM
CD SHEAR SOUND VELOCITY
SOIL LEVEL ≧ 9 (E SERIES)
% of samples
0
4
8
12
16
20
24
28
32
36
40
0.4
0.8
1.2
1.6
2.0
2.4
2.8
km/sec

Figure 33

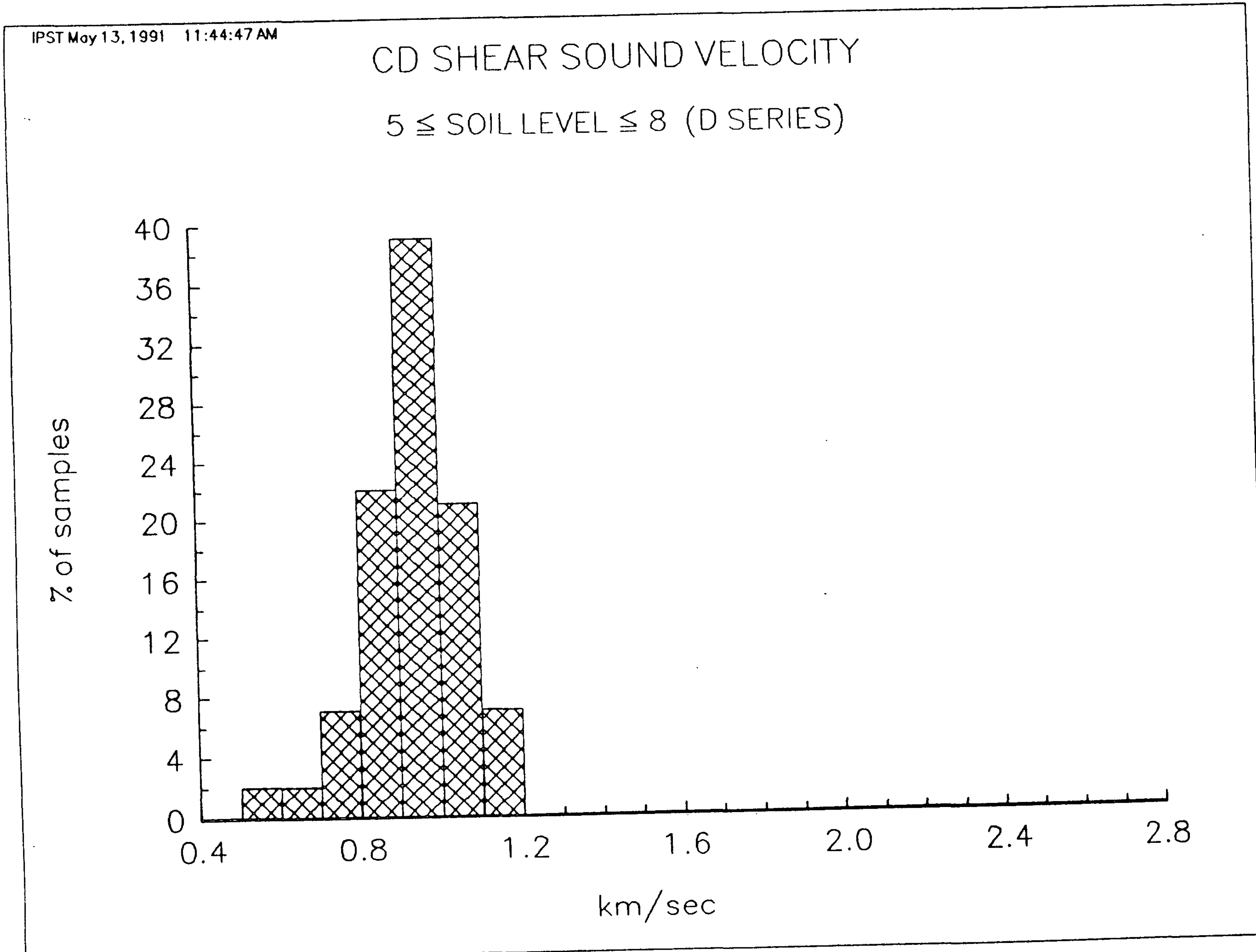

IPST May 13, 1991 11:44:47 AM
CD SHEAR SOUND VELOCITY
5 ≦ SOIL LEVEL ≦ 8 (D SERIES)
% of samples
40
36
32
28
24
20
16
12
8
4
0
0.4
0.8
1.2
1.6
2.0
2.4
2.8
km/sec

Figure 34

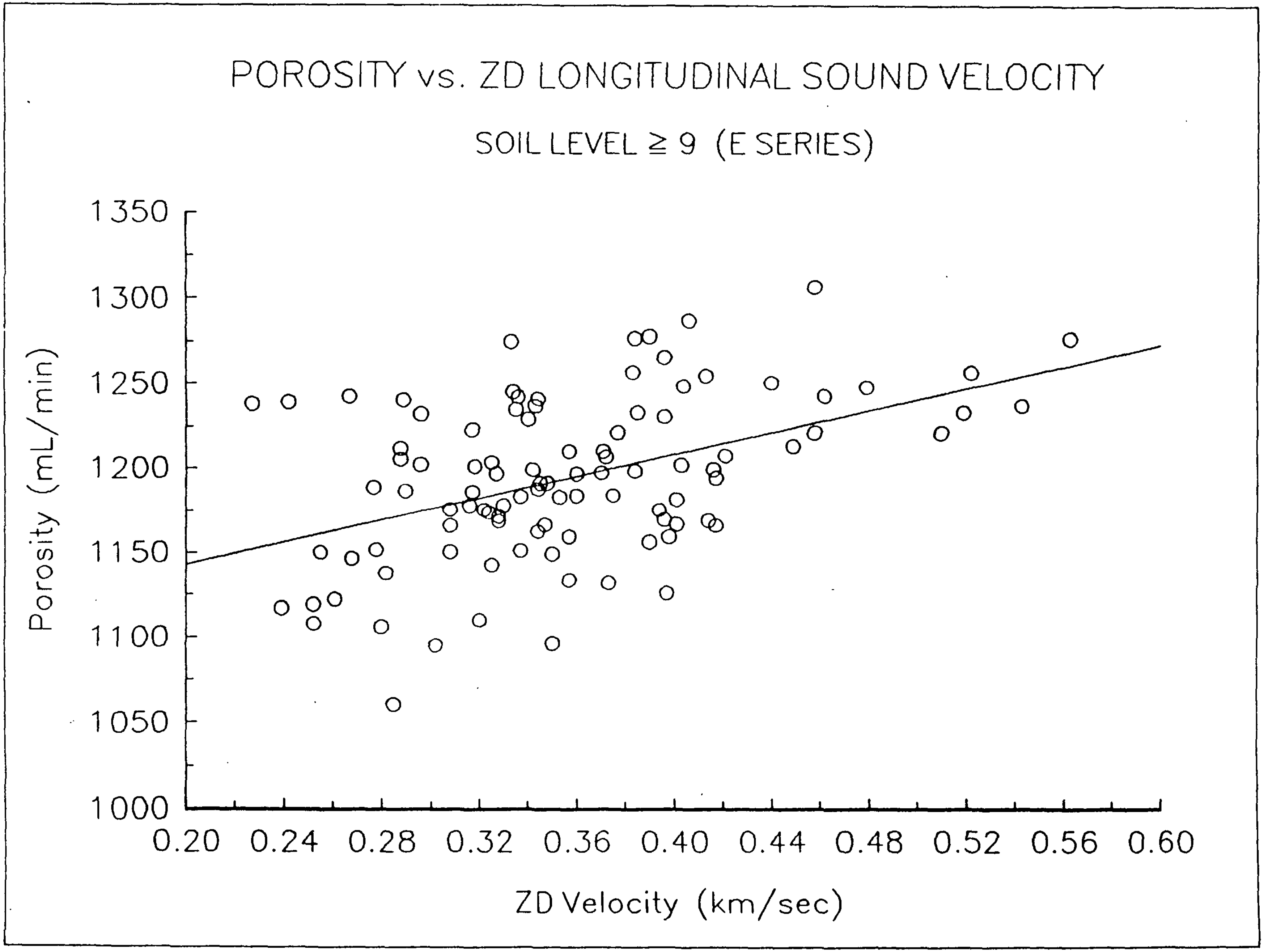

POROSITY vs. ZD LONGITUDINAL SOUND VELOCITY
SOIL LEVEL ≧ 9 (E SERIES)
Porosity (mL/min)
1350
1300
1250
1200
1150
1100
1050
1000
0.20
0.24
0.28
0.32
0.36
0.40
0.44
0.48
0.52
0.56
0.60
ZD Velocity (km/sec)

Figure 35

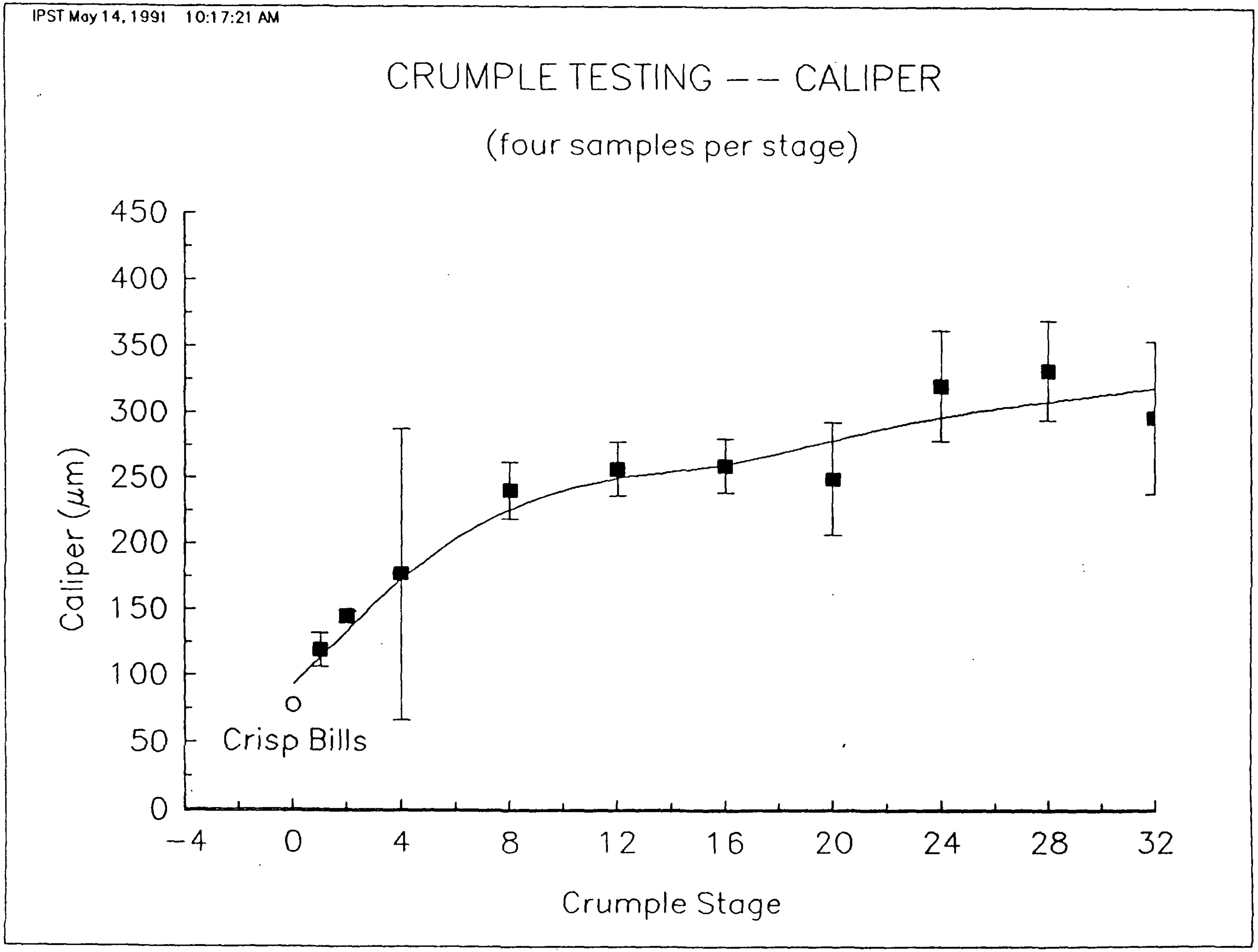

IPST May 14, 1991 10:17:21 AM
CRUMPLE TESTING -- CALIPER
(four samples per stage)
Caliper (μm)
450
400
350
300
250
200
150
100
50
0
Crisp Bills
-4
0
4
8
12
16
20
24
28
32
Crumple Stage

Figure 36

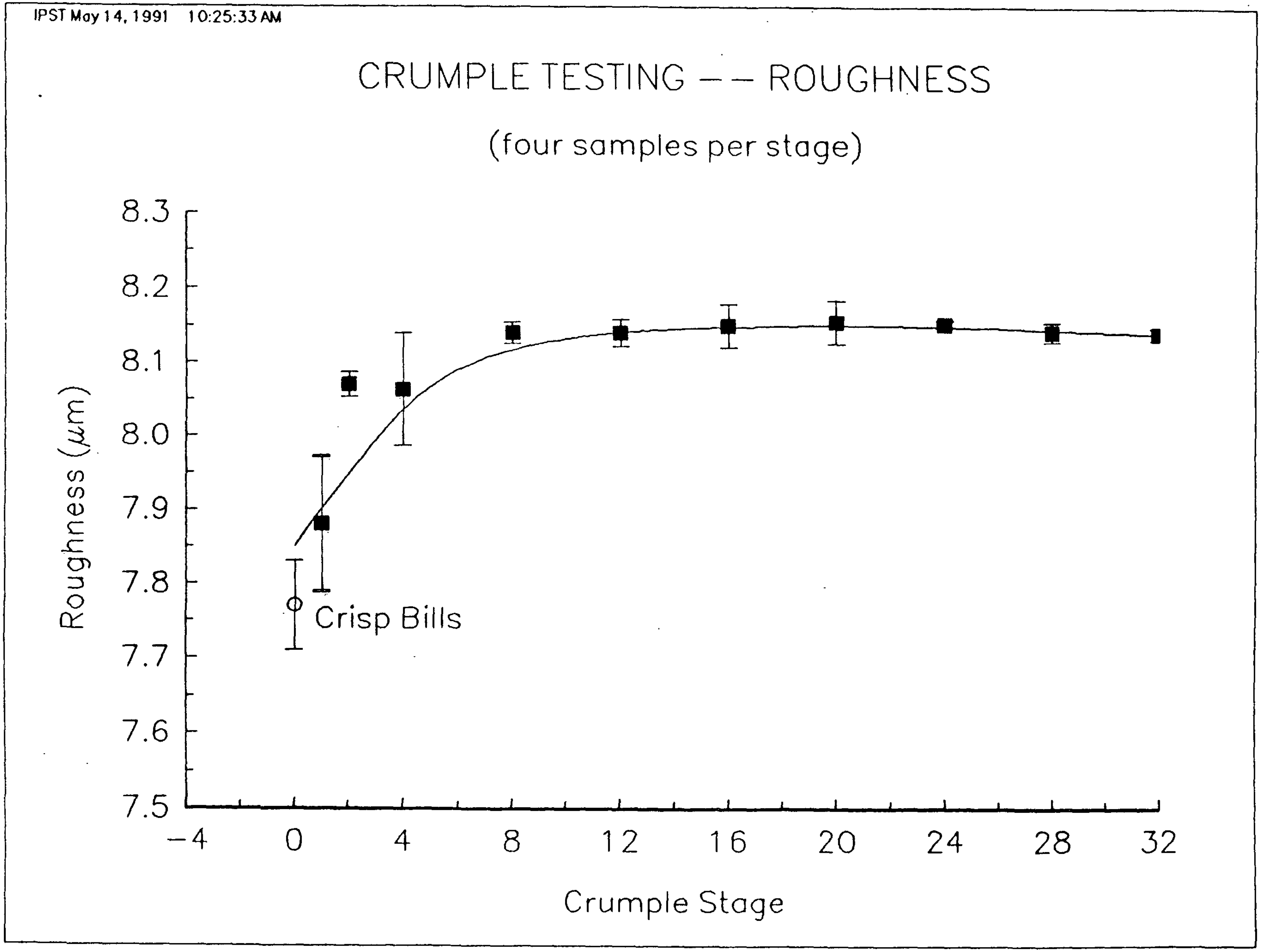

IPST May 14, 1991 10:25:33 AM
CRUMPLE TESTING -- ROUGHNESS
(four samples per stage)
8.3
8.2
8.1
8.0
7.9
7.8
7.7
7.6
7.5
Roughness (μm)
Crisp Bills
-4
0
4
8
12
16
20
24
28
32
Crumple Stage

Figure 37

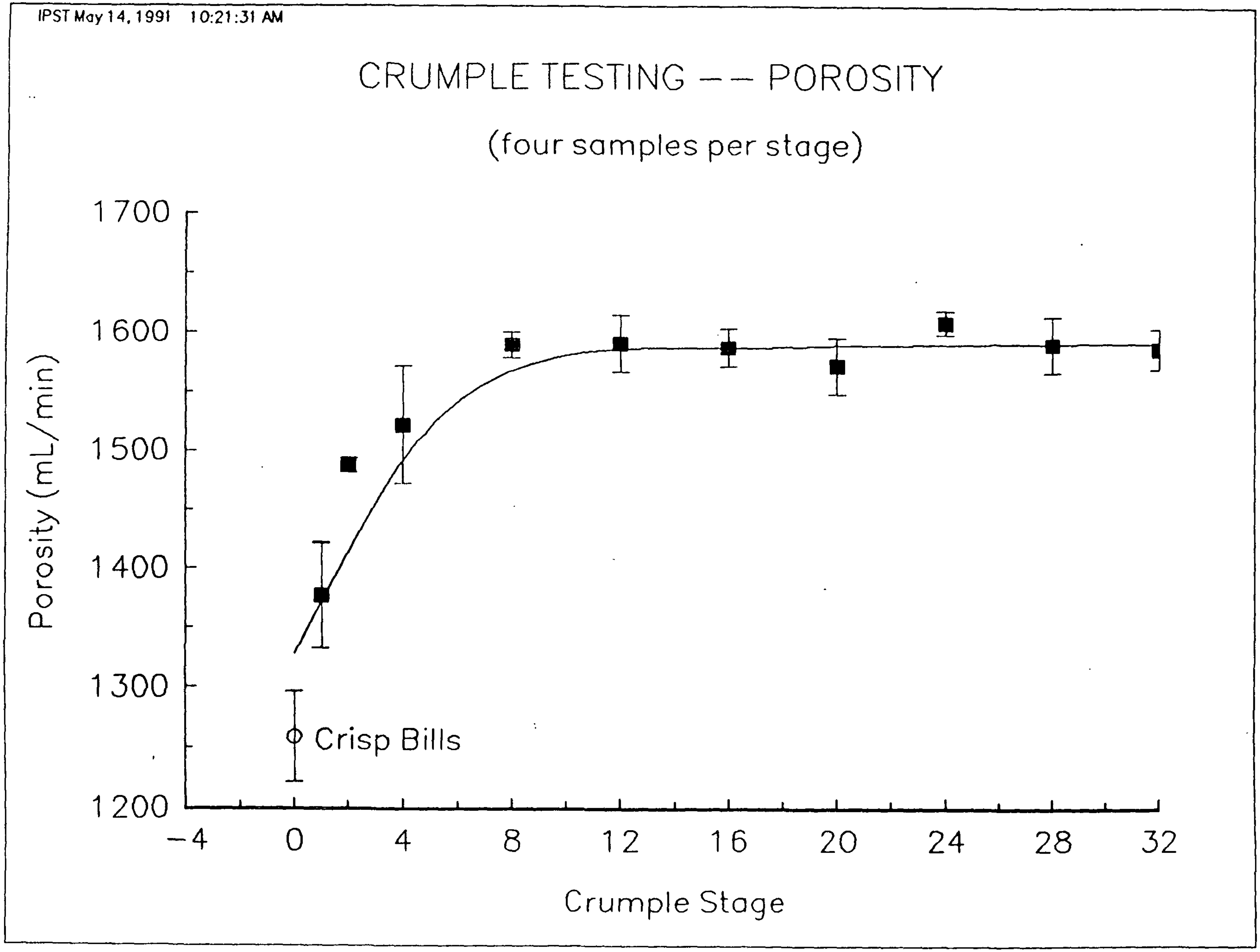

IPST May 14, 1991 10:21:31 AM
CRUMPLE TESTING -- POROSITY
(four samples per stage)
Porosity (mL/min)
1700
1600
1500
1400
1300
1200
Crisp Bills
-4
0
4
8
12
16
20
24
28
32
Crumple Stage

Figure 38

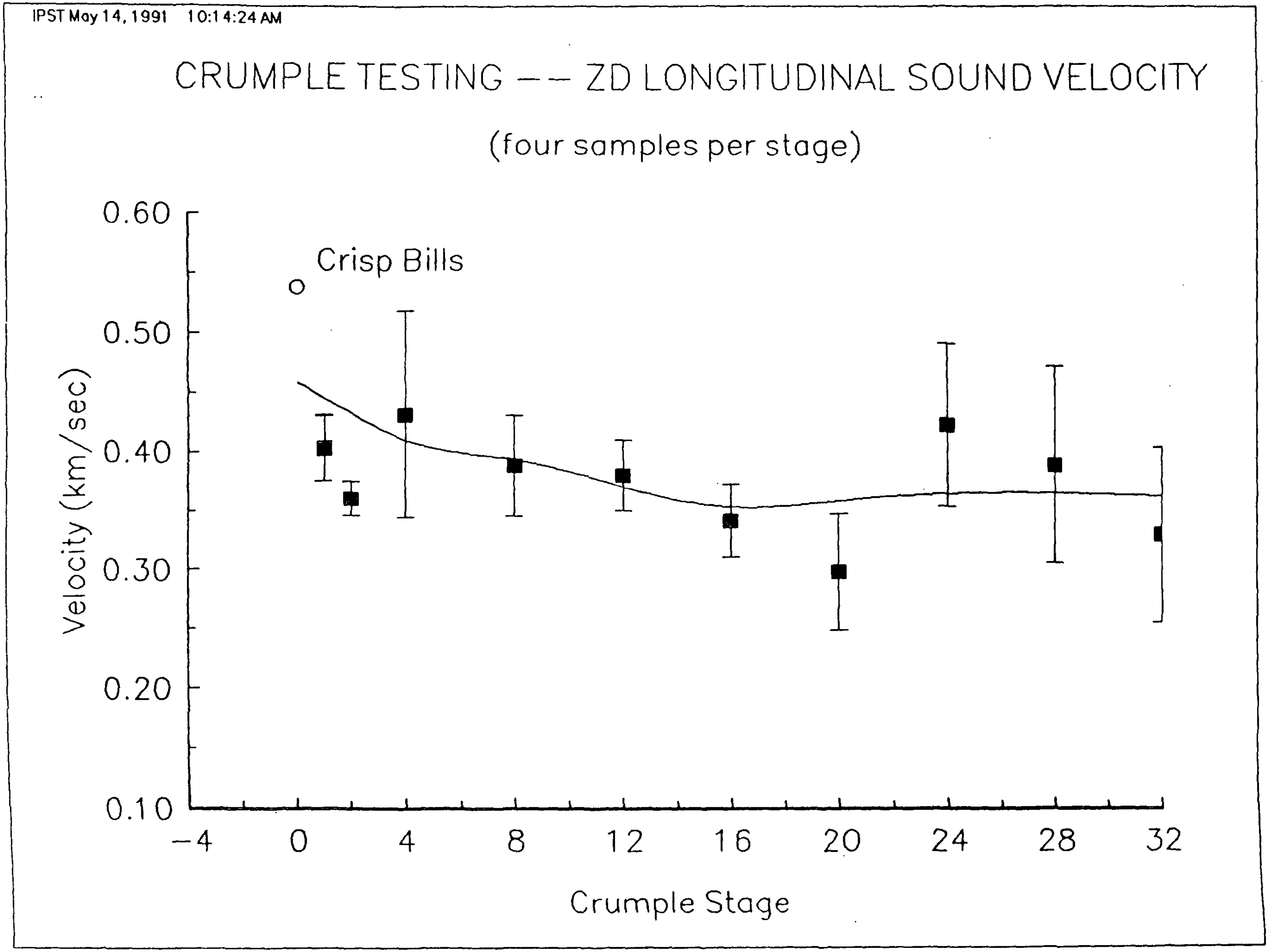

IPST May 14, 1991 10:14:24 AM
CRUMPLE TESTING -- ZD LONGITUDINAL SOUND VELOCITY
(four samples per stage)
Crisp Bills
Velocity (km/sec)
0.60
0.50
0.40
0.30
0.20
0.10
-4
0
4
8
12
16
20
24
28
32
Crumple Stage

Figure 39

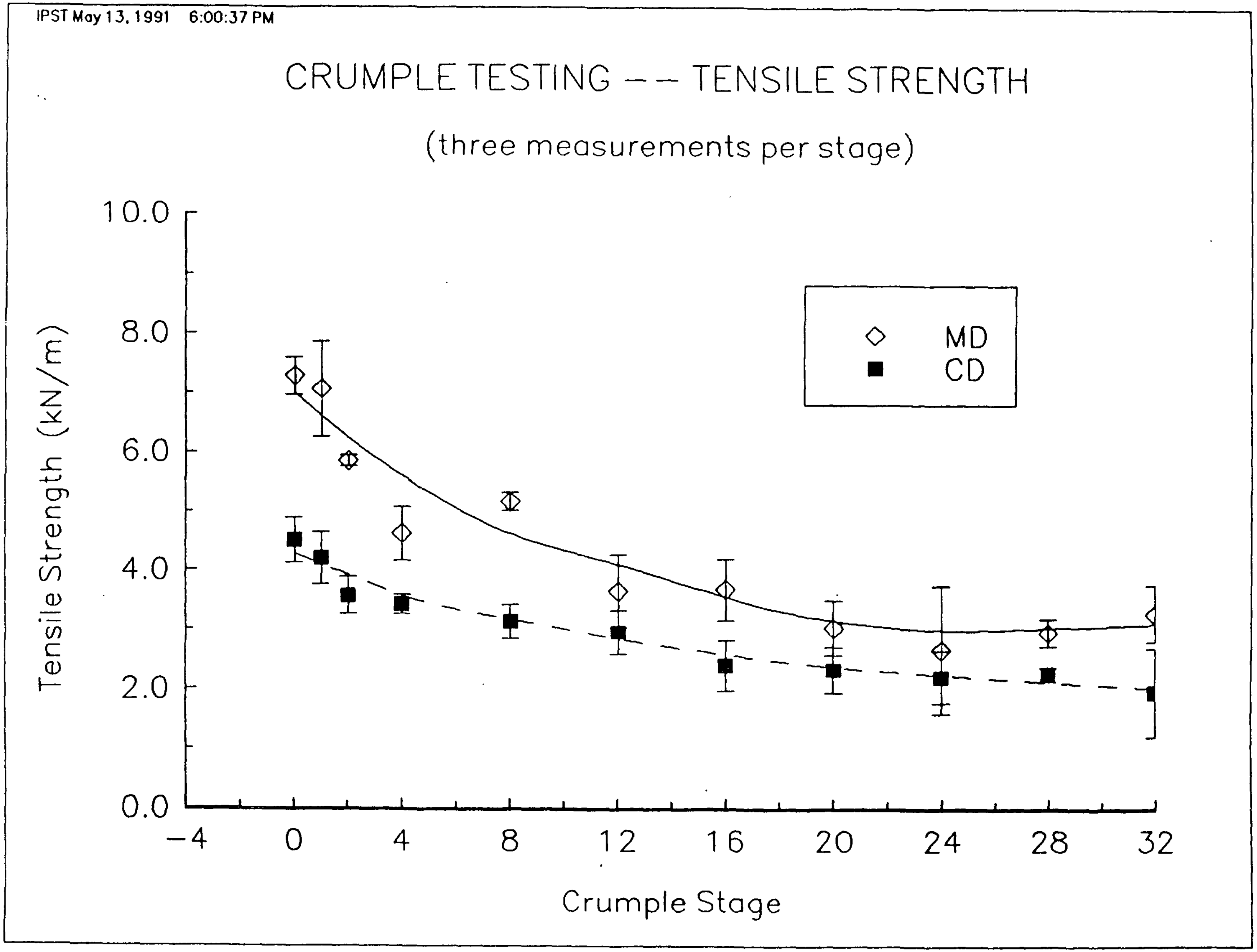

IPST May 13, 1991 6:00:37 PM
CRUMPLE TESTING -- TENSILE STRENGTH
(three measurements per stage)
Tensile Strength (kN/m)
10.0
8.0
6.0
4.0
2.0
0.0
-4
0
4
8
12
16
20
24
28
32
Crumple Stage
MD
CD

Figure 40

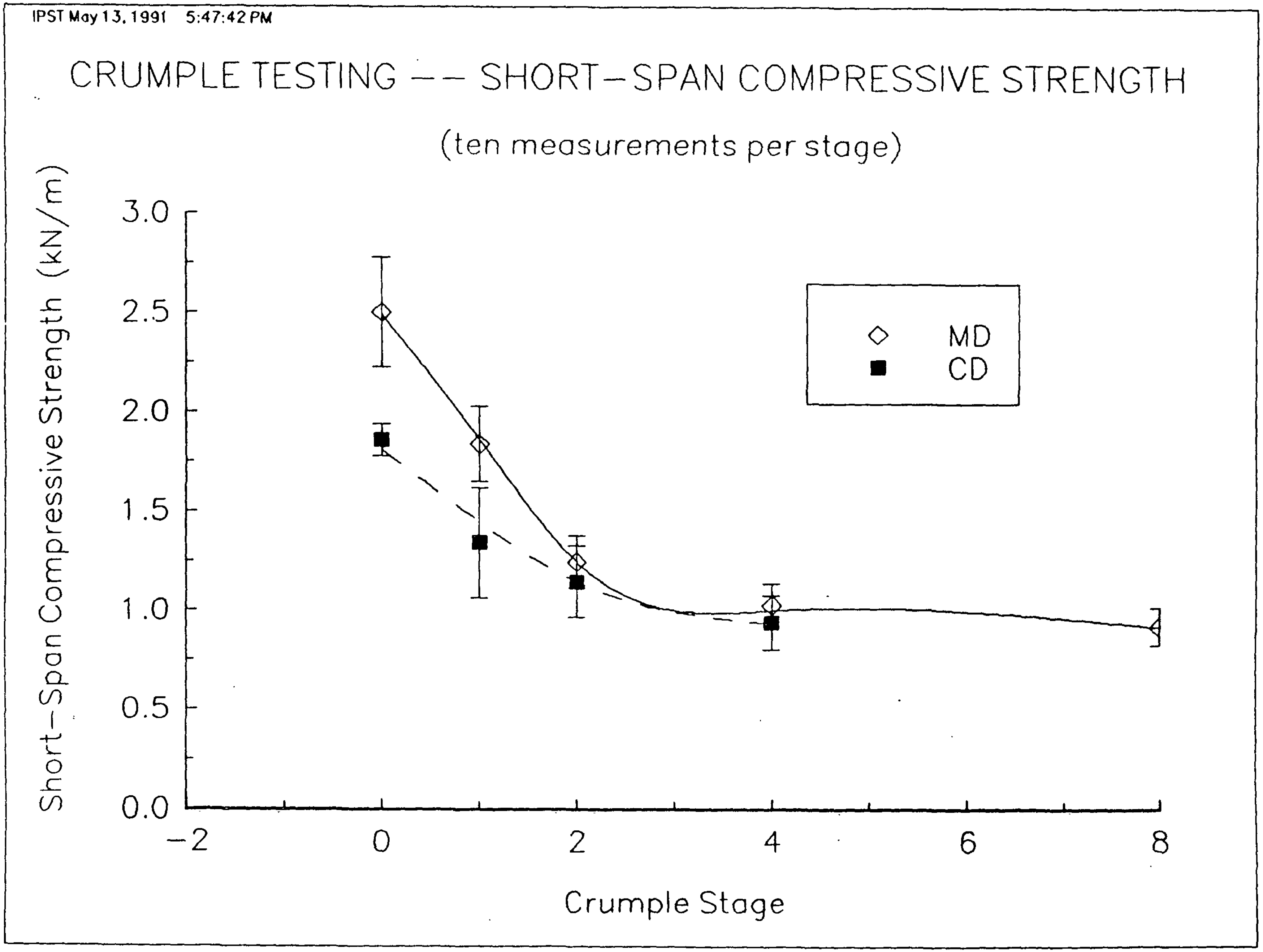

IPST May 13, 1991 5:47:42 PM
CRUMPLE TESTING -- SHORT-SPAN COMPRESSIVE STRENGTH
(ten measurements per stage)
Short-Span Compressive Strength (kN/m)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-2
0
2
4
6
8
Crumple Stage
MD
CD

Figure 41

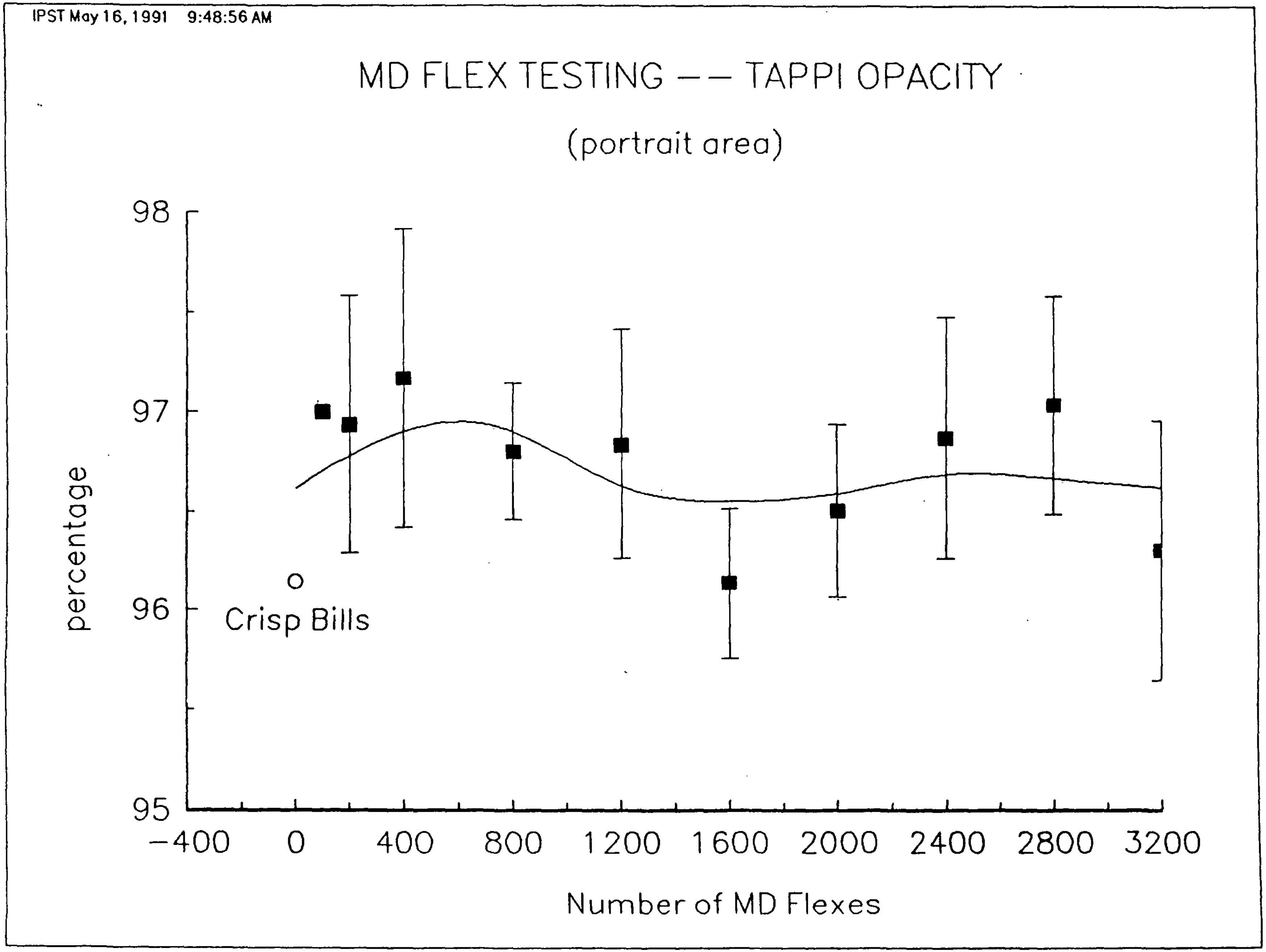
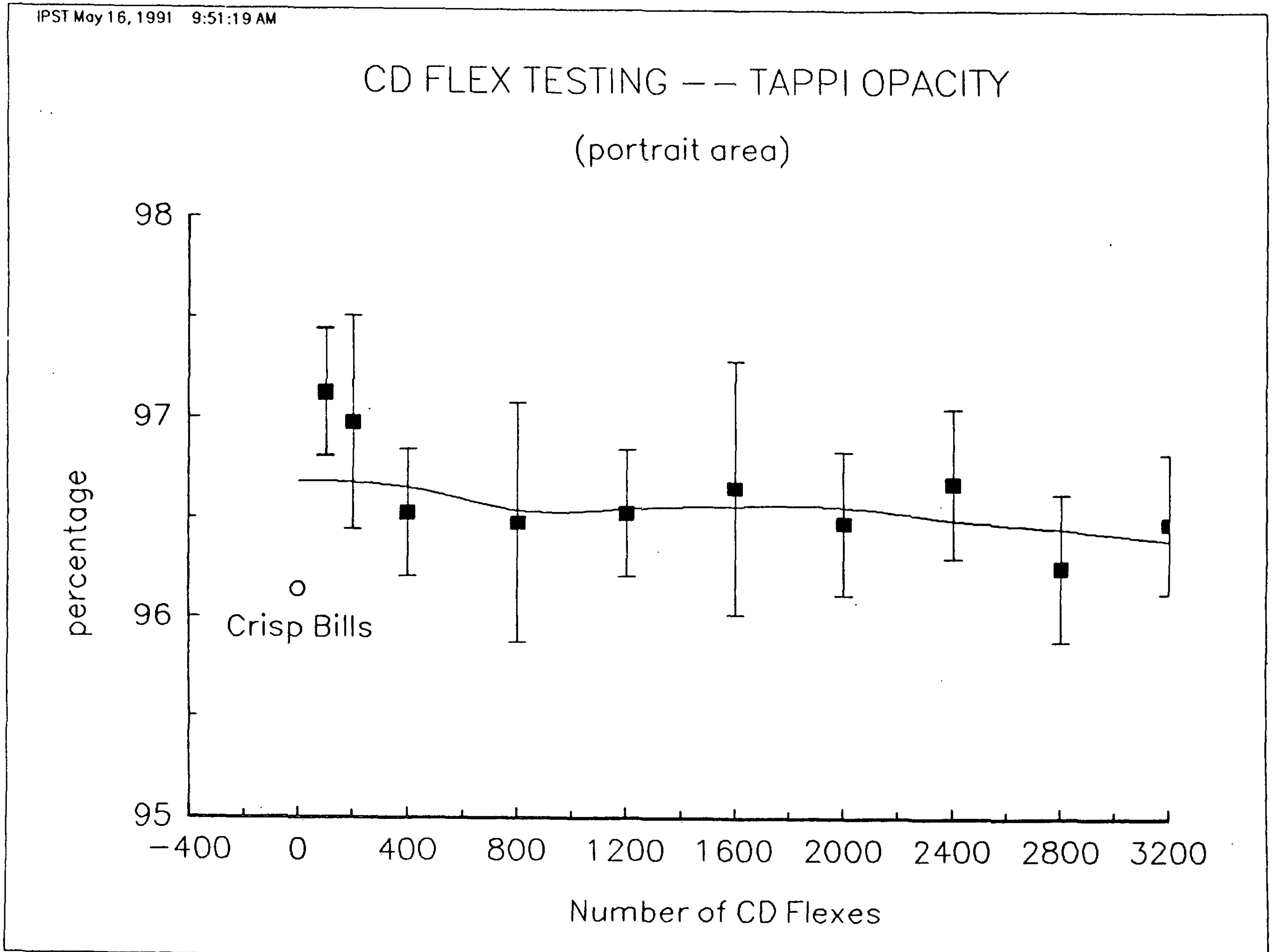

IPST May 16, 1991 9:48:56 AM
MD FLEX TESTING -- TAPPI OPACITY
(portrait area)
98
97
96
95
percentage
Crisp Bills
-400
0
400
800
1200
1600
2000
2400
2800
3200
Number of MD Flexes

Figure 42


IPST May 16, 1991 9:51:19 AM
CD FLEX TESTING -- TAPPI OPACITY
(portrait area)
98
97
96
95
percentage
Crisp Bills
-400
0
400
800
1200
1600
2000
2400
2800
3200
Number of CD Flexes
Figure 43

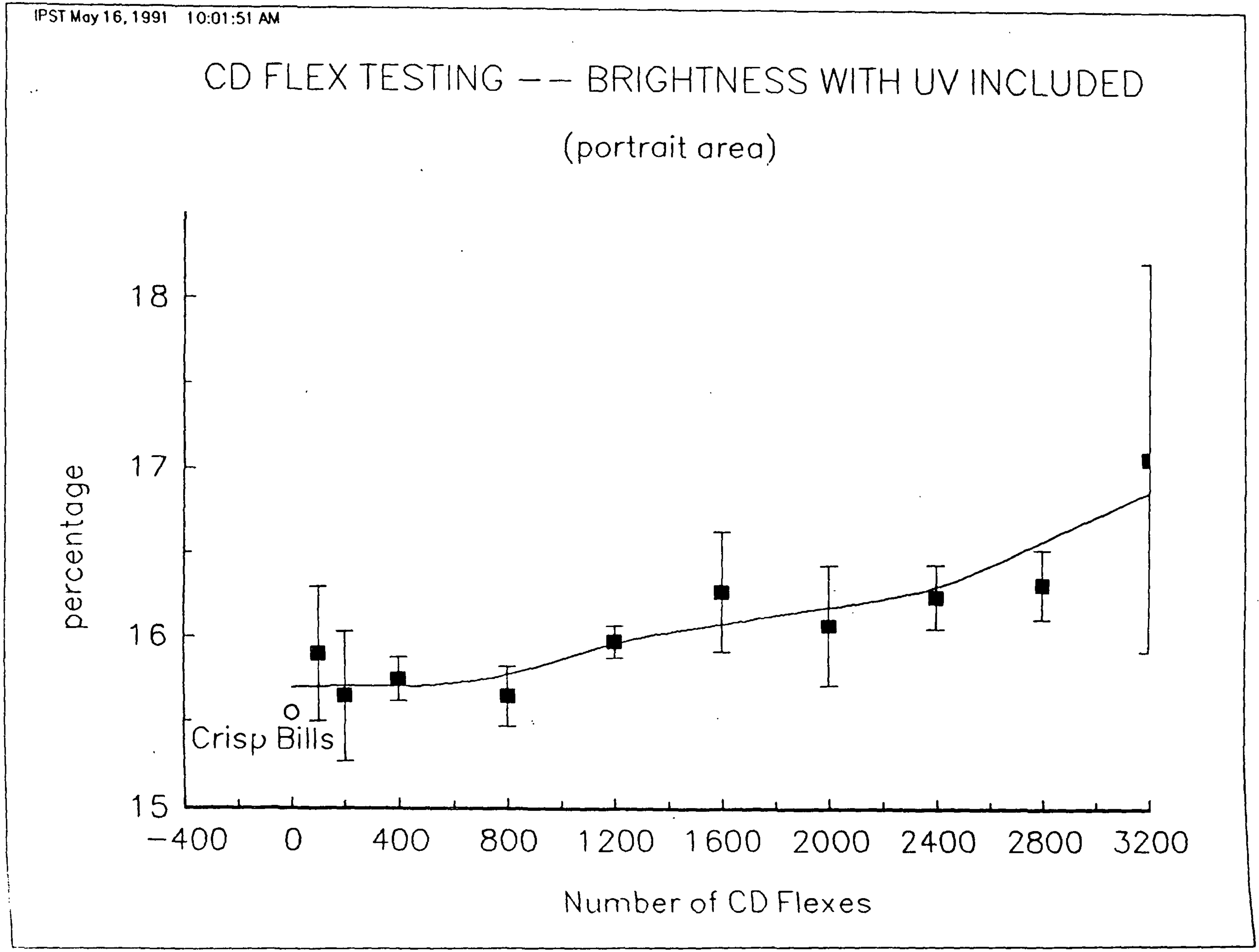

IPST May 16, 1991 10:01:51 AM
CD FLEX TESTING -- BRIGHTNESS WITH UV INCLUDED
(portrait area)
percentage
18
17
16
15
Crisp Bills
-400
0
400
800
1200
1600
2000
2400
2800
3200
Number of CD Flexes

Figure 45

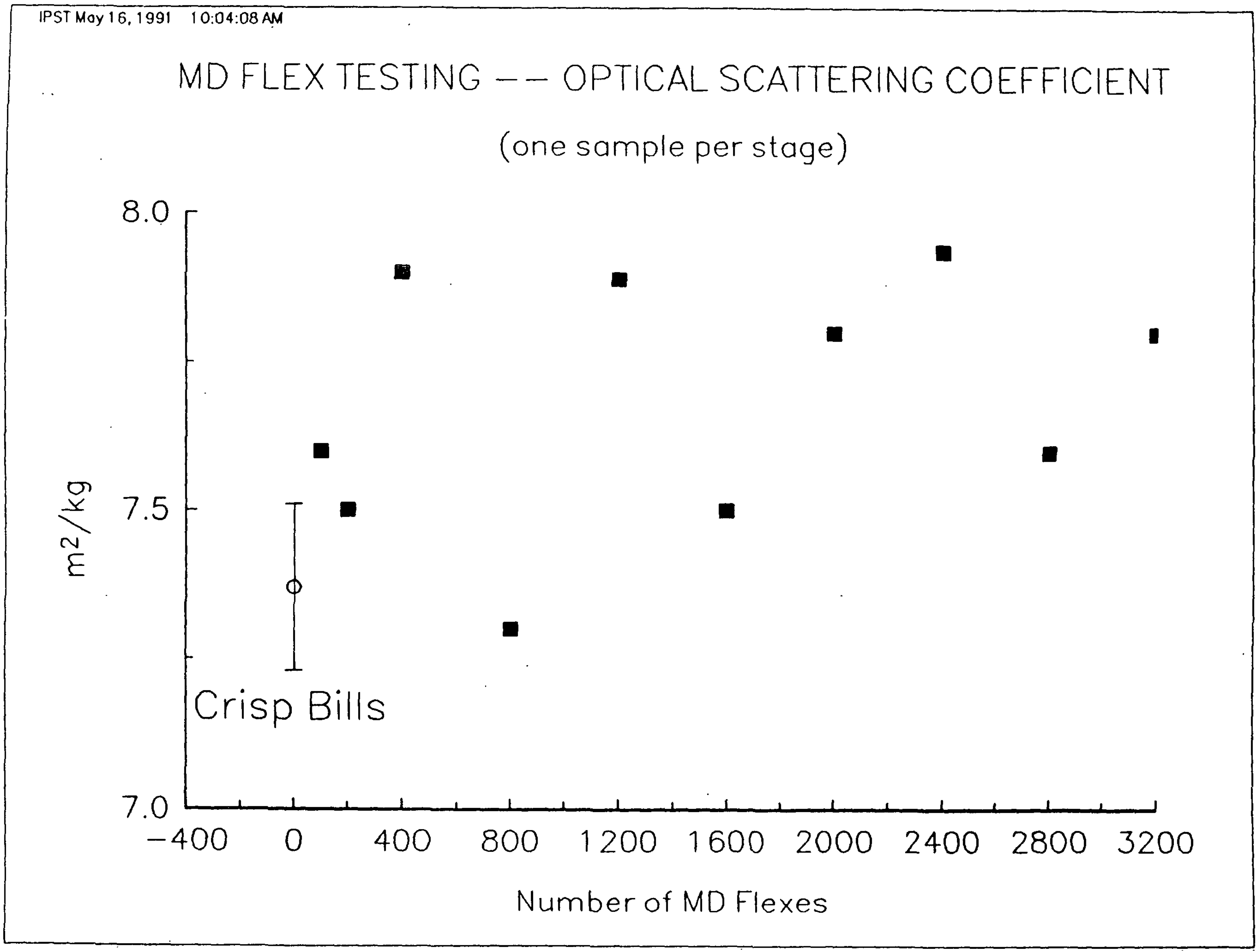

IPST May 16, 1991 10:04:08 AM
MD FLEX TESTING -- OPTICAL SCATTERING COEFFICIENT
(one sample per stage)
8.0
7.5
7.0
m2/kg
Crisp Bills
-400
0
400
800
1200
1600
2000
2400
2800
3200
Number of MD Flexes

Figure 46

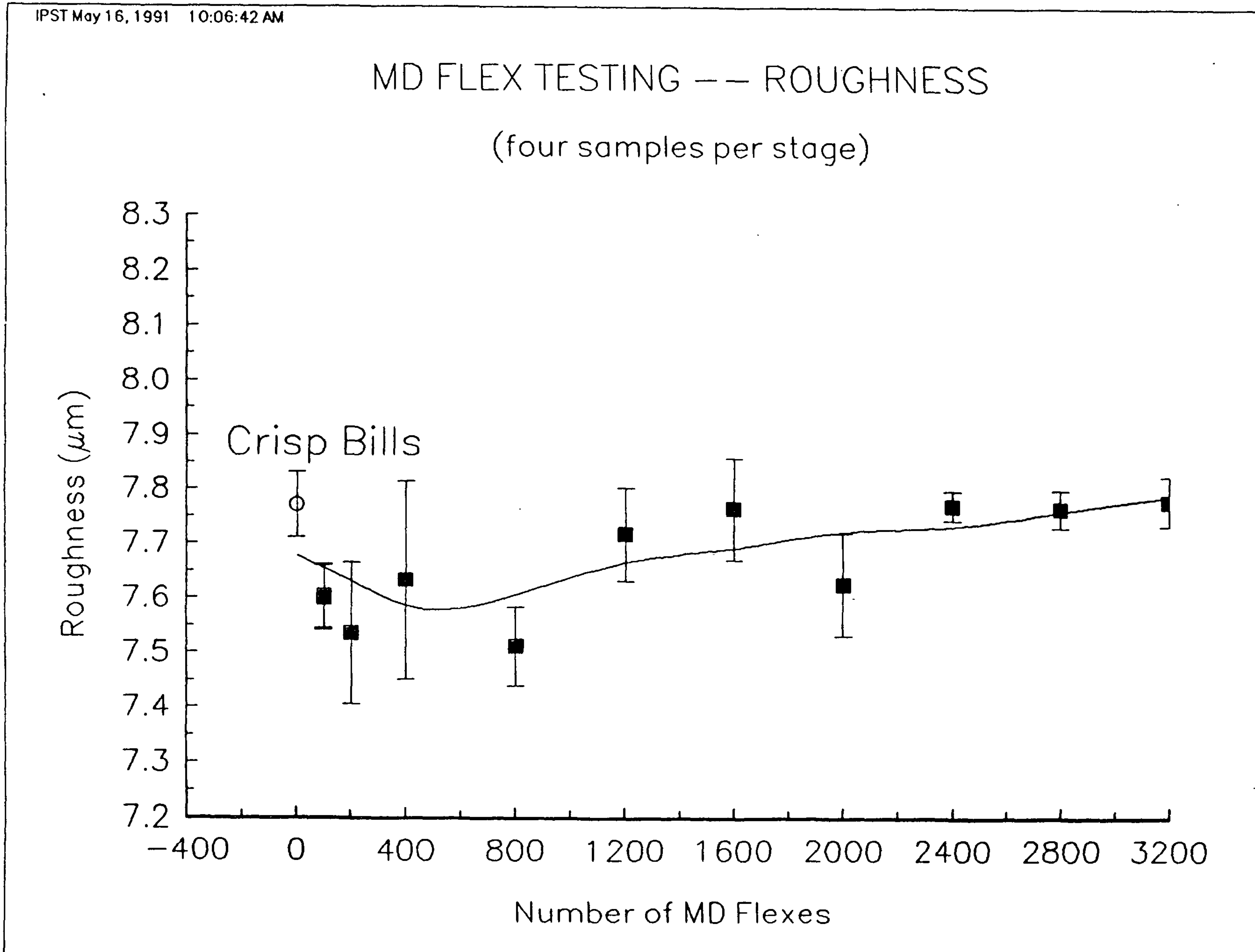

IPST May 16, 1991 10:06:42 AM
MD FLEX TESTING -- ROUGHNESS
(four samples per stage)
Crisp Bills
Roughness (μm)
8.3
8.2
8.1
8.0
7.9
7.8
7.7
7.6
7.5
7.4
7.3
7.2
-400
0
400
800
1200
1600
2000
2400
2800
3200
Number of MD Flexes

Figure 47

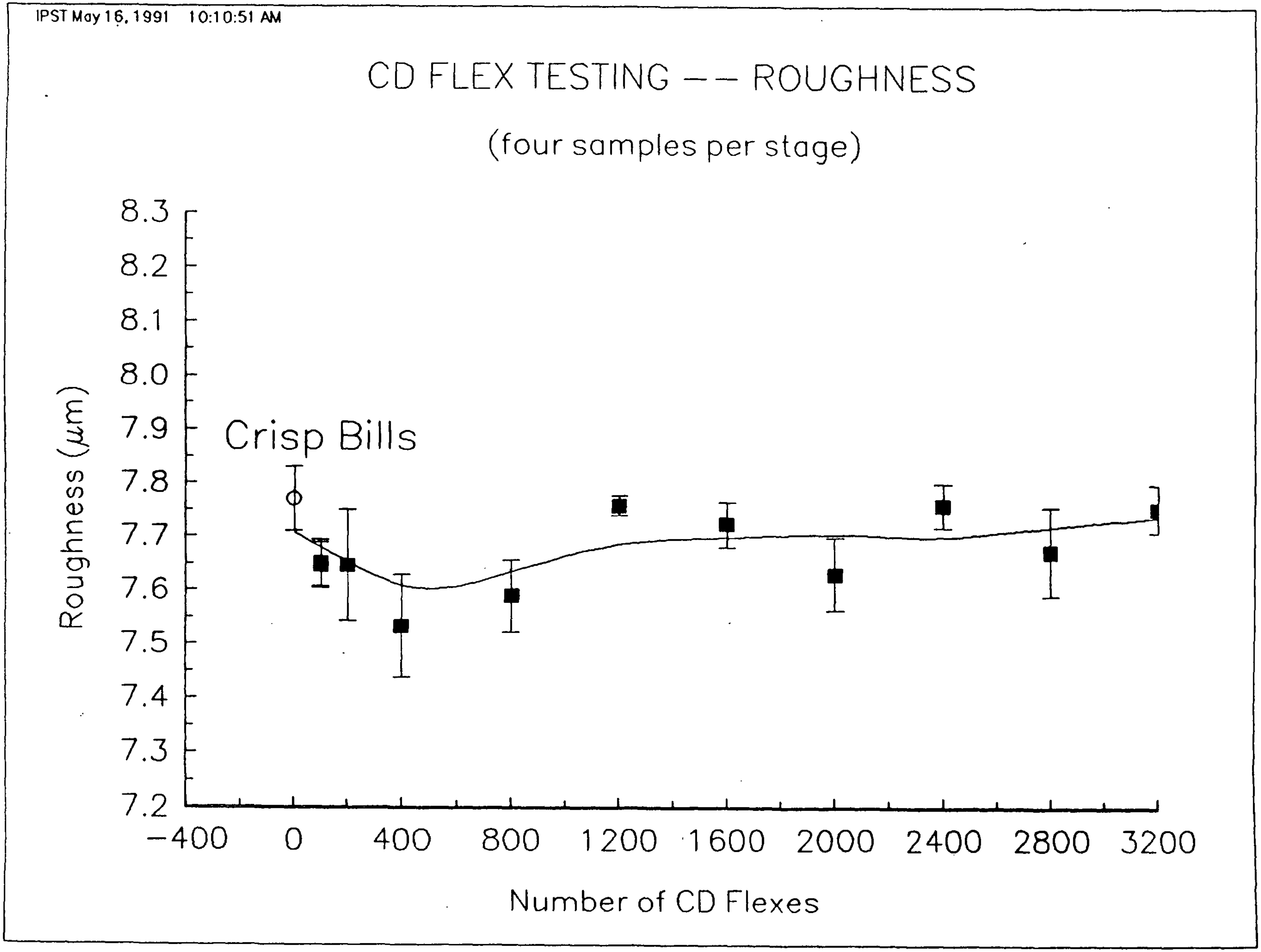

IPST May 16, 1991 10:10:51 AM
CD FLEX TESTING -- ROUGHNESS
(four samples per stage)
Roughness (μm)
8.3
8.2
8.1
8.0
7.9
7.8
7.7
7.6
7.5
7.4
7.3
7.2
Crisp Bills
−400
0
400
800
1200
1600
2000
2400
2800
3200
Number of CD Flexes

Figure 48

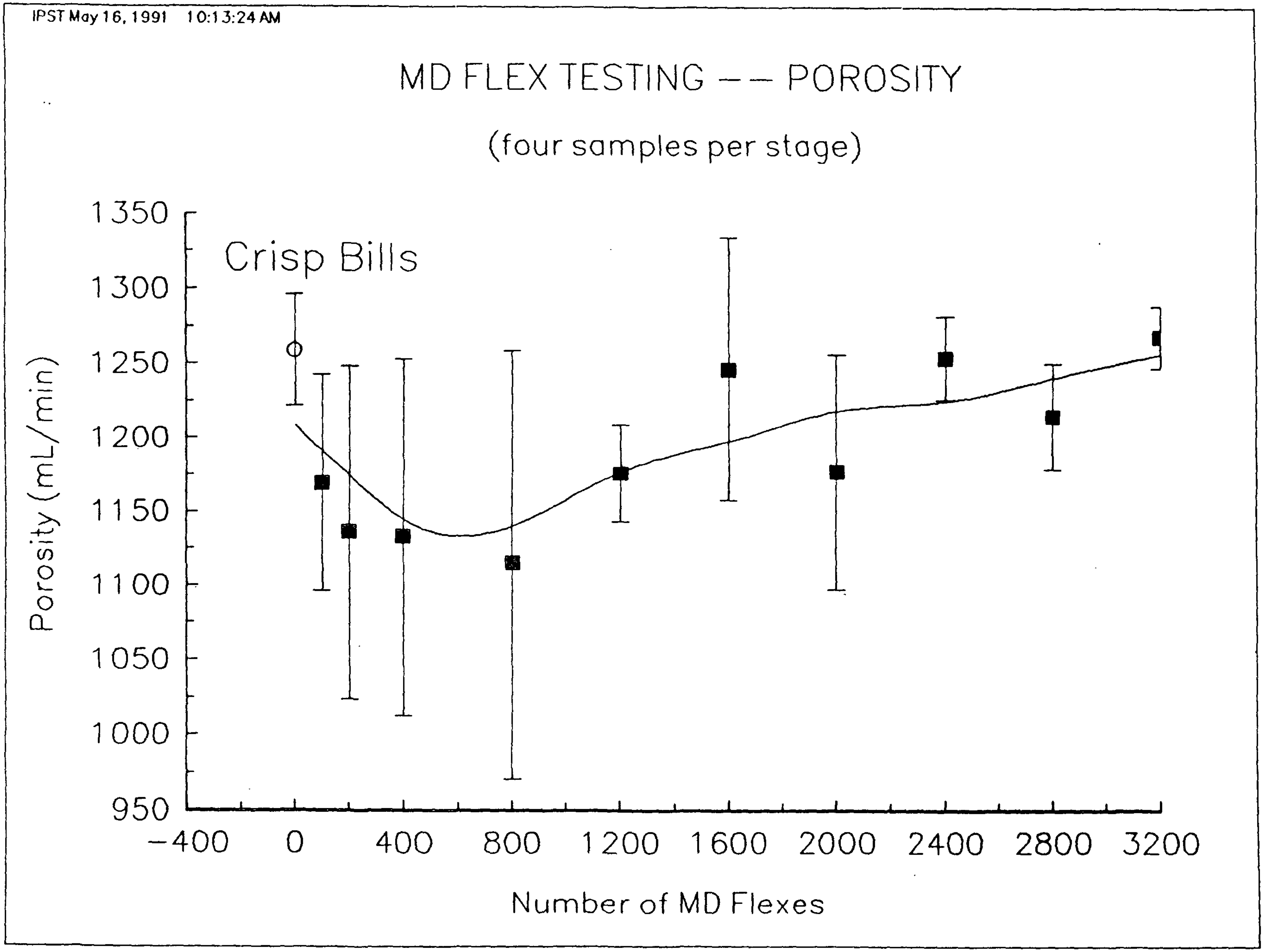

IPST May 16, 1991 10:13:24 AM
MD FLEX TESTING -- POROSITY
(four samples per stage)
Crisp Bills
Porosity (mL/min)
1350
1300
1250
1200
1150
1100
1050
1000
950
-400
0
400
800
1200
1600
2000
2400
2800
3200
Number of MD Flexes

Figure 49

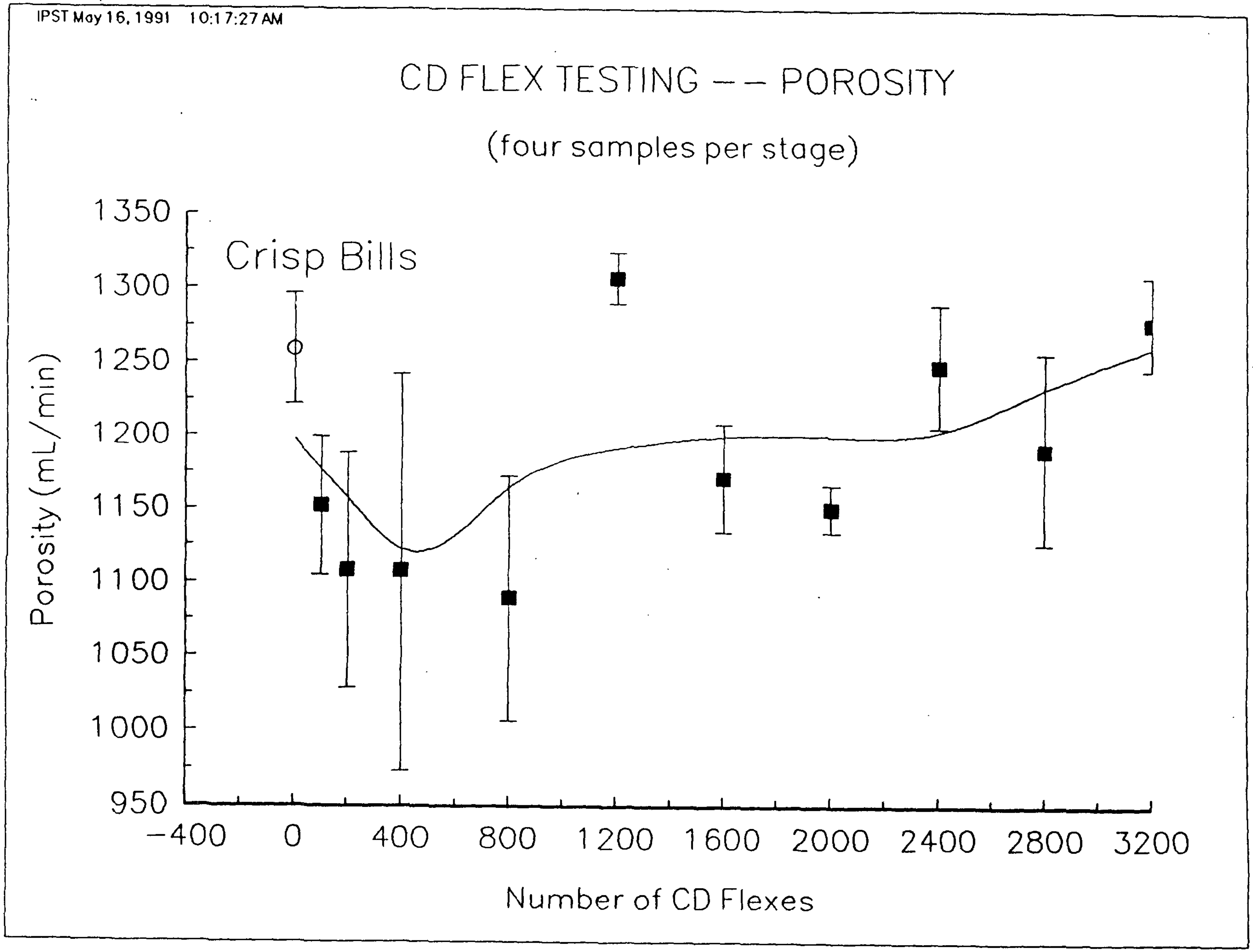

IPST May 16, 1991 10:17:27 AM
CD FLEX TESTING -- POROSITY
(four samples per stage)
Crisp Bills
Porosity (mL/min)
1350
1300
1250
1200
1150
1100
1050
1000
950
-400
0
400
800
1200
1600
2000
2400
2800
3200
Number of CD Flexes

Figure 50

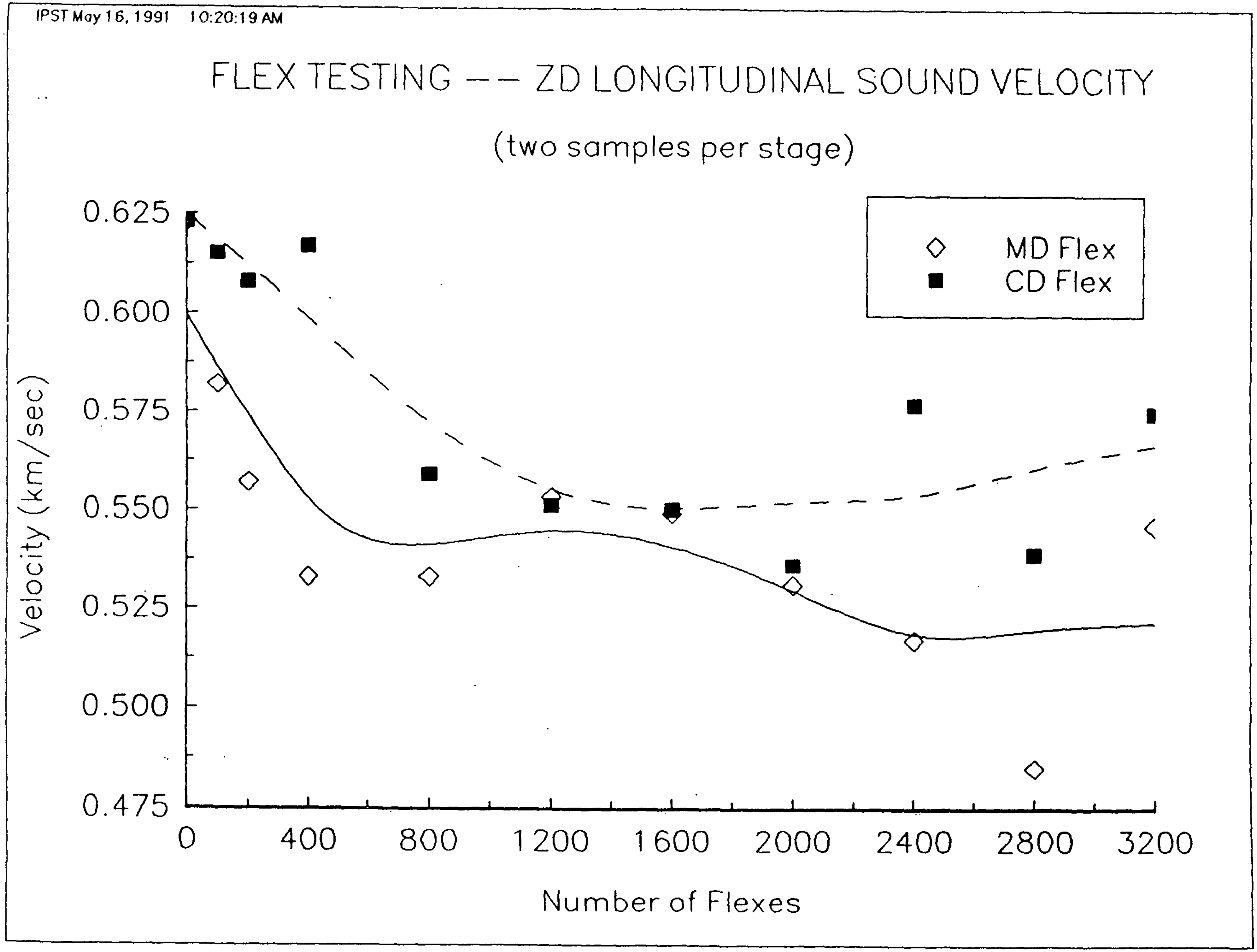

IPST May 16, 1991 10:20:19 AM
FLEX TESTING -- ZD LONGITUDINAL SOUND VELOCITY
(two samples per stage)
MD Flex
CD Flex
Velocity (km/sec)
0.625
0.600
0.575
0.550
0.525
0.500
0.475
0
400
800
1200
1600
2000
2400
2800
3200
Number of Flexes

Figure 51

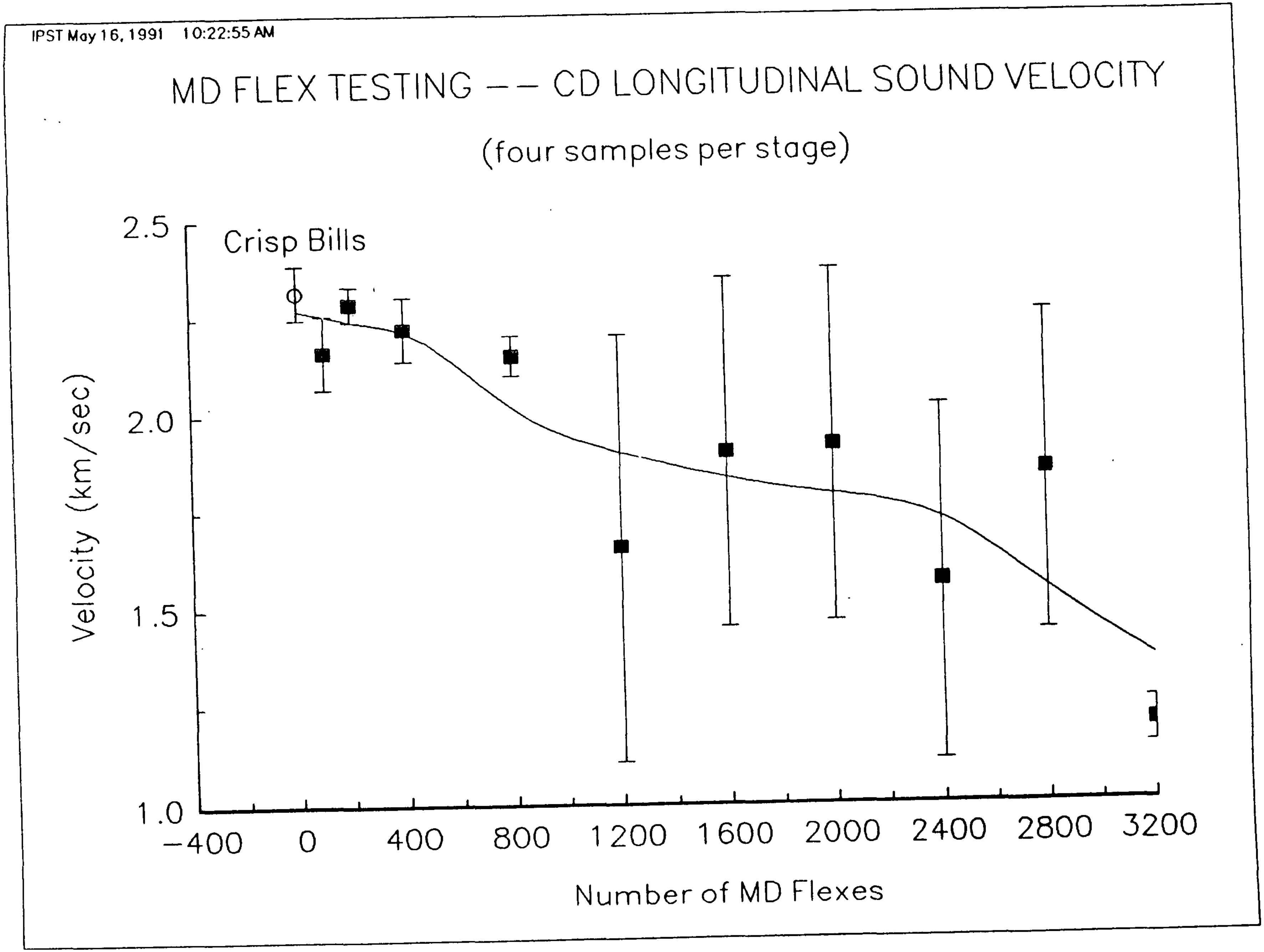

IPST May 16, 1991 10:22:55 AM
MD FLEX TESTING -- CD LONGITUDINAL SOUND VELOCITY
(four samples per stage)
Crisp Bills
Velocity (km/sec)
2.5
2.0
1.5
1.0
-400
0
400
800
1200
1600
2000
2400
2800
3200
Number of MD Flexes

Figure 52

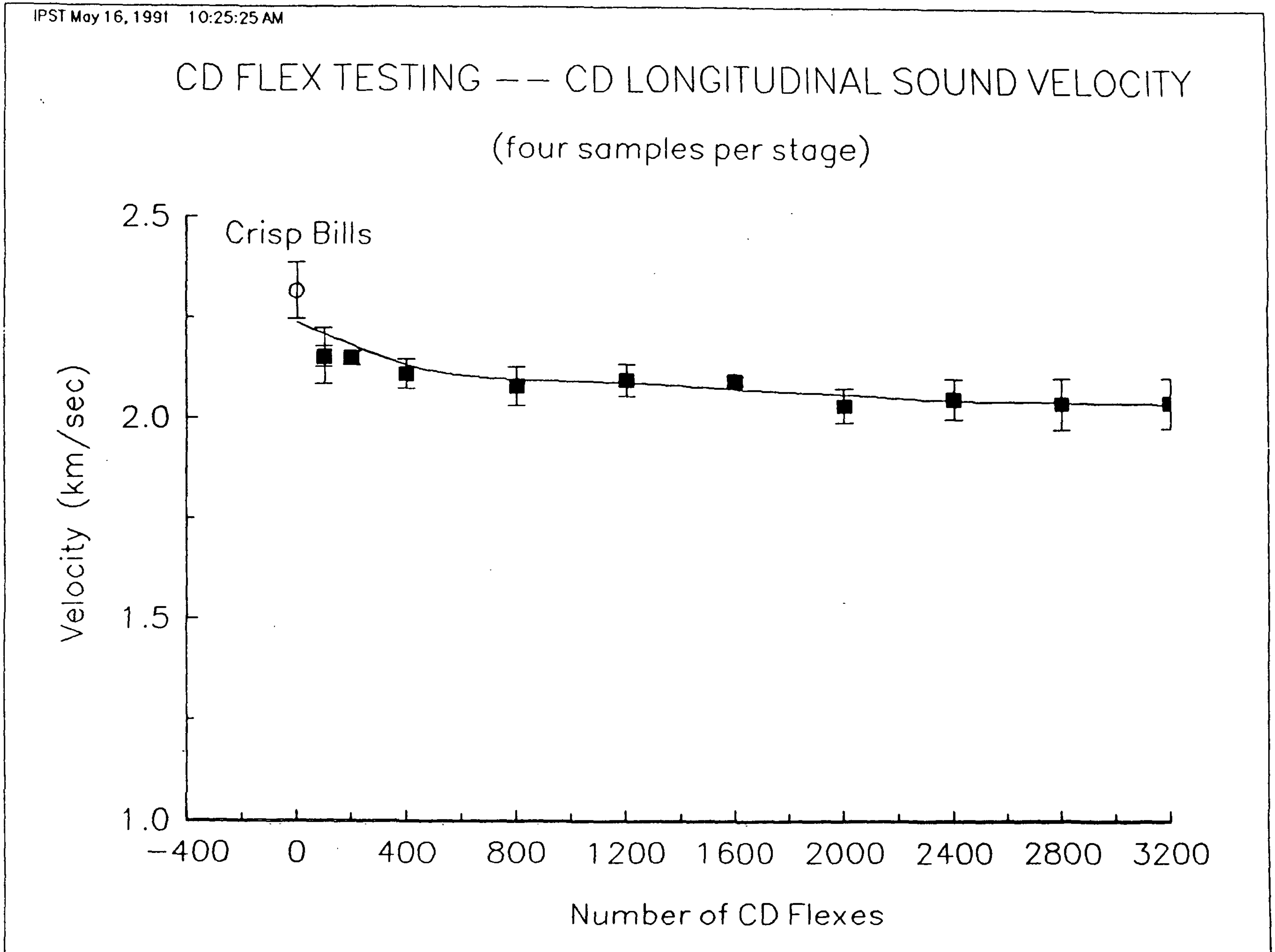

IPST May 16, 1991 10:25:25 AM
CD FLEX TESTING -- CD LONGITUDINAL SOUND VELOCITY
(four samples per stage)
Crisp Bills
Velocity (km/sec)
2.5
2.0
1.5
1.0
-400
0
400
800
1200
1600
2000
2400
2800
3200
Number of CD Flexes

Figure 53

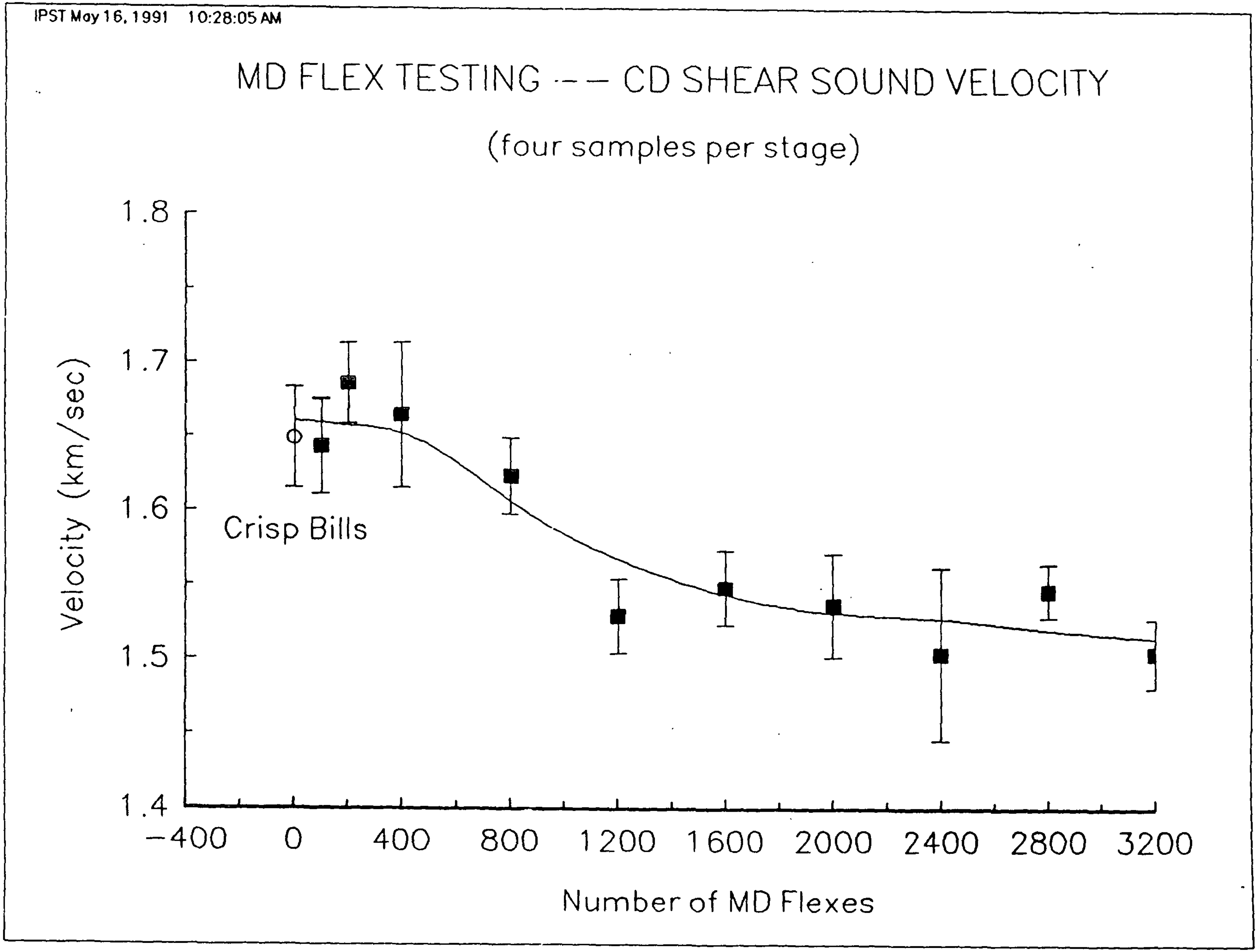

IPST May 16, 1991 10:28:05 AM
MD FLEX TESTING --- CD SHEAR SOUND VELOCITY
(four samples per stage)
Velocity (km/sec)
1.8
1.7
1.6
1.5
1.4
Crisp Bills
-400
0
400
800
1200
1600
2000
2400
2800
3200
Number of MD Flexes

Figure 54

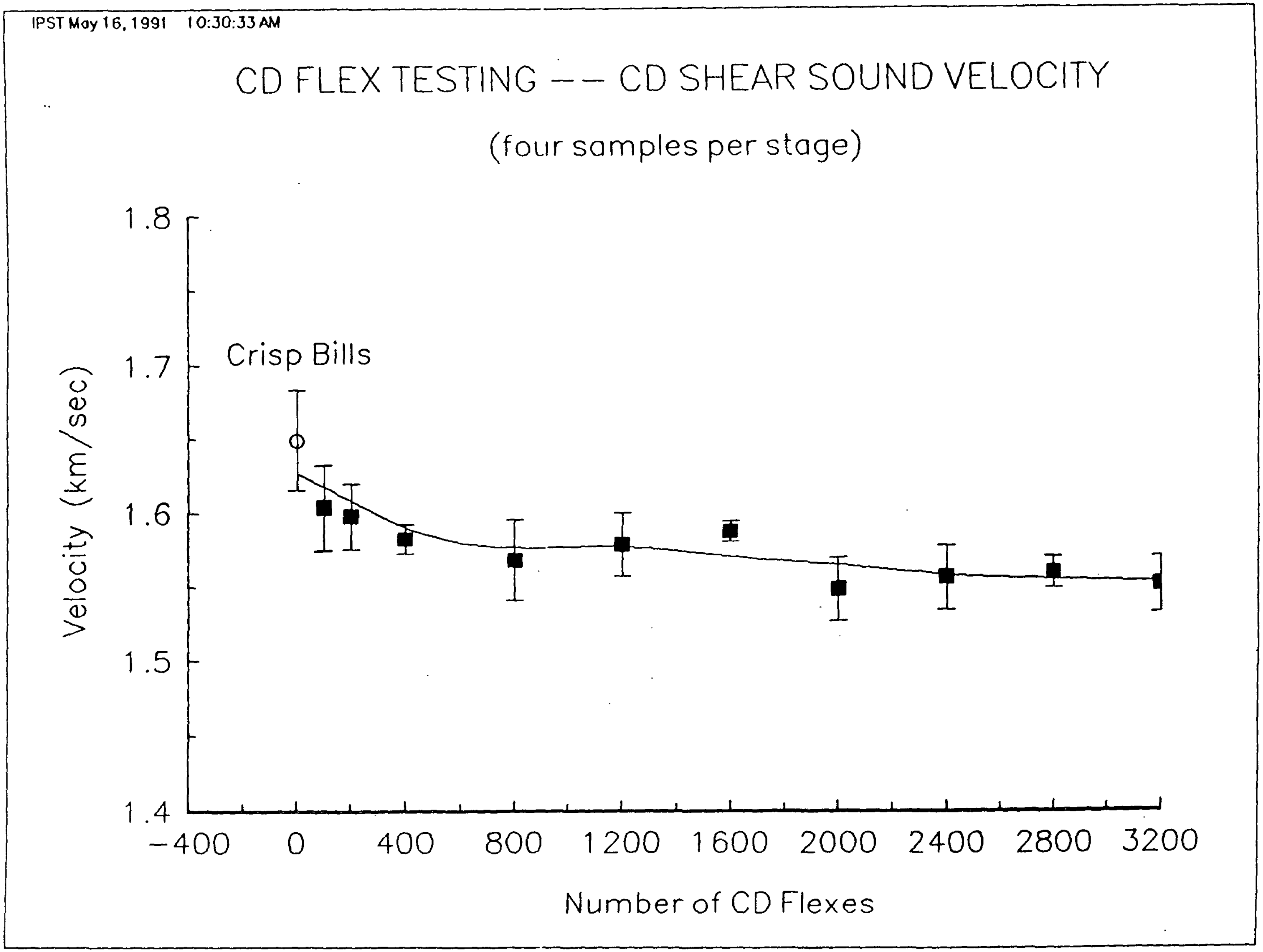
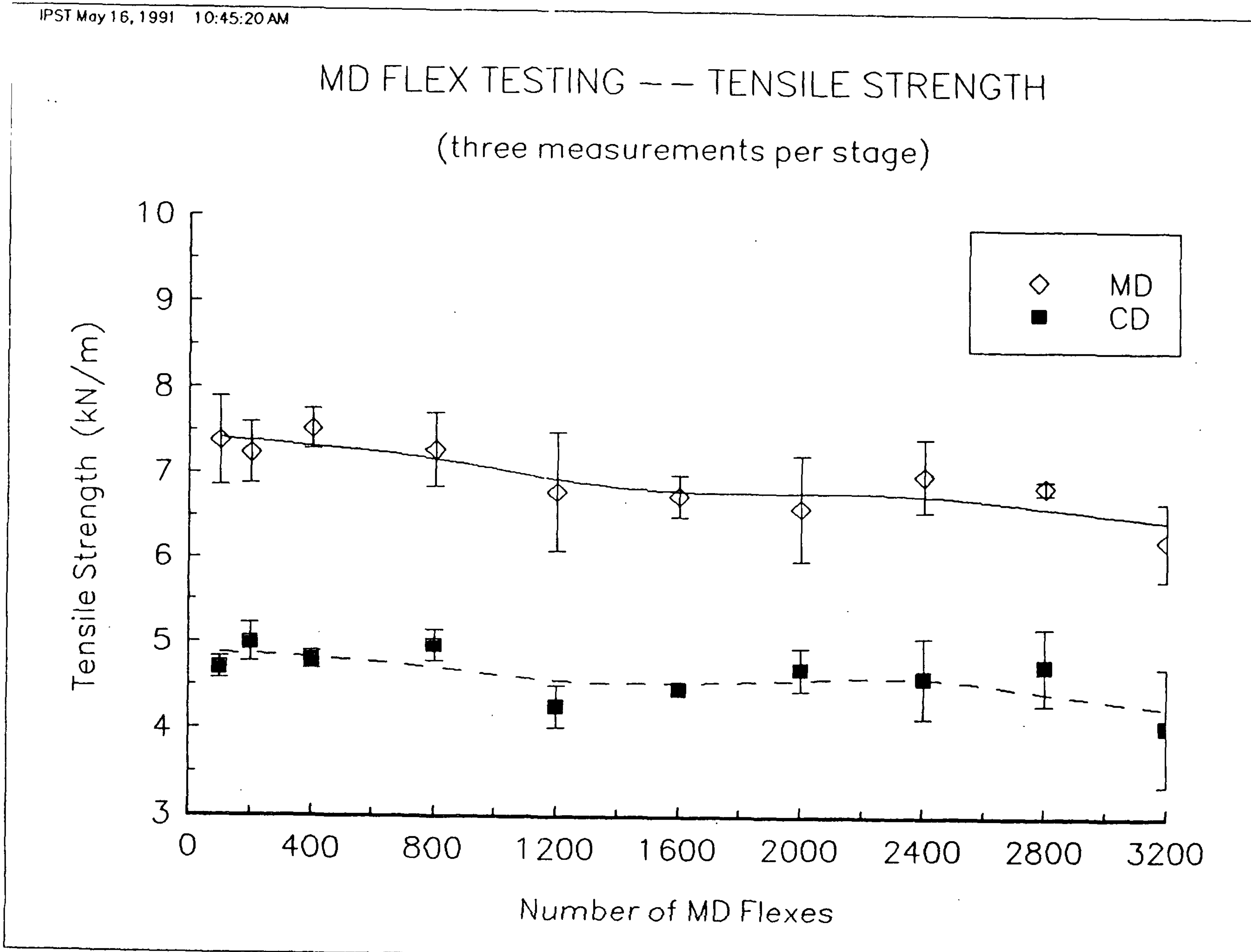

IPST May 16, 1991 10:30:33 AM
CD FLEX TESTING -- CD SHEAR SOUND VELOCITY
(four samples per stage)
Crisp Bills
Velocity (km/sec)
1.8
1.7
1.6
1.5
1.4
-400
0
400
800
1200
1600
2000
2400
2800
3200
Number of CD Flexes

Figure 55



IPST May 16, 1991 10:45:20 AM
MD FLEX TESTING -- TENSILE STRENGTH
(three measurements per stage)
Tensile Strength (kN/m)
10
9
8
7
6
5
4
3
0
400
800
1200
1600
2000
2400
2800
3200
Number of MD Flexes
MD
CD

Figure 56

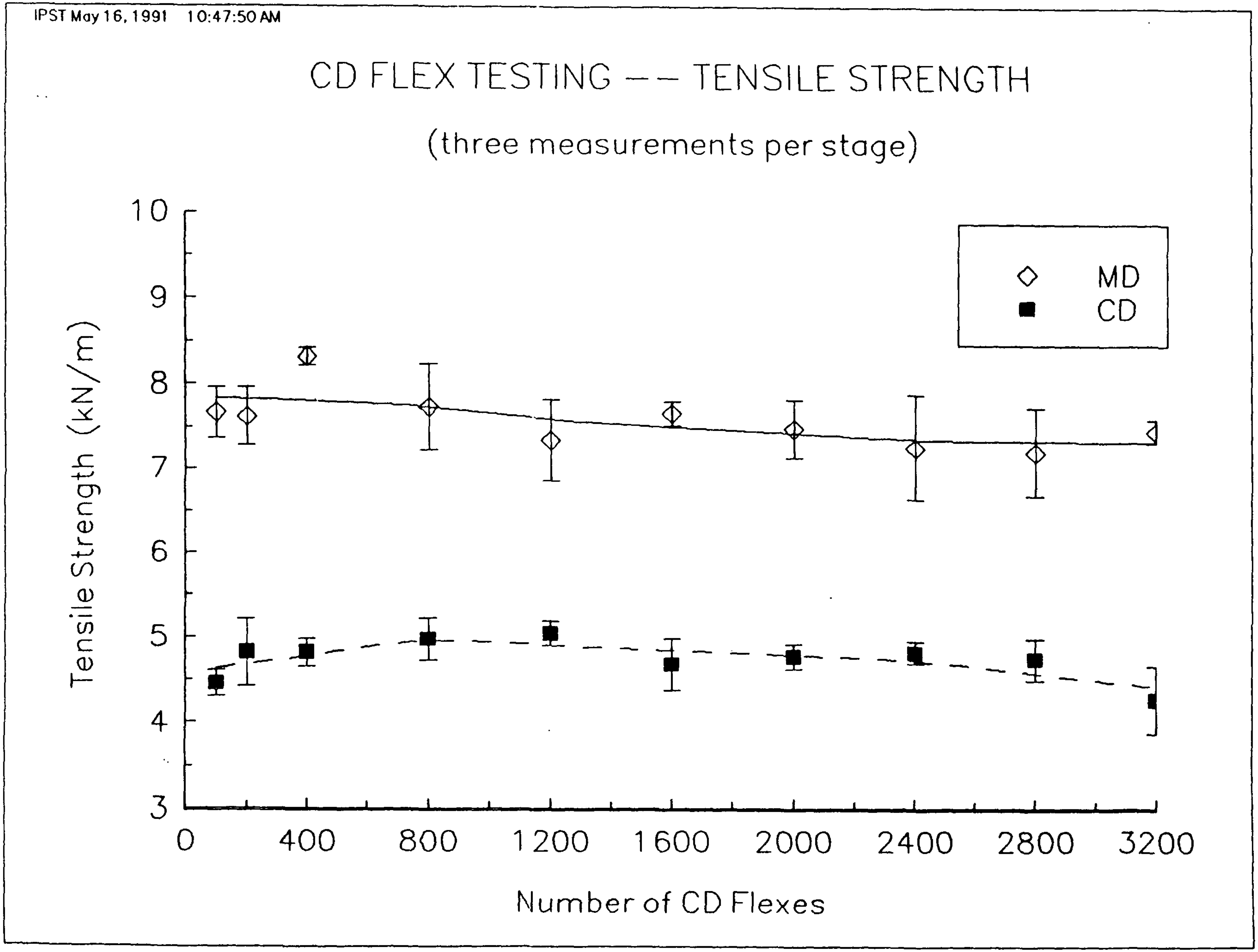

IPST May 16, 1991 10:47:50 AM
CD FLEX TESTING -- TENSILE STRENGTH
(three measurements per stage)
Tensile Strength (kN/m)
10
9
8
7
6
5
4
3
0
400
800
1200
1600
2000
2400
2800
3200
Number of CD Flexes
MD
CD

Figure 57

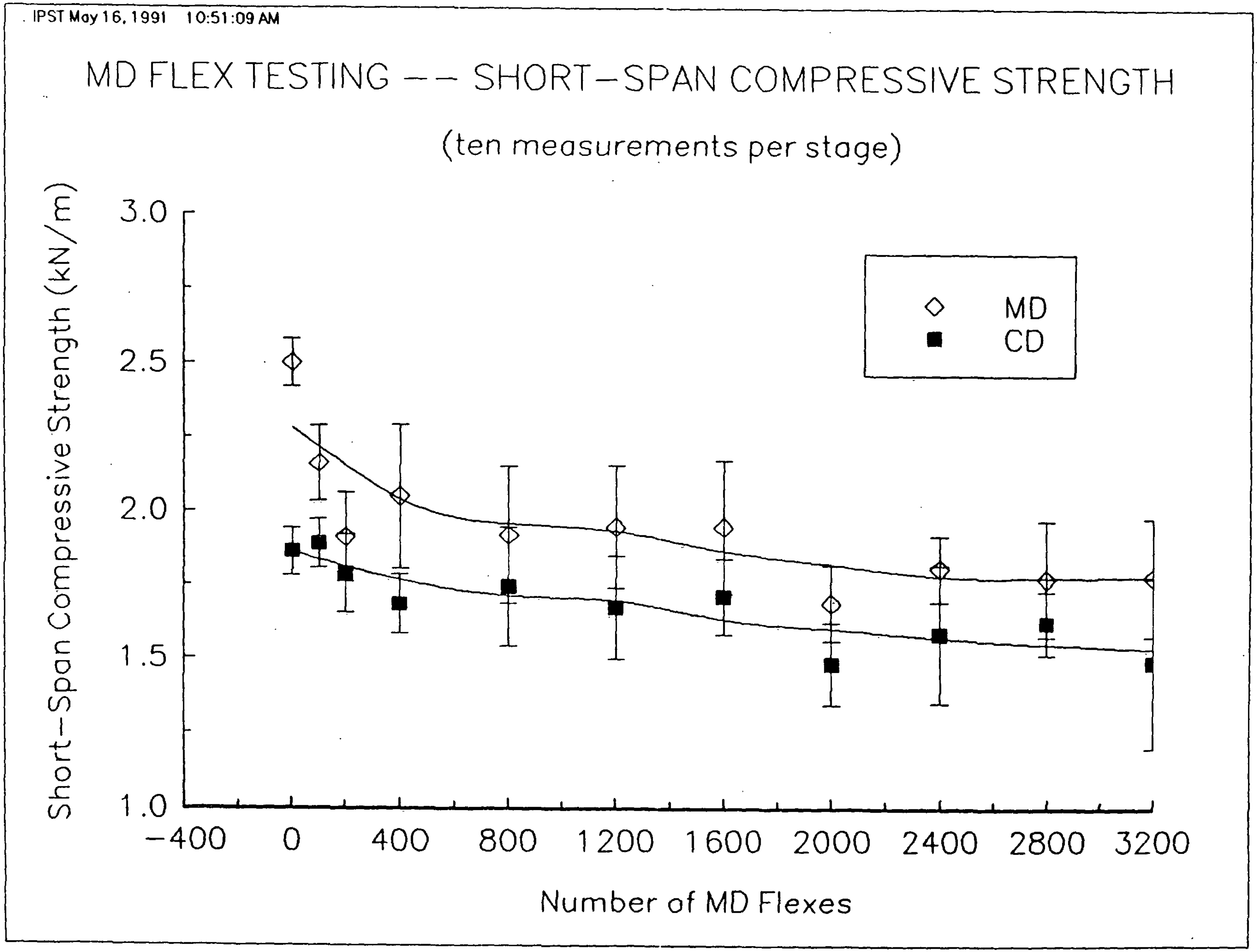

IPST May 16, 1991 10:51:09 AM
MD FLEX TESTING -- SHORT-SPAN COMPRESSIVE STRENGTH
(ten measurements per stage)
MD
CD
Short-Span Compressive Strength (kN/m)
3.0
2.5
2.0
1.5
1.0
-400
0
400
800
1200
1600
2000
2400
2800
3200
Number of MD Flexes

Figure 58

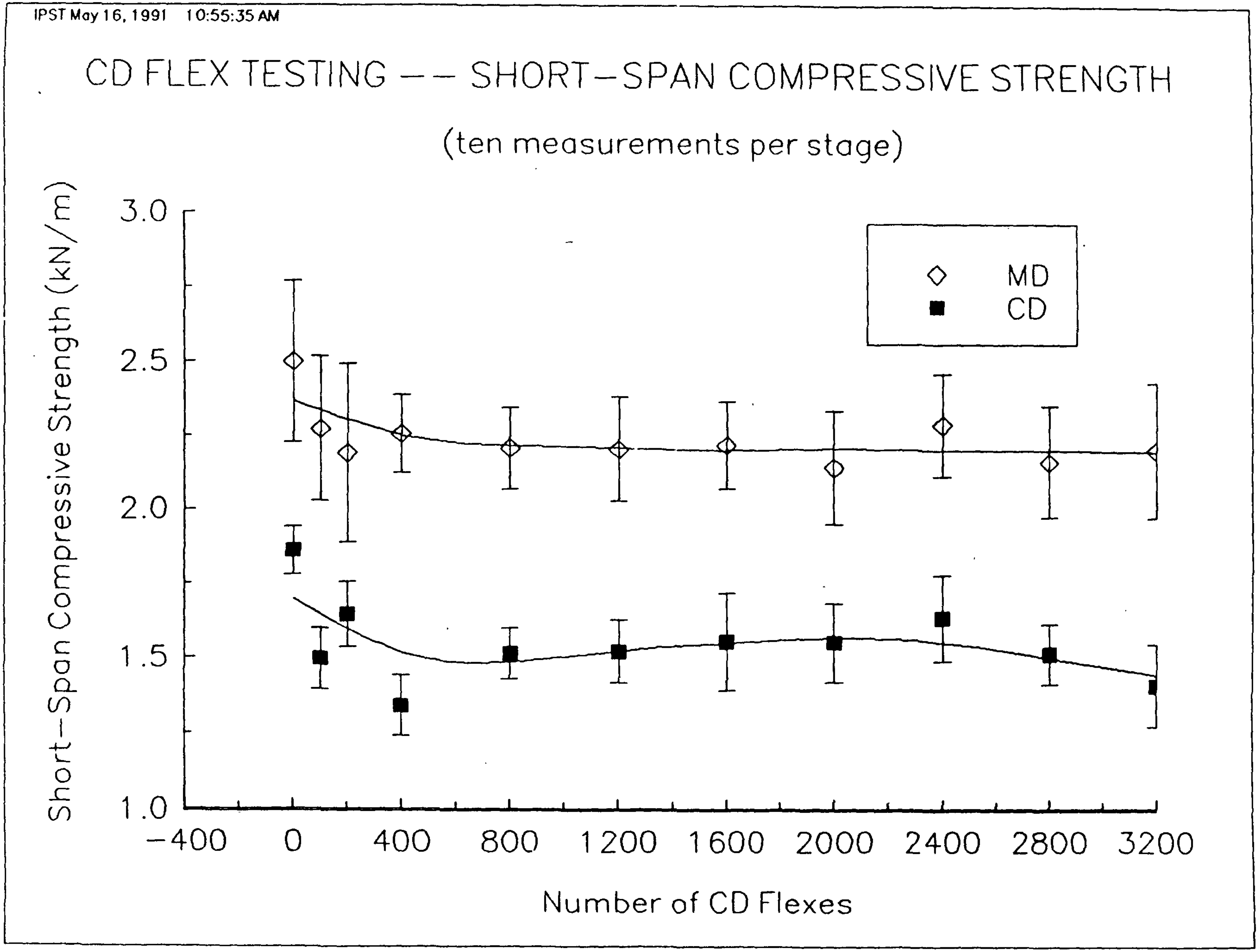

IPST May 16, 1991 10:55:35 AM
CD FLEX TESTING -- SHORT-SPAN COMPRESSIVE STRENGTH
(ten measurements per stage)
Short-Span Compressive Strength (kN/m)
3.0
2.5
2.0
1.5
1.0
-400
0
400
800
1200
1600
2000
2400
2800
3200
Number of CD Flexes
MD
CD

Figure 59

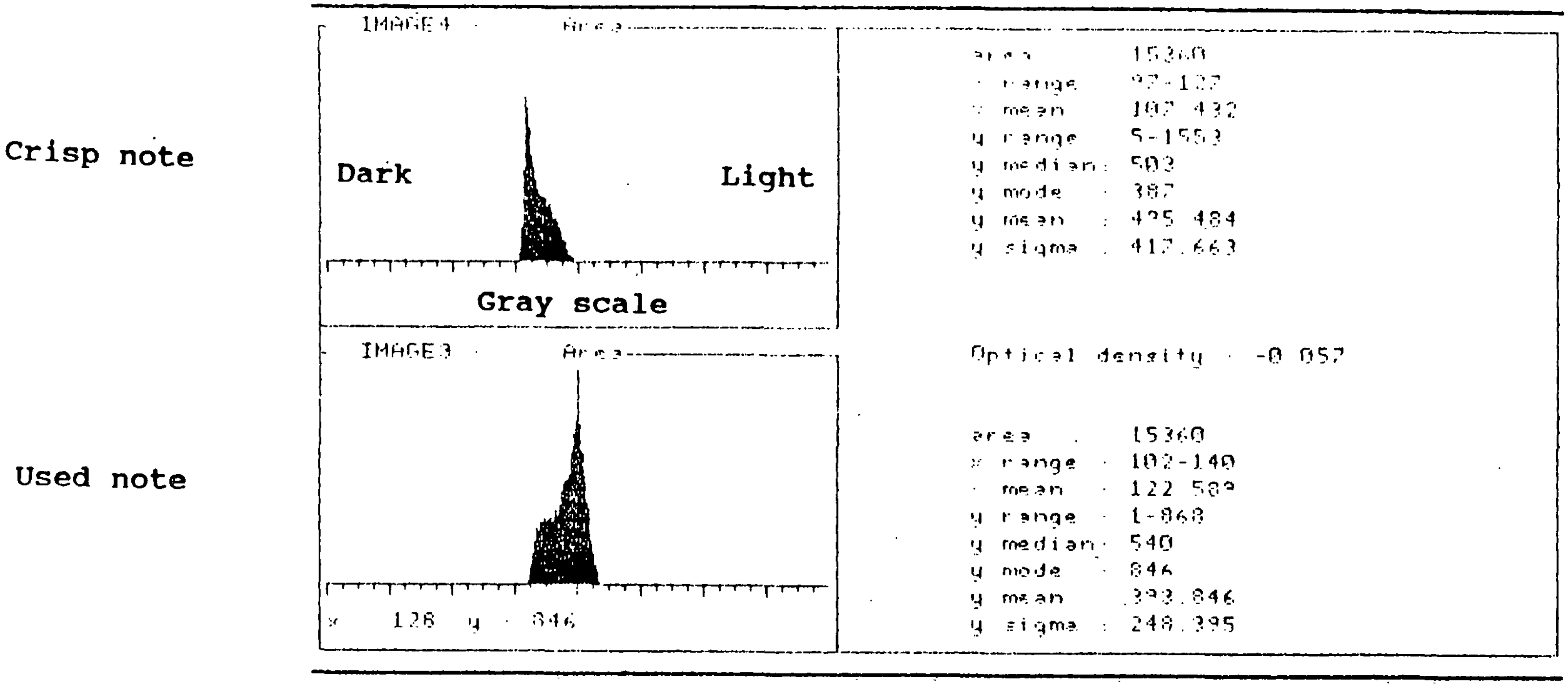

Crisp note
Used note
IMAGE4
Dark
Light
Gray scale
IMAGE3
x 128 y 846
area 15360
y range 5-1553
y median 503
y mode 387
y sigma 417.663
Optical density -0.057
area 15360
x range 102-140
y range 1-868
y median 540
y mode 846
y mean 393.846
y sigma 248.395

Figure 60

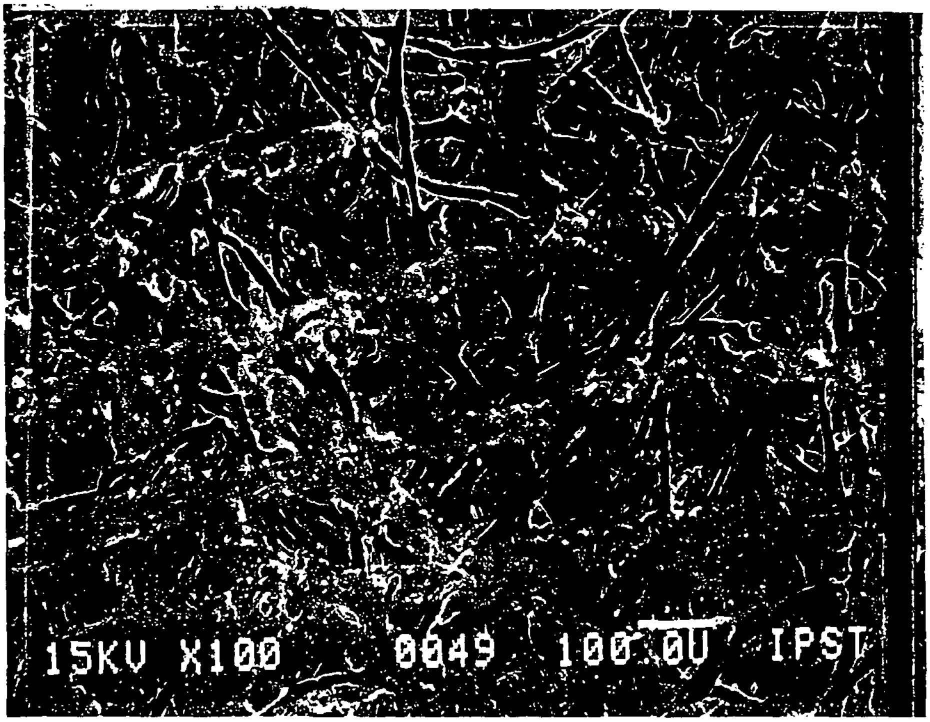


Figure 61

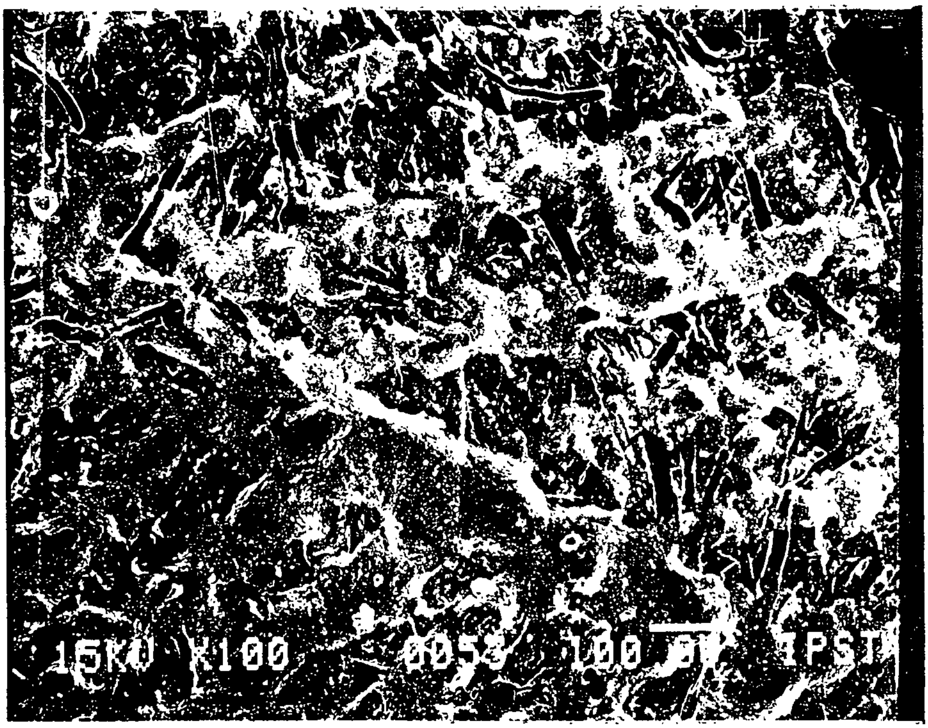


Figure 62

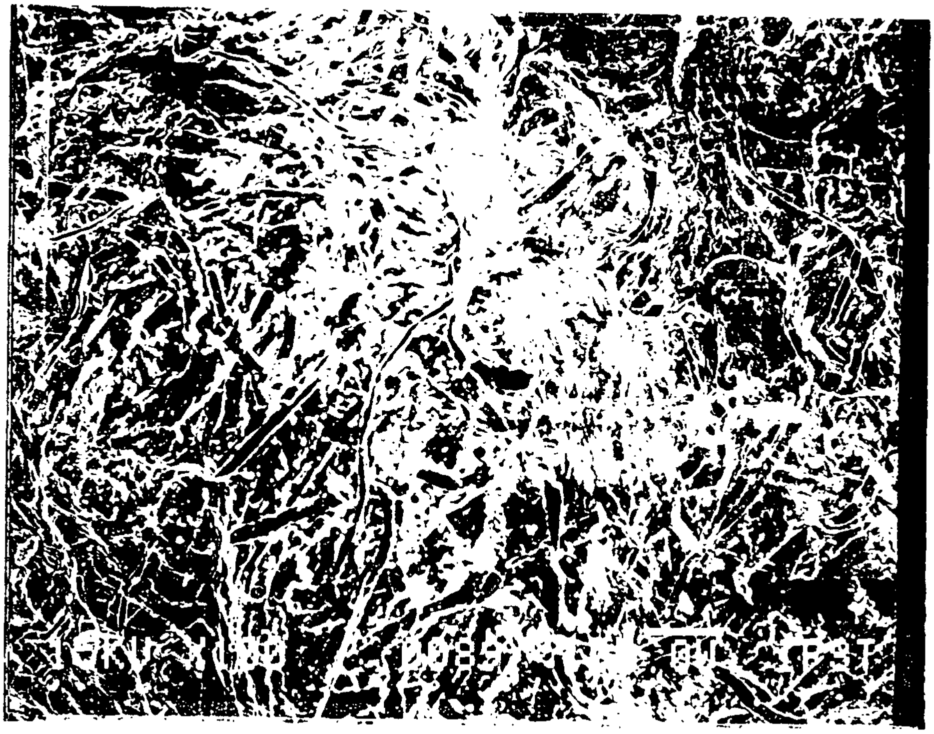
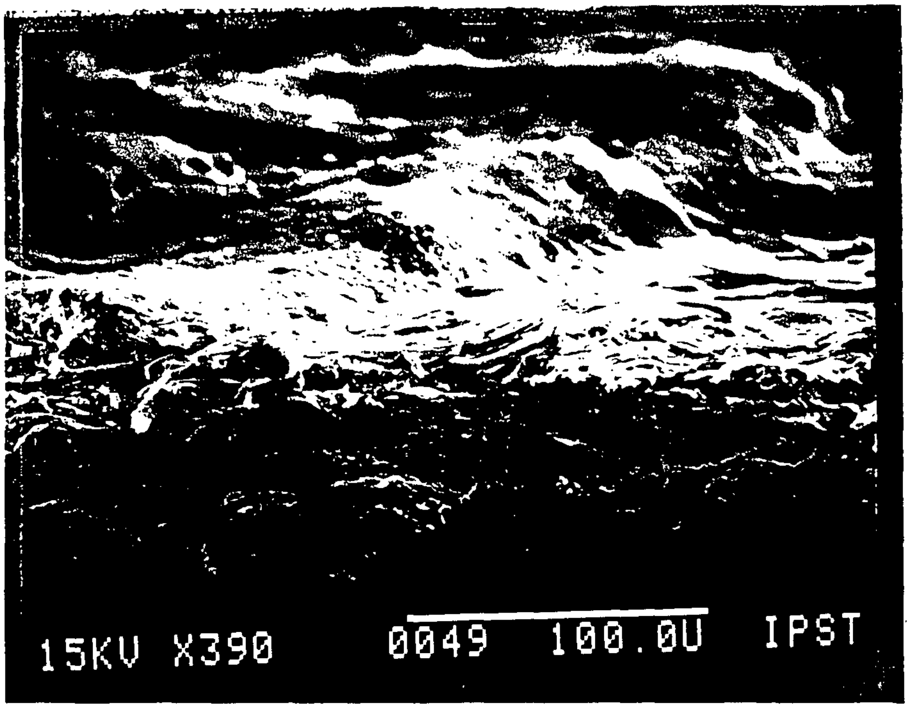


Figure 63



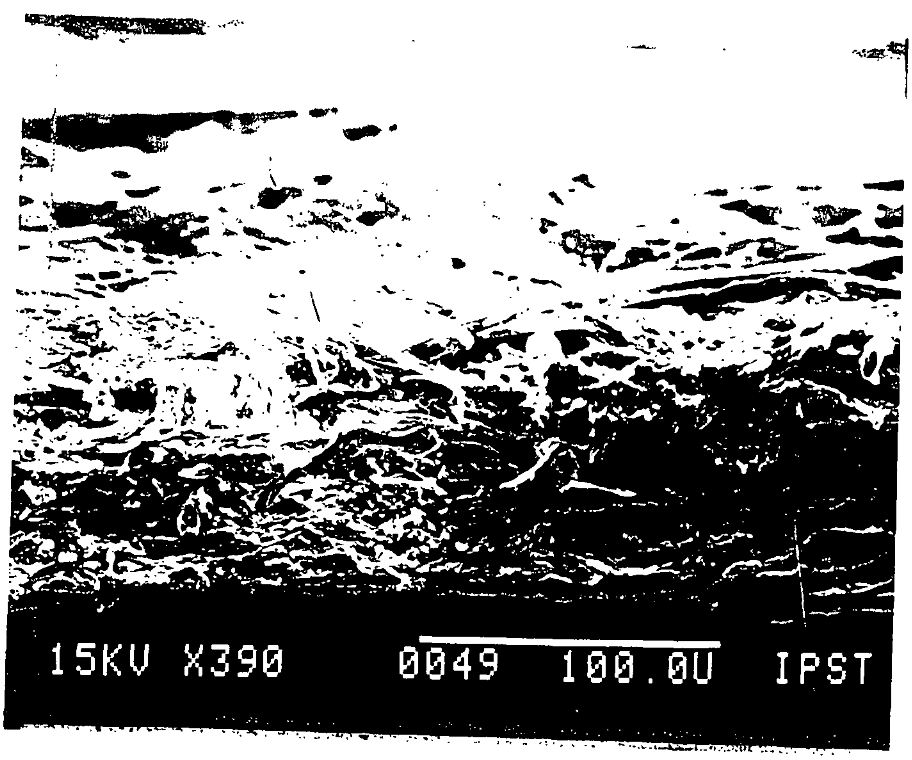
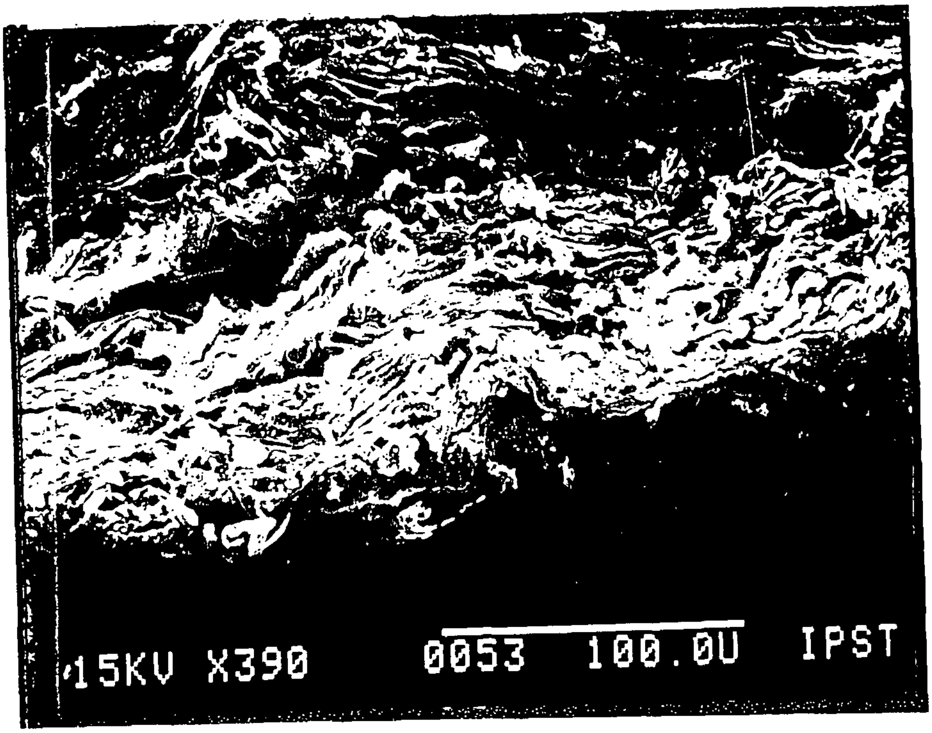


Figure 64



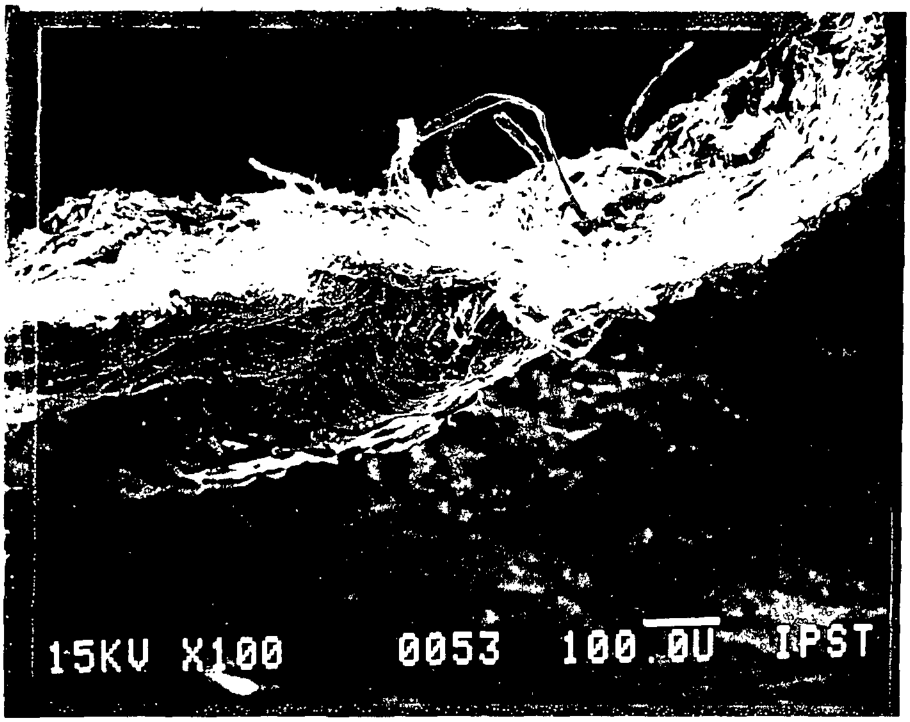


Figure 65

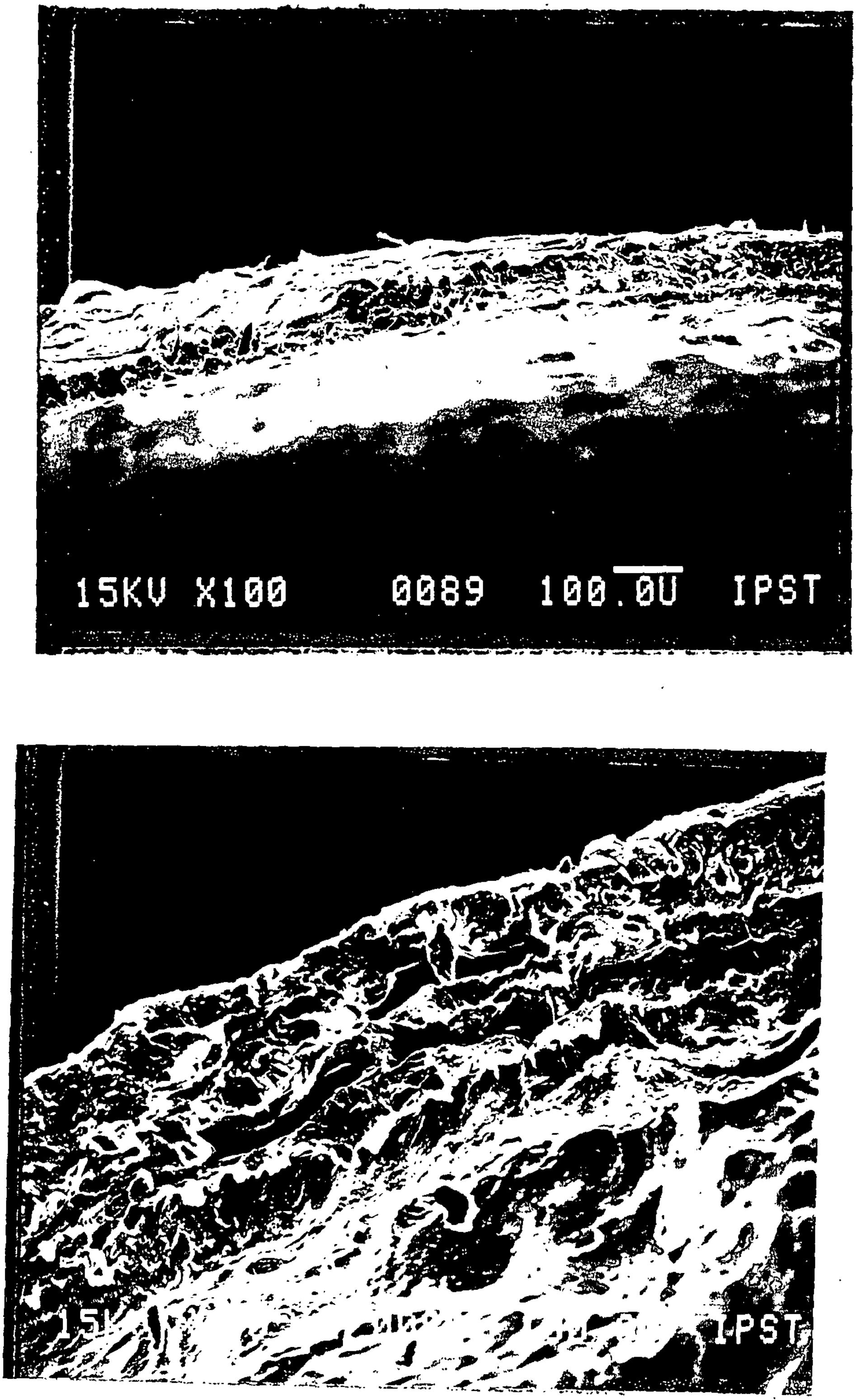


Figure 66