FEASIBILITY OF USING A TILLAGE TOOL AS A MOBILE PENETROMETER

By

CRAIG CLAYTON REISBECK

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FEASIBILITY OF USING A TILLAGE

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PENETROMETER

Thesis Approved:

James D. Summers

Thesis Adviser

John B. Solie

David G. Batchelder

Norman N. Durham

Dean of the Graduate College

PREFACE

Tests were performed to determine the feasibility of using forces acting on tillage tools to predict soil cone index. The tools which do a good job of predicting cone index can than be used as a mobile penetrometer.

I wish to express by sincere gratitude to my major thesis adviser, Dr. James D. Summers, for his guidance and assistance throughout this study. Special thanks are also due to the staff of the Oklahoma State University Agricultural Engineering Laboratory for their help in completing this project.

Finally, I would like to express my appreciation to my family, my parents, Dr. and Mrs. Robert F. Reisbeck, and my younger sister, Holly. Without their encouragement the work would never have been completed.

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CHAPTER I

INTRODUCTION

Cone index is used as an indicator of soil strength. It is the resistance of soil to penetration by a right circular cone. Numerically, cone index is the ratio of the force required to push a cone into the soil at a constant rate of penetration to the base area of the cone. Different penetrometers with varying base areas, cone angles, and penetration velocities bave been used (Gill and Vanden Berg, 1968; Durgunoglu and Mitchel, 1975; Johnson, Jensen, Schafer, and Bailey, 1980). In an effort to to provide a common method of expressing general soil conditions, the American Society of Agricultural Engineers has developed a standard specifying the geometry and operating procedures for cone penetrometers (ASAE, 1984b).

Cone index has been utilized for many purposes, such as predicting tractive performance of off-road vehicles, evaluating tillage tool performance, predicting draft forces, and determining root penetration and seedling emergence (Ayers and Bowen, 1983). The procedure used to evaluate tillage tools at Oklahoma State University requires cone index readings to be taken before and after the tillage operation is performed (Khalilian, Self, and Batchelder, 1983). This is expensive in terms of time required to collect the penetration data. It would be advantageous to develop a faster method of determining cone index. The problem addressed by this research is the development of a system that would make measurements related to cone index from a moving vehicle. This mobile penetrometer could then be used to gather values related to cone index while performing some tillage operation thereby reducing the time required to collect penetration data.

Objectives

The overall objective of this research is to determine the feasibility of using a tillage tool as a mobile penetrometer. The specific objectives are:

1. Evaluate four tillage tools for possible use as a mobile penetrometer.

2. Define the pertinent quantities for the tool-penetrometer systems.

3. Develop prediction equations relating cone index to forces acting on each tillage tool from field test data.

CHAPTER II

LITERATURE REVIEW

Factors Affecting Cone Index

Frietag (1968) described the advantages and disadvantages of using cone penetromers to measure in situ soil strength. Shear strength of soil is a function of two components, cohesion and the internal angle of friction. On most soils it is impossible, using the cone penetrometer, to separate these two components. Experiments were conducted on air-dry sand where cone index was interpretable in terms of the friction angle. Since the cohesion in sand was considered to be negligible, data collected with the cone penetrometer were meaningful measurments of soil strength.

Durgunoglu and Mitchell (1975), proposed a new technique for prediction of penetration resistance. It was stated that penetration resistance is a function of cone geometry, cone surface roughness, soil strength parameters, soil compressibility, in situ lateral stress, and penetration depth. Above a certain critical depth penetration resistance increased rapidly with depth. At depths greater than the critical depth, soil compression became the controlling factor and the rate of penetration resistance with depth decreased. This critical depth was directly proportional to the soil friction angle and the roughness of the penetrometer surface. Experiments conducted on air-dry sand produced measurements of cone index which agreed with predicted values calculated by the proposed technique.

Ayers and Perumpral (1981) investigated the effects of soil moisture content and dry density on cone index. Experiments were performed using mixtures of Zircon sand and Fire clay. Mixtures were placed in a cylindrical mold. Changes in dry density were achieved by compacting soil samples with the use of a drop hammer. Water was added to soil samples to vary the moisture content. Penetration resistance was measured with a standard ASAE cone penetrometer with a base area of 3.2 cm^2. The cone index was determined by averaging the penetration force over the first 15.2 cm and dividing by the base area of the the cone. Results of the test yielded a prediction equation for cone index as a function of dry bulk density, moisture content, and soil type. The prediction equation was more valid for soils with a high percentage of clay and less accurate for 100% sand.

Using a similitude approach, Upadhyaya, Kemble, Collins, and Wiliams (1982) developed a prediction equation for cone index in Delaware soils. Cone index was found to be a function of the moisture content, particle density, bulk density, and bulk modulus. Two different soil types were investigated, silty clay and sandy loam. Bulk density of the soil was varied using a rotary tiller. Different values of moisture content were achieved by applying water to the surface of the soil with a calibrated sprayer. Bulk modulus of the soil was determined by measuring the ratio of the change in pressure to the change in volume for a water saturated soil placed in a watertight container. A significant correlation was observed for the ratio of cone index to bulk modulus and soil moisture content.

Cone Index-Tool Force Relationships

Sirohi and Reaves (1969) reported a study of the performance of cultivator sweeps to determine the feasibility of using similitude techniques to predict draft of cultivator sweeps. Pertinent quantities used to describe the soil were resistance to penetration and bulk volume weight, which is analogous to bulk density. Penetration resistance was measured using a 30° cone penetrometer. Tests were conducted on sand at the National Tillage Machinery Laboratory. Results of the study showed that similitude techniques are an effective method of studying cultivator sweeps. Results also indicated that a relationship existed between cone index of soil and draft of a cultivator sweep.

Johnson et al. (1980) used an analog-prototype system to predict draft forces acting on tillage tools. Cone penetrometers were used to model disks and chisels. Different sizes of cone pentrometers, chisels, and disks were used. Tests were performed on two types of soil, Norfolk sandy loam and Decatur clay loam. An integrated average was used to determine the penetration resistance over the depth of operation. Results of the test showed the system where cone penetrometers were used to model disks was the best analog-prototype system tested because the coefficients in the prediction equation were constant for varying soil conditions.

Factors Affecting Tool Forces

Rowe and Barnes (1961) have shown that draft of a tillage tool can be approximated by an analytical procedure based on soil mechanics. The tool used for the experiment was an inclined flat blade. It was assumed that the soil failed in shear. Soil types used were sand, silt loam, silty clay loam, and silty clay. Results indicated that soil shear strength increased as the rate of shear increased. This increase in shear strength was less for soils low in clay. Thus, the draft of the implement was a function of soil type and velocity.

Using dimensional analysis, Wang, Lo, and Liang (1972) predicted the draft force on a horizontal chisel using four soil parameters. Soil parameters studied were friction between the soil and tillage tool, apparent cohesion, bulk volume weight, and internal angle of friction of the soil. Tool properties used in the analysis were velocity and depth. Cohesion and soil friction angle were determined by the direct shear method while soil-tool friction was measured with a slider. Tests were performed in a soil bin on a soil with 0.3% sand 5.5% silt, and 94.2% clay. Different soil conditions were prepared by varying cohesion, bulk volume weight, soil friction angle, and soil-tool friction. Results showed draft could be predicted with acceptable accuracy using these four soil properties.

The soil reacting forces acting on disks were measured by Harrison (1977). Factors of interest were disk angle, depth and velocity of tillage as well as soil type. Forces measured were draft, lateral force and vertical force. The experiment was conducted on silty loam and clay loam soils with varying densities and moisture contents. Analysis of the results showed velocity did not contribute significantly to the change in draft or vertical force, but was significantly related to lateral force. Soil type, depth of tillage and disk angle did contribute significantly to all three forces measured.

Bloome, Batchelder, Khalilian, and Riethmuller (1983) measured the effect of velocity on draft of tillage tools in typeical Oklahoma soils. The soil types were Port silt loam and Meno loamy fine sand. Tillage tools used were a moldboard plow, sweep plow, chisel plow, and tandem disk. Results showed draft for the moldboard plow was a function of the velocity squared. The drafts of the chisel plow and disk were linearly proportional to velocity. For one soil type the draft of the sweep plow varied with the velocity squared while for the other soil type draft varied linearly with velocity.

Effects of velocity and depth of tillage on implement draft were reported by Summers, Khalilian, and Batchelder

(1984). Tillage implements used were a moldboard plow, chisel plow, disk, and sweep plow. Soil types were Tabler silt loam, Holister clay loam, and Reinach silt loam. Draft was found to vary linearly with velocity for chisel plows, disks, and sweep plows and quadraticly with velocity for moldboard plows. The draft was linearly propertional to depth for all implements tested.

Kydd, Frehlich, and Boyden (1984) developed prediction equations for draft of tillage tools operating in Canadian soils. Tools used were cultivators, tandem disk harrows, rod weeders, and one-way disk harrows. The prediction equations showed draft was a function of velocity and depth of tillage. In addition, draft of tandem disk harrows was dependent on the disk angle. It was concluded that draft depends primarily on tillage depth.

Draft prediction equations for tillage tools are included in the Agricultural Engineers Yearbook (ASAE, 1984a). The draft of moldboard plows and disk plows is a function of velocity squared. Draft of disk harrows is dependent on the mass of the implement and draft of cultivators is a function of depth and an interaction of depth and velocity.

Nicholson, Bashford, and Mielke (1984) reported that draft of sweep and chisel plows was affected by velocity and depth in the same manner as that described by the ASAE prediction equations. The draft of tandem disks was not affected by velocities in the range of 1 to 8 km/h. Tests were conducted on silt loam and silty clay loam soils.

CHAPTER III

EXPERIMENTAL EQUIPMENT AND PROCEDURE

Research has shown that soil cone index is a function of soil properties. Cone index is also dependent on penetrometer geometry and operational procedures. The mode of soil failure for penetrometers is shear for shallow depths and compression for deeper depths. Literature indicates a positive correlation between cone index and tillage tool draft, as cone index increases draft increases. Tool forces are also dependent on velocity and depth of tillage as well as soil properties.

Tools selected to perform this experiment were a chisel, sweep, disk and rolling coulter. Research has indicated a relationship between draft and cone index for chisels, sweeps and disks. The rolling coulter was selected based on the assumption that a significant portion of the draft on coulters is due to soil-metal friction. This was assumed to be similar to the significance of the soil-metal friction of the penetrometer being a factor of cone index.

The chisel selected was a standard chisel point such as those used on a chisel plow. Width of the chisel was 5.1 cm. Dimensions of the sweep were: width, 26.0 cm; approach angle, 0^{o}; lift angle, 20.3^{o}; and lift height, 6.4 cm. The disk had a radius of 27.9 cm and a concavity of 6.35 cm. It was mounted with a disk angle of 45^{o} and a 0^{o} tilt angle. The coulter used in the test had a radius of 27.9 cm.

Pertinent Quantities

Soil properties which affect cone index are cohesion, internal angle of friction, soil-metal friction, bulk density, moisture content, and soil type. Pertinent geometric properties of the penetrometer are cone apex angle and base area. Cone index is also dependent on rate of penetration. If the same penetrometer is used for collecting all cone index data and operated at a constant rate of penetration, geometric and operating parameters of the penetrometer can be omitted from the analysis because they will be constant. Soil properties can be omitted if it is assumed that soil properties affect tool forces and cone index in the same manner.

Tillage tool properties should include a characteristic length of the tillage tool and the type of tool. Characteristic length used for the chisel and sweep was width. Radius was used for the characteristic length of the disk and coulter. Operational parameters for tillage tools are velocity and depth of tillage. The five quantities which are then needed to describe the tool-penetrometer system are:

1. Cone index

2. Force acting on the tillage tool
3. Velocity of tillage
4. Depth of tillage
5. Characteristic length of the tool

Design of Tool Bar

The tool bar was designed so the four tools could be tested simultaneously. This allowed variation in tool forces due to changing soil conditions to be minimized. Other factors included in the tool bar design are maintainance of a constant depth, velocity measurement, and tool force measurement.

Frame Design

The simplest frame to satisfy the requirements was three-point hitch mounted with the tools mounted side by side. To allow the tools to act independently, the width of the frame was determined by a suggested minimum distance between tools of 2.5 times the depth of tillage (Gill and Vanden Berg, 1968). When the frame was first tested, the lateral force on the disk caused the frame to pull at an angle. To overcome this problem, a stabilizer disk was added facing the opposite direction of the test disk. Both disks were then mounted far enough behind the other tools so the soil displacement wave caused by the disks would not interfere with the other tools.

An analysis was performed to determine frame member size. Estimates for forces acting on the tillage tools were made from data in literature. A maximum of 4.8 kN was used for the draft of the chisel and sweep (ASAE, 1984a). Maximum estimated draft for the rolling coulter was 3.6 kN (Ferguson, 1970). Disk draft of 1.8 kN and lateral force of 1.4 kN were used (Kepner, Bainer, and Barger, 1972). Stress analysis using these forces resulted in a 76 mm x 76 mm x 6 mm square tube frame member. This mass was not sufficient to counteract the estimated vertical forces. Therefore, a final member size of 76 mm x 51 mm bar was used. Figure 1 shows the completed frame. Frame dimensions are shown in Figures 2 and 3.

Depth

Depth of tillage was varied with the three-point hitch of the tractor. To maintain a constant depth for each test run, two 15.2 cm x 22.9 cm tires were placed at each corner of the frame. Tires were mounted so depth could be changed (Figure 4). Eight tires were originally used to minimize sinkage of tires into the soil. After inital tests, the inside rear tires were removed because they were riding on soil displaced by the disks causing the disks to operate at a depth shallower than the other tools.

Velocity

Velocity of tillage was maintained by the tractor and monitored using a fifth wheel attached to the frame. A 45

Figure 1. Tool Bar Mounted on the Tractor During Tests

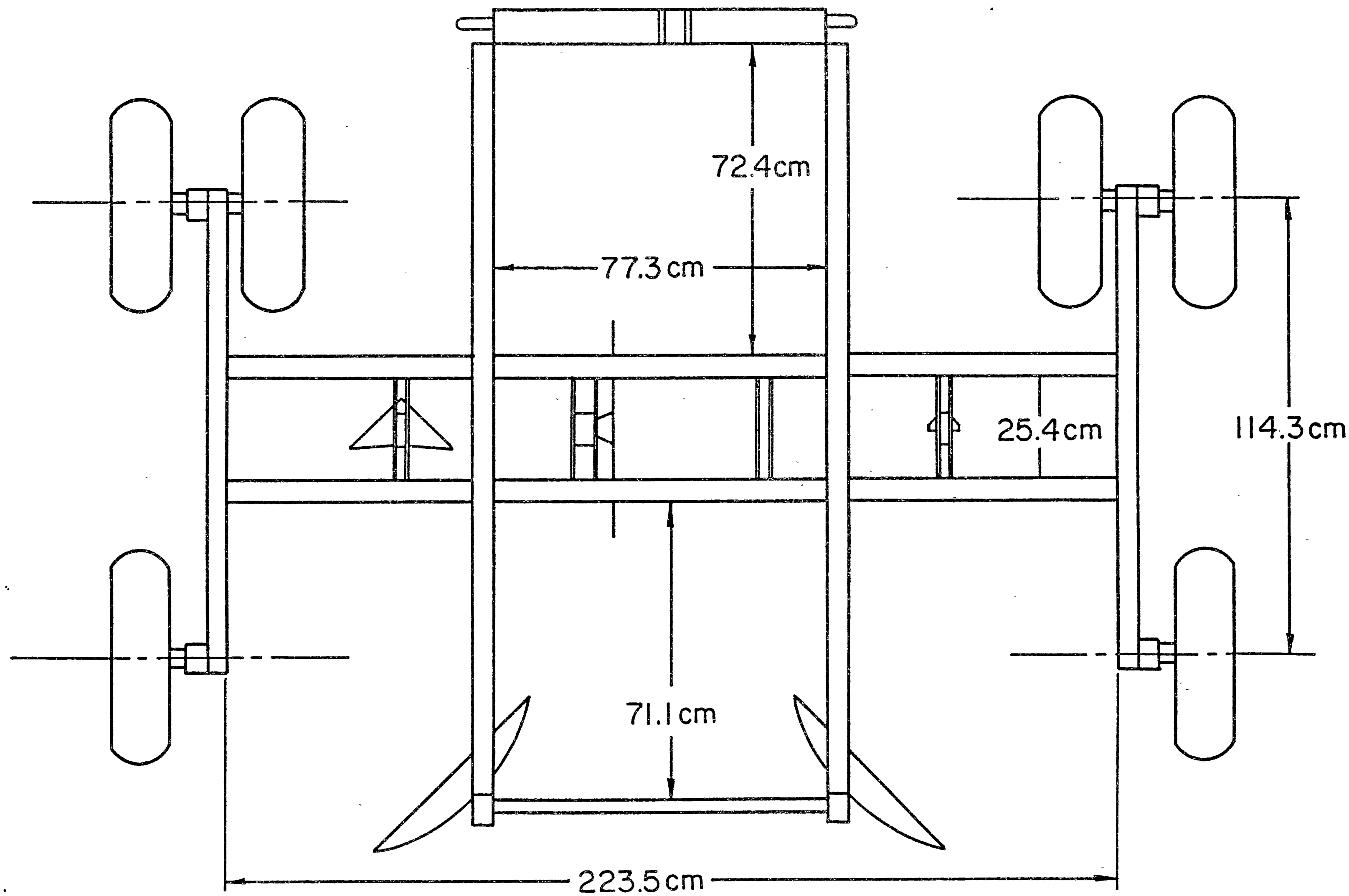

Figure 2. Top View of Tool Bar

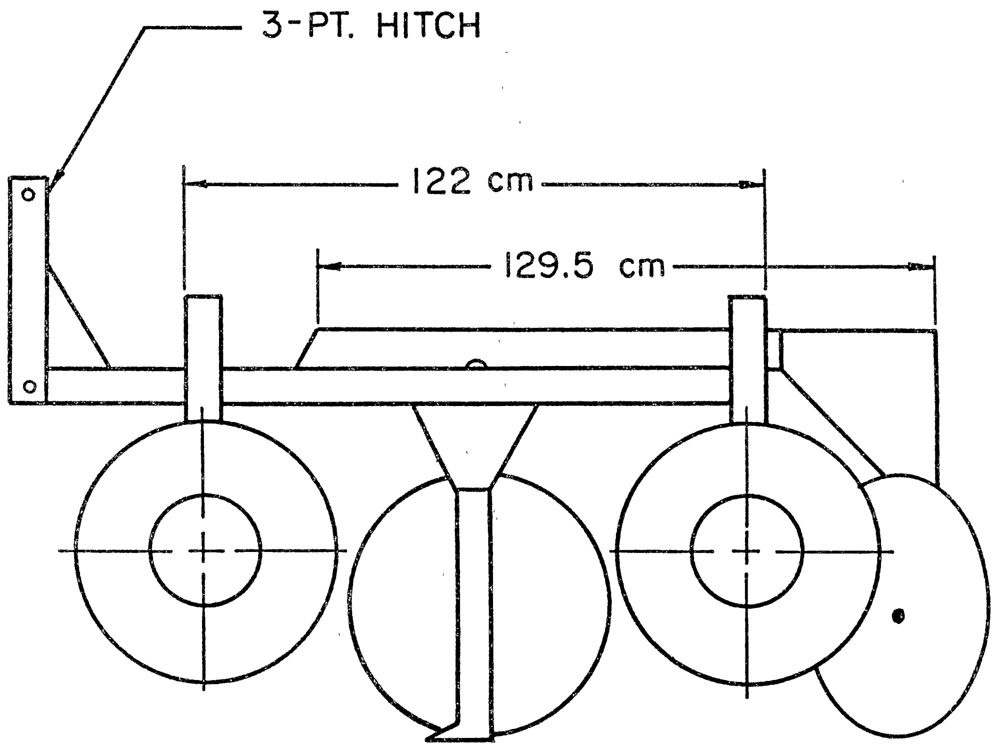

Figure 3. Side View of Tool Bar

Figure 4. Adjusting Height of Gage Wheels

tooth sprocket was fixed to the fifth wheel hub with a Di-Mag Digital #58423 magnetic sensor manufactured by the Electro Corp. mounted adjacent to the sprocket as shown in Figure 5. Using sensitivity curves for the sensor, the required gap between the sensor pole and the gear teeth was set at 0.127 mm so velocities in the range of 4.0 km/h to 8.7 km/h could be measured.

Tool Shanks and Force Measurement

Using estimated values of forces acting on the tools, an analysis was performed to select tool shank sizes. Shank dimensions for the chisel, sweep and coulter were 1.91 cm by 7.62 cm. Shank dimensions for the disk were 5.08 cm by 7.62 cm. The larger shank size was needed for the disk to resist the added lateral force.

Draft and vertical force acting on each tool were predicted using strain gage bridge voltage measurements. Gages used were type CEA-06-125UW-350 manufactured by Micro-Measurements Group, Inc. Gages were configured so one bridge measured draft and another measured the vertical force on each shank. Effects due to forces other than those of consideration were eliminated by gage placement. The procedures used to mount the strain gages were outlined in M-Line Accessories Instruction Bulletin B-137-11 (Micro-Measurements, 1979). Figure 6 shows gage configuration on the tool shanks. The output voltage, V_o, and the strain in the tool shank at the location of the gages along their princi-

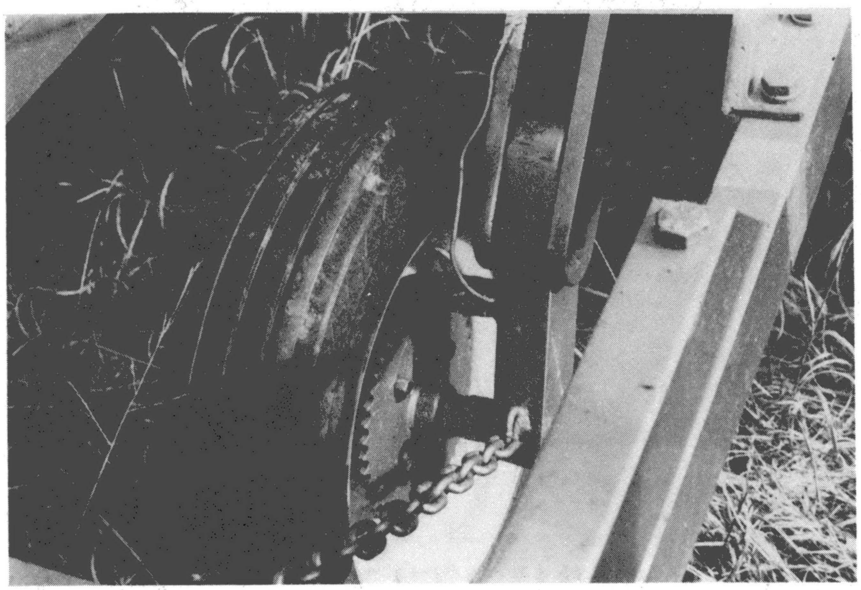

Figure 5. Fifth Wheel Assembly and Magnetic Sensor

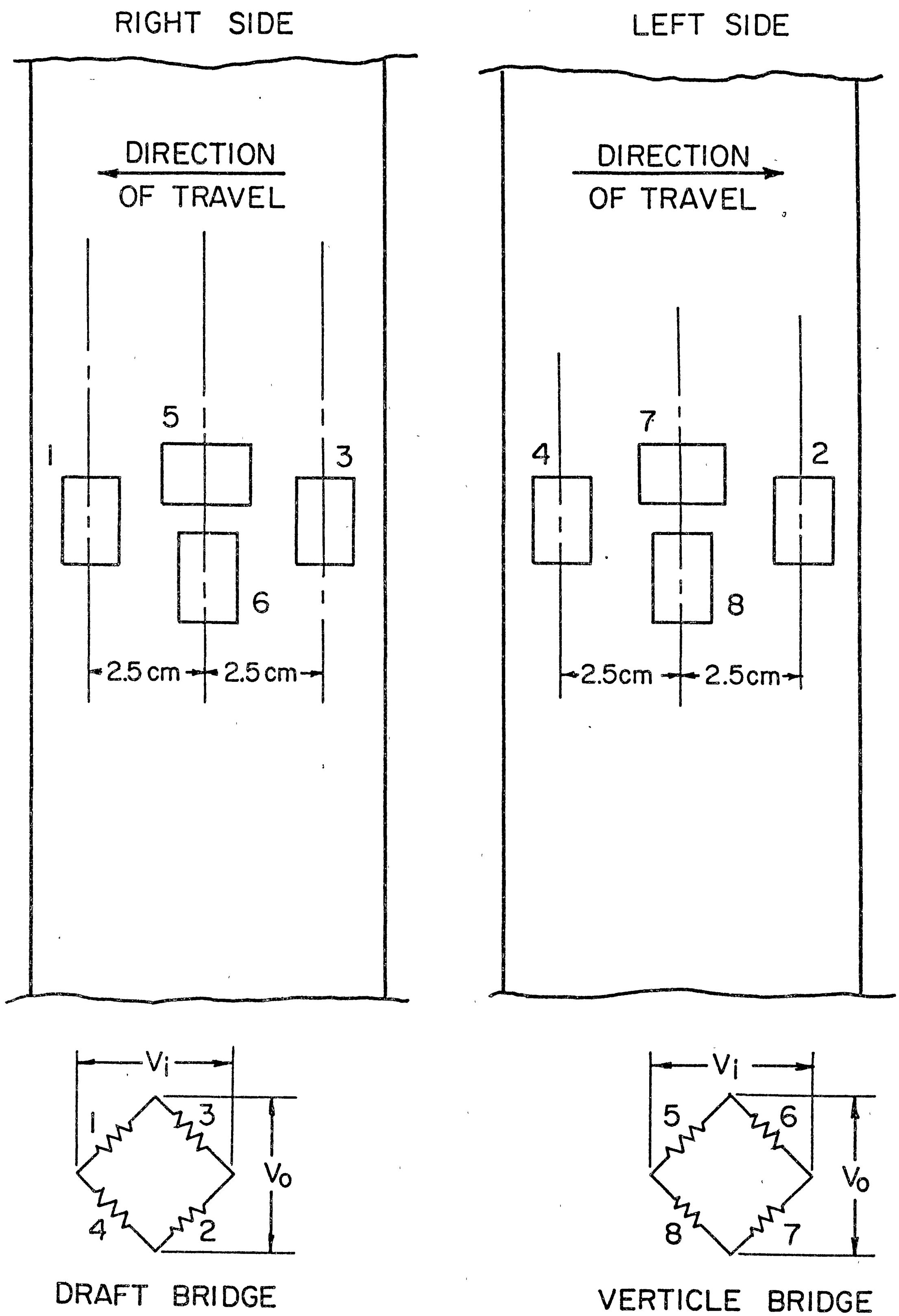

Figure 6. Arrangement of Strain Gages on Tool Shanks

pal axes, ε, are related according to the following equation:

$$V_o = V_i * F * \varepsilon * n/4 \qquad (1)$$

Where V_i is the input voltage to the bridge, F is the gage factor and n is the number of active arms in the strain gage bridge (Micro-Measurments, 1982). For the gages used, F was 2.08. The value of n for the draft bridges was four and two for the vertical force bridges. The input voltage to the strain gage bridges was +10 VDC. Using beam theory and the maximum estimated forces, the theoretical strains can be calculated. Table I lists the maximum strain in each tool shank due to the estimated draft and vertical force on each tool.

TABLE I

MAXIMUM EXPECTED STRAIN DUE TO DRAFT AND VERTICAL FORCE

Tool	Force Component	Force (kN)	Strain
Chisel	draft	4.8	.000420
	vertical	1.8	.000005
Sweep	draft	4.8	.000390
	vertical	1.8	.000005
Coulter	draft	3.6	.000320
	vertical	1.8	.000005
Disk	draft	1.8	.000060
	vertical	1.8	.000002

Using equation (1) and the maximum expected value of strain, the maximum strain gage bridge output voltage expected is +8.74 mVDC for +10 VDC input.

Data Logger

Force and velocity data were gathered and stored using an AIM 65 micro-computer based data logger (Summers, Batchelder, and Lambert, 1984). The data logger has an analog to digital converter, A/D, capable of converting the analog voltage signals from the force measuring strain gage bridges to digital output. Output from the A/D board was address selected as the high byte of the original twelve bit word. The A/D board was configured to measure a full scale voltage of ±10 mVDC. Output signals from the strain gage bridges were used as input signals to the A/D board. Comparing the maximum expected output voltages of the bridges with the maximum input voltages to the A/D board, it was determined that the A/D board was capable of measuring the strain gage bridge outputs for the maximum expected tool forces.

The +10 mVDC input to the A/D board corresponded to a reading of 4080 for the high byte of the twelve bit output word. Using this relationship to determine a value for V_O from the A/D board reading and equation (1) to calculate tool shank strain from the value of V_O, the forces acting on the tool could have been calculated using beam theory.

Considerable errors may be included in the calculated forces due to material in the shanks not behaving as assumed, nonsymmetrical bending of shanks, improper placement and alignment of gages and the bridges not being purely temperature compensated. Therefore, the tool shanks were calibrated to compensate for possible errors.

Calibration was performed by reading the output from the A/D board during loading and unloading of each tool shank. Load increments of 670 N were applied up to a maximum load approximately equal to the maximum force expected on the tool. Plots of draft and vertical force versus the A/D output for each tool are shown in Figures 7 through 14. Regression equations for each tool corresponding to the line on the Figures are listed in Table II along with strain gage bridge resolutions. A positive draft acts in the opposite direction of travel and a positive vertical force acts upward.

During the field tests, measurements were made at a sampling frequency of 814 Hz. This was the maximum frequency at which the data logger could collect data. Appendix A lists the machine language subroutine used by the AIM 65 to collect the force and velocity measurements. Appendix B lists the BASIC computer program used to average the force measurements into one value for each force component per tool per plot. This program also stores the force and velocity data on cassette tape. The machine language program to transfer the data from the cassette tape to the Oklahoma State University IBM 3081D mainframe computer is listed in Appendix C.

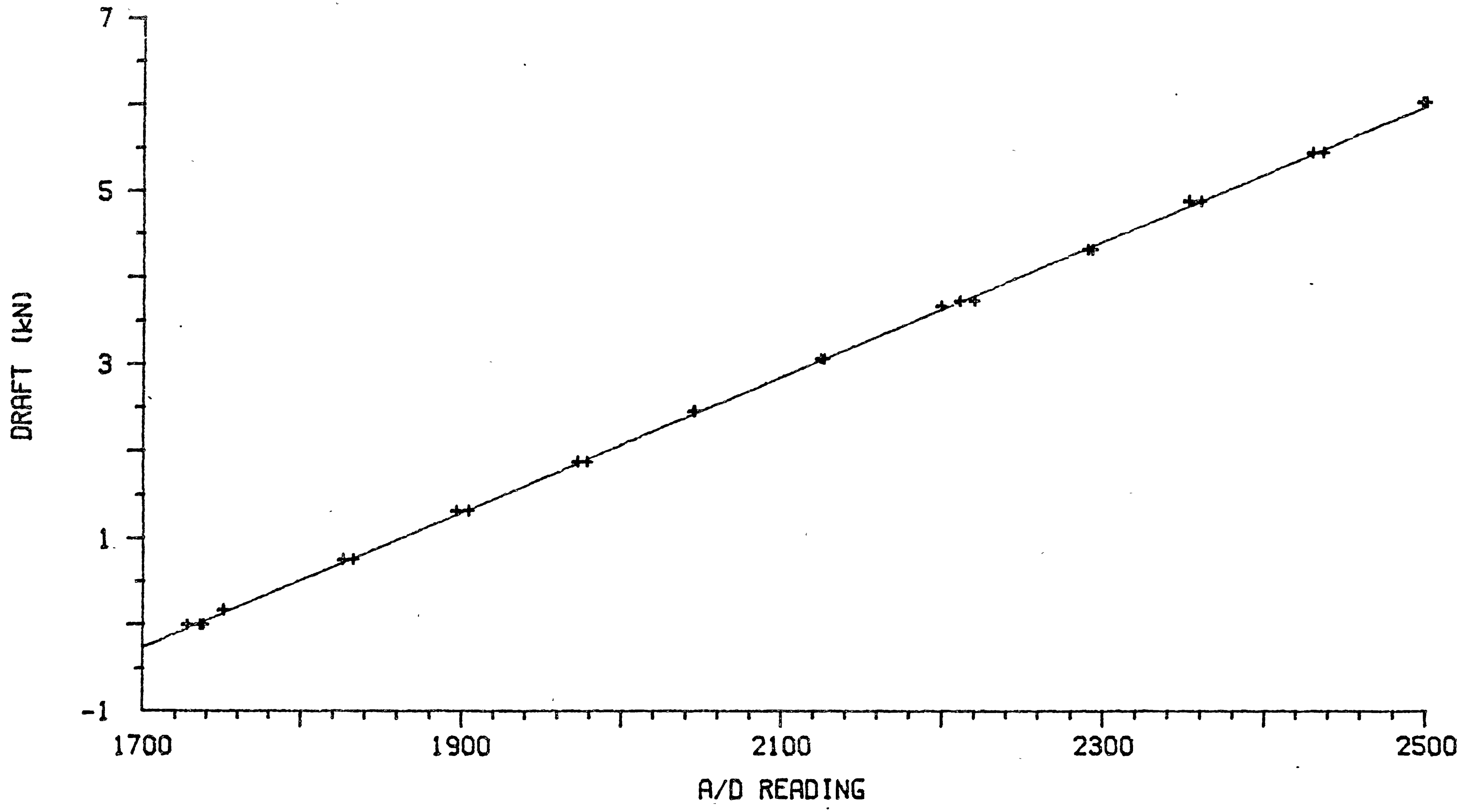

Figure 7. Calibration Data for Chisel Draft

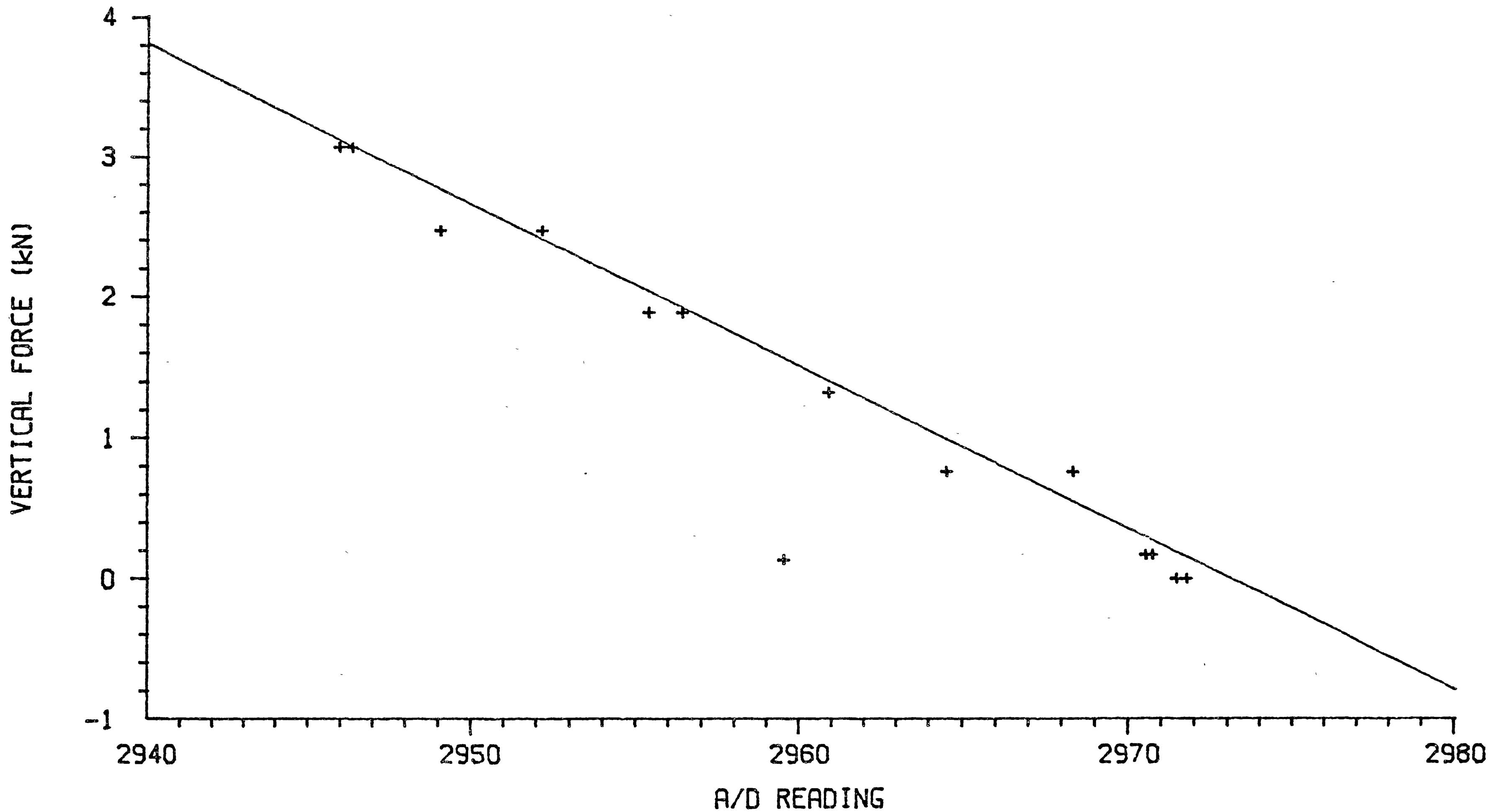

Figure 8. Calibration Data for Chisel Vertical Force

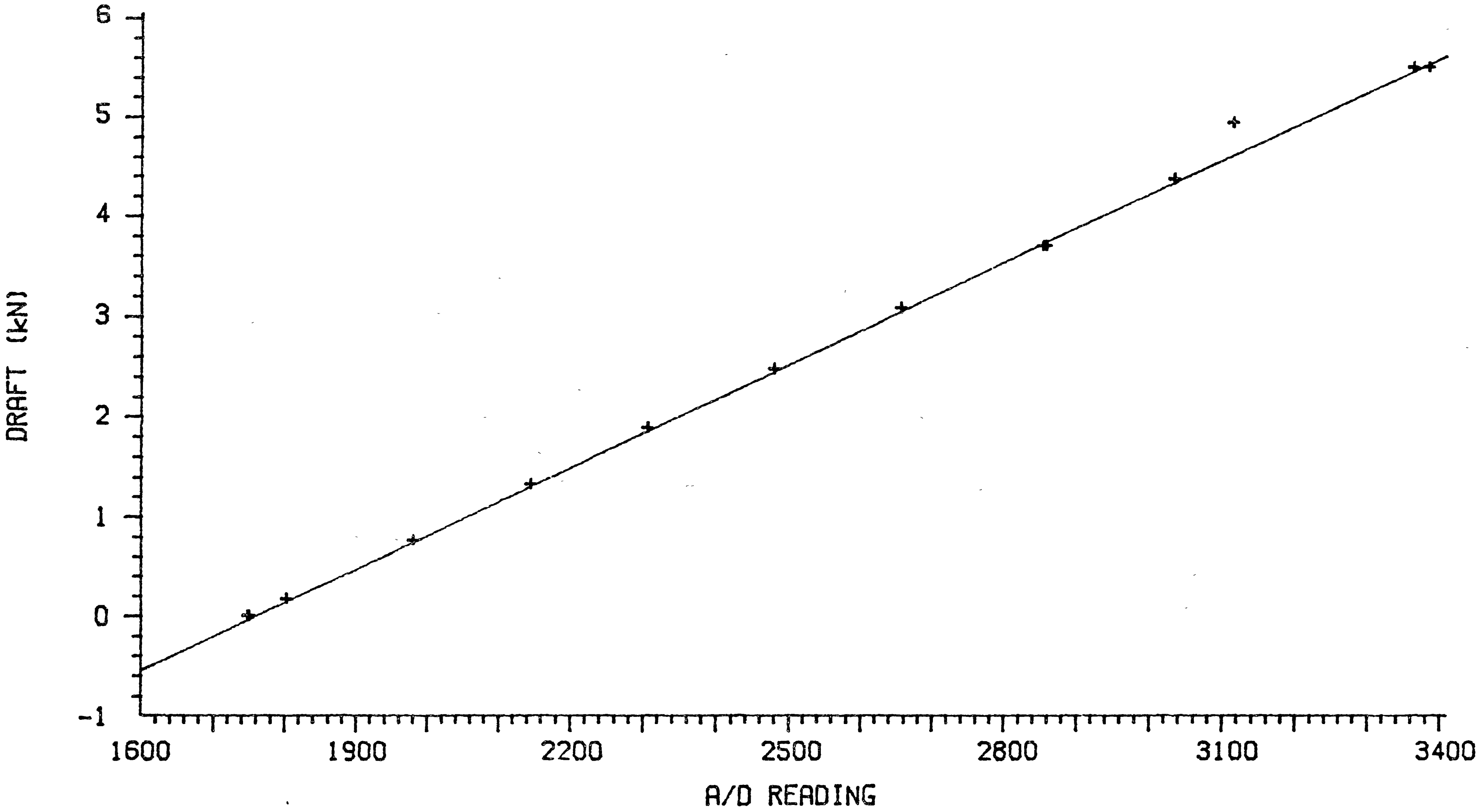

Figure 9. Calibration Data for Sweep Draft

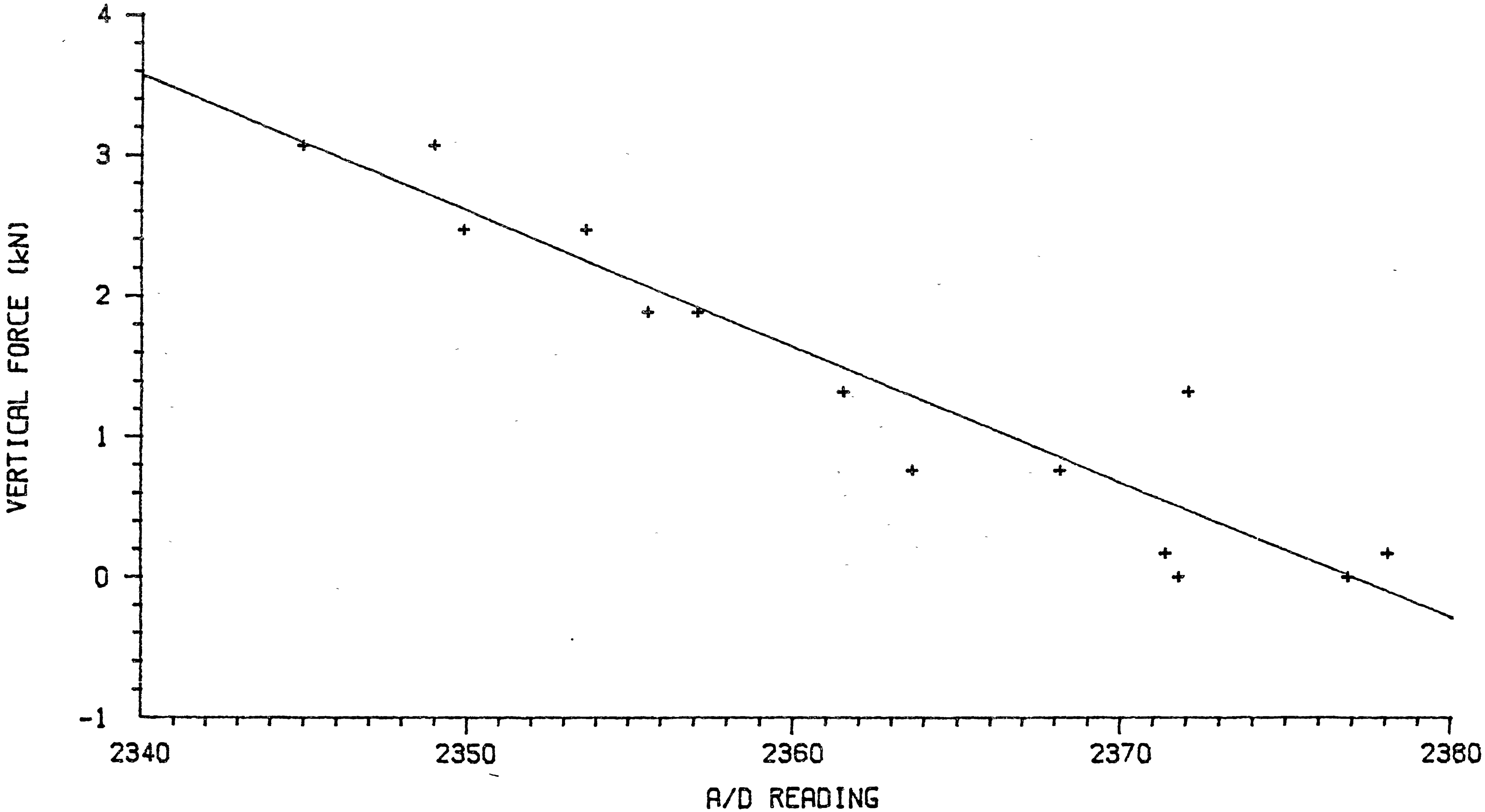

Figure 10. Calibration Data for Sweep Vertical Force

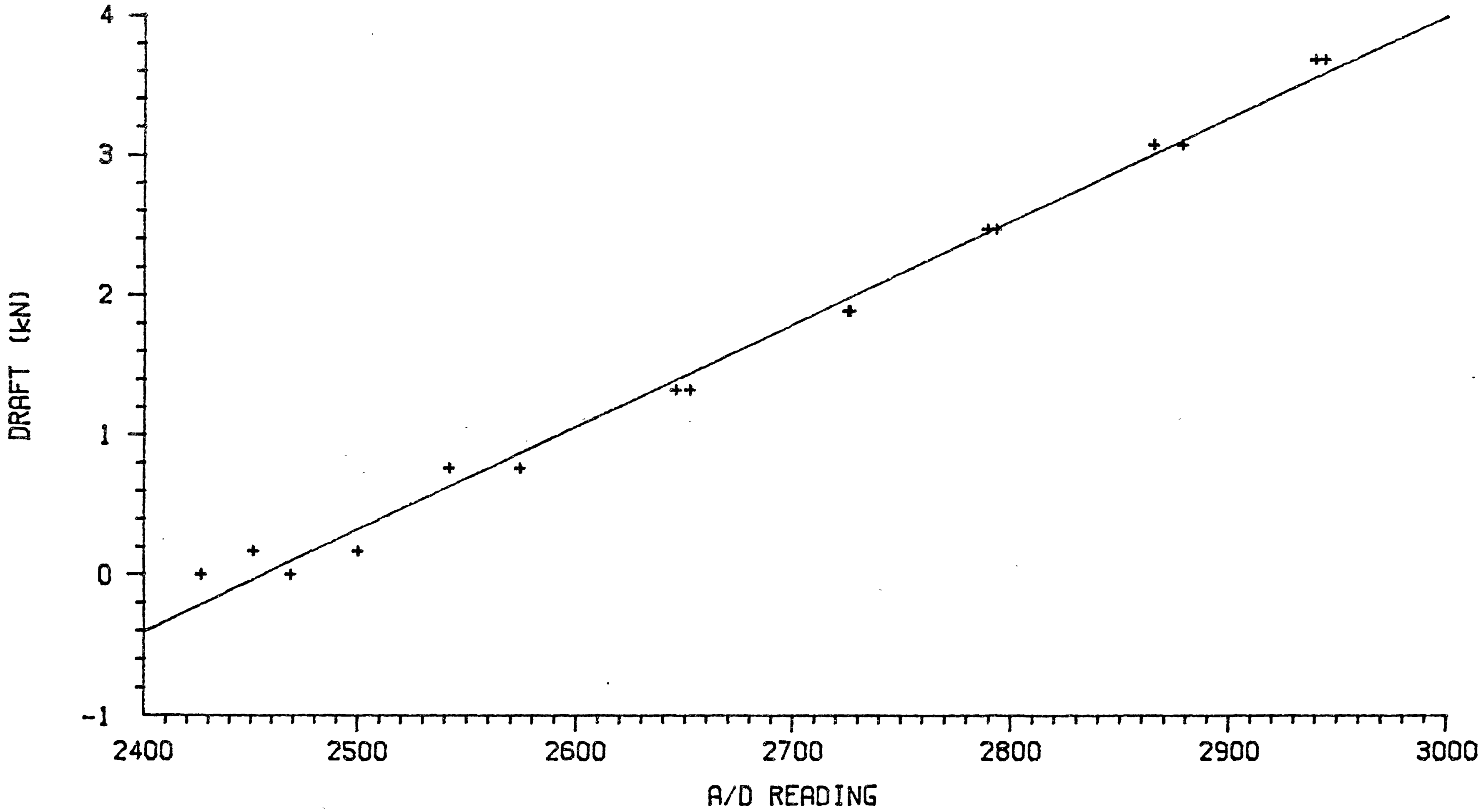

Figure 11. Calibration Data for Coulter Draft

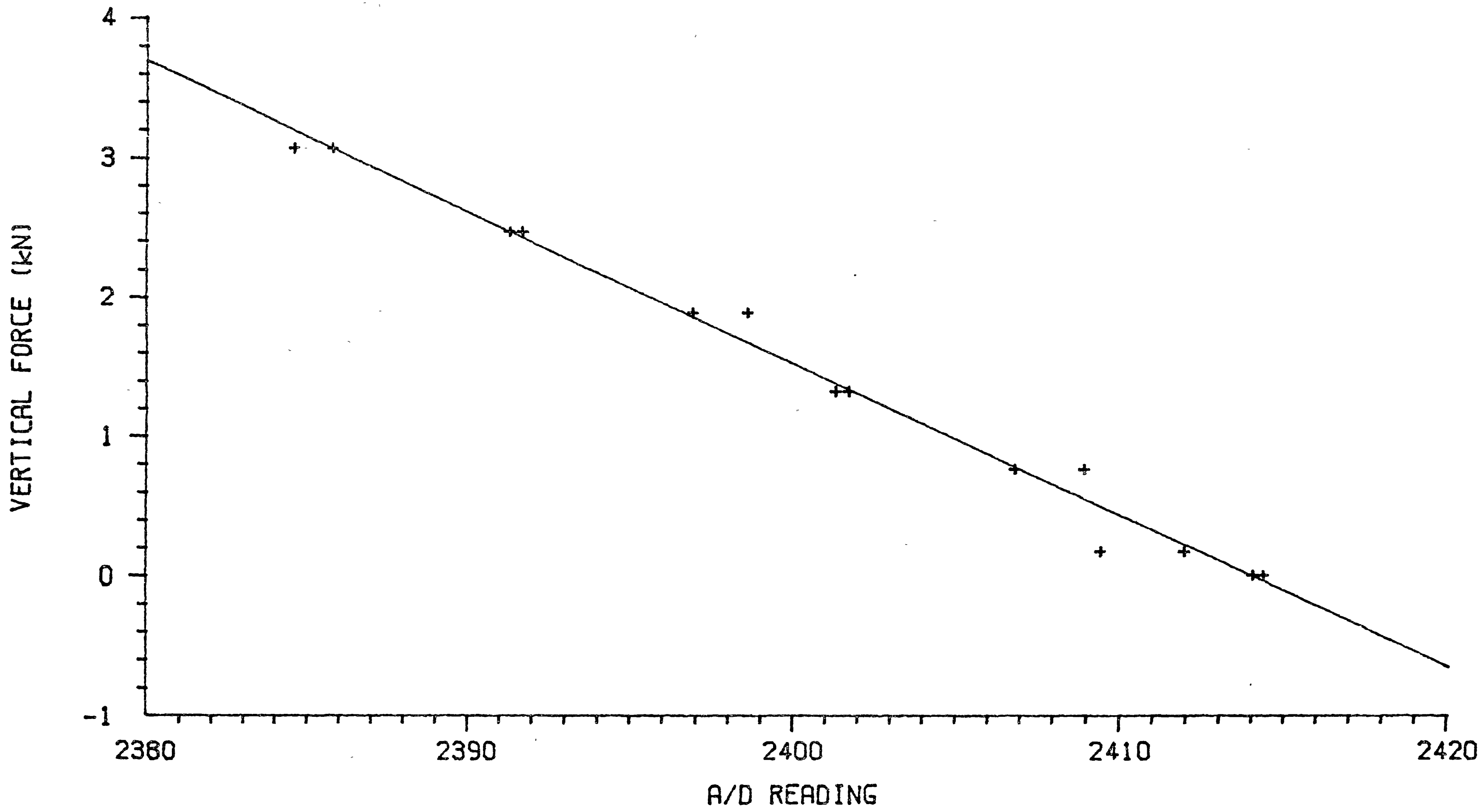

Figure 12. Calibration Data for Coulter Vertical Force

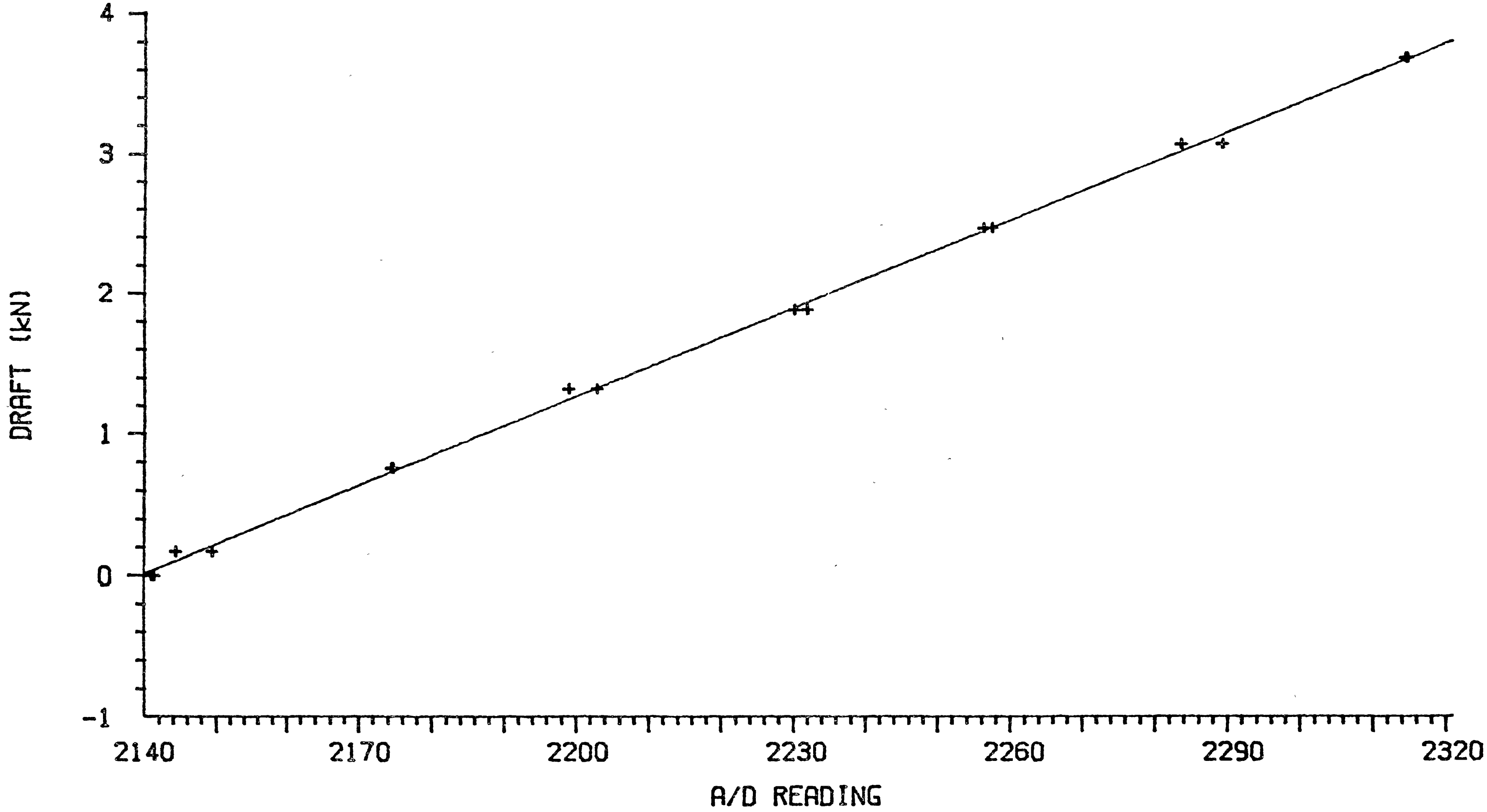

Figure 13. Calibration Data for Disk Draft

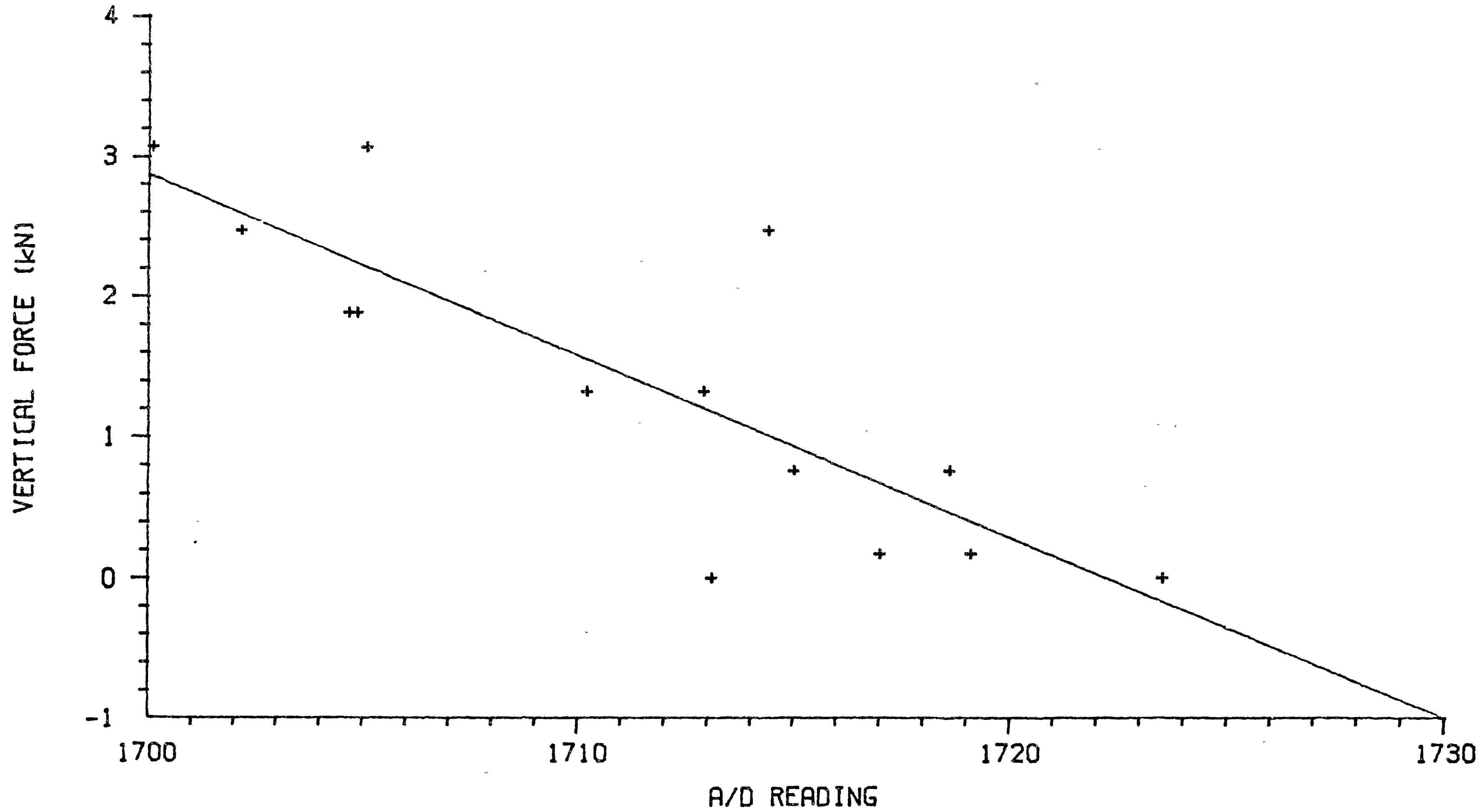

Figure 14. Calibration Data for Disk Vertical Force

TABLE II

CALIBRATION EQUATIONS
FORCE (kN) = A + Bx

Tool	Force Component	A	B	Res. (kN)	r^2	PR>F
Chisel	draft	-13.52	0.008	±.004	0.999	.001
	vertical	345.91	0.115	±.055	0.892	.001
Sweep	draft	-5.93	0.003	±.002	0.998	.001
	vertical	229.37	-0.097	±.049	0.892	.001
Coulter	draft	-18.00	0.007	±.004	0.991	.001
	vertical	262.42	-0.109	±.055	0.986	.001
Disk	draft	-44.94	0.021	±.011	0.998	.001
	vertical	222.23	-0.129	±.065	0.683	.001

Field Tests

Experimental Design

The experiment was performed using an experimental design based on theories of similitude (Murphy, 1950). The advantage of using a similitude approach is that fewer observations are needed to determine the relationship between tool forces and cone index. The first step in a dimensional analysis is to determine pertinent quantities. Quantities needed to describe the tool-penetrometer system are listed in Table III.

TABLE III

PERTINENT QUANTITIES AND SYMBOLS

Parameter	Symbol	Units
Cone index	CI	N/cm^2
Force on tool	F	N
Velocity	V	cm/s
Depth	D	cm
Characteristic length	L	cm
Acceleration of gravity	g	cm/s^2

Acceleration of gravity was added so dimensional homogeneity of dimensionless terms could be maintained. Utilization of Buckingham's Pi Theorem results in the combination of the pertinent quantities into Π-terms. One valid set of Π-terms is:

$$\Pi_1 = \frac{F}{CI*D^2} \tag{2}$$

$$\Pi_2 = \frac{V^2}{L*g} \tag{3}$$

$$\Pi_3 = \frac{L}{D} \tag{4}$$

where $\Pi_1 = f(\Pi_2, \Pi_3)$. Velocity was used to vary Π_2 and Π_3 was varied by changing the depth of tillage. Values of velocity used to design the experiment were 4.0, 5.6, 7.1 and 8.7 km/h. Design values of depth were 5.1, 10.2, 15.2 and 20.3 cm. These velocities and depths were selected to cover the range of velocity and depth used for most tillage operations.

Data Collection

Field tests were performed at Lake Carl Blackwell Experimental Range Area, Stillwater Oklahoma. Cone index data were collected from January 14 to January 18, 1985. Force data were collected on January 19, 1985. Air temperature ranged from 0 ^{o}C to 7.2 ^{o}C.

Experimental plots were arranged in a randomized complete block design. Each plot consisted of one combination of depth and velocity. This resulted in sixteen plots. Each group of plots, block, was then replicated six times. Due to space limitations, four blocks were placed in one field and the remaining two blocks were placed in a second field. Figures 15 and 16 show the layout of plots. Plot size was determined by the width of the frame and the minimum length needed to collect data. These specifications resulted in plots 3.1 m wide and 12.2 m long.

Soil type for the four replicatins shown in Figure 15 was Pulaski fine sandy loam. This field had not been tilled in a minimum of three years. The field surface had a cover of cheat, which was growing, and bluestem. Soil type for the two blocks shown in Figure 16 was Mclain silt loam. A sweep plow had been used to till this field approximately one year prior to testing. The surface of this field also had a cover of growing cheat and dead bluestem.

Moisture content of the soil was high, but it was not above the range where most tillage is done. Soil moisture content and dry bulk density for each plot are listed in Appendix D.

Cone index data were taken at six locations in each plot. Cone index data were collected using a tractor mounted, hydraulically operated, digital recording soil penetrometer system developed by Riethmuller, Batchelder, and, Bloome (1982). Data from these six locations were averaged resulting in one value of cone index for each 20 mm of depth. These were further reduced to one value of cone

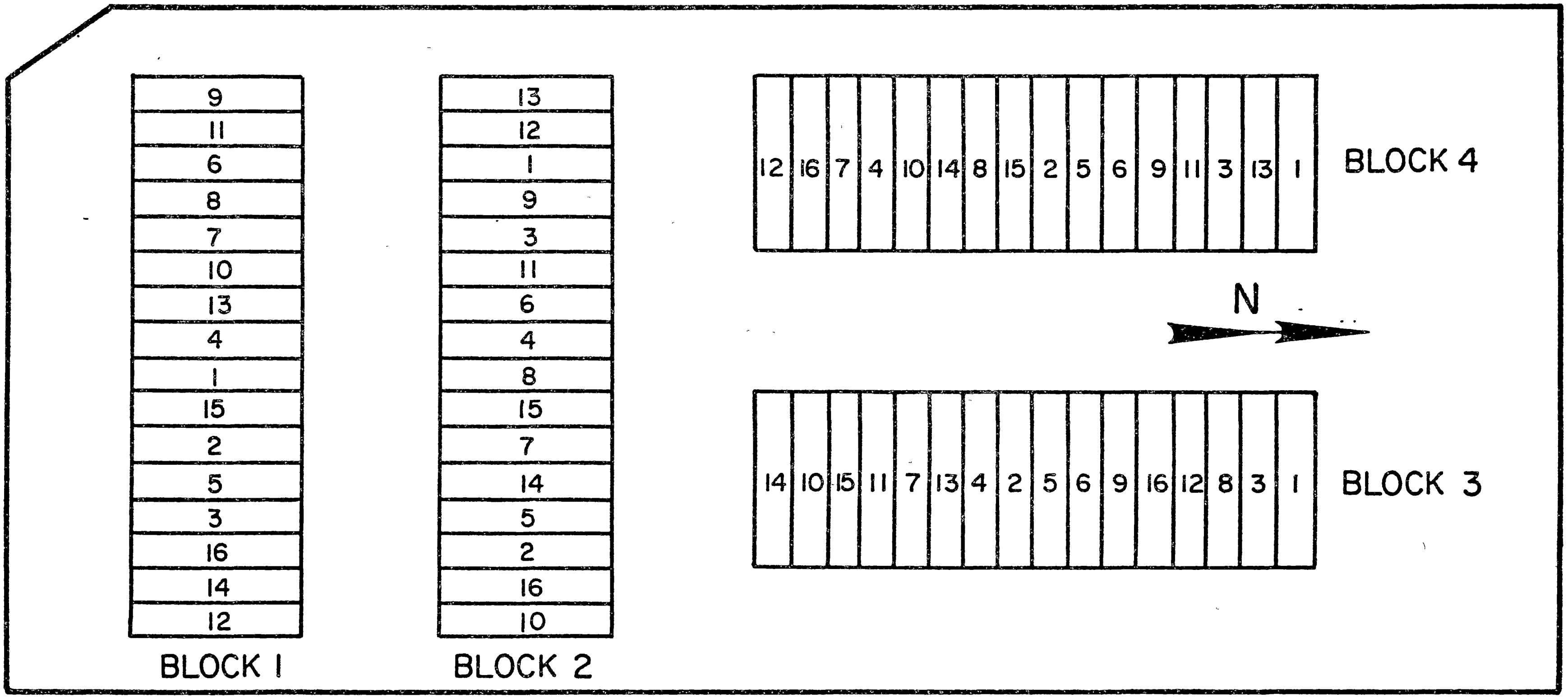

Figure 15. Arrangement of Blocks One through Four

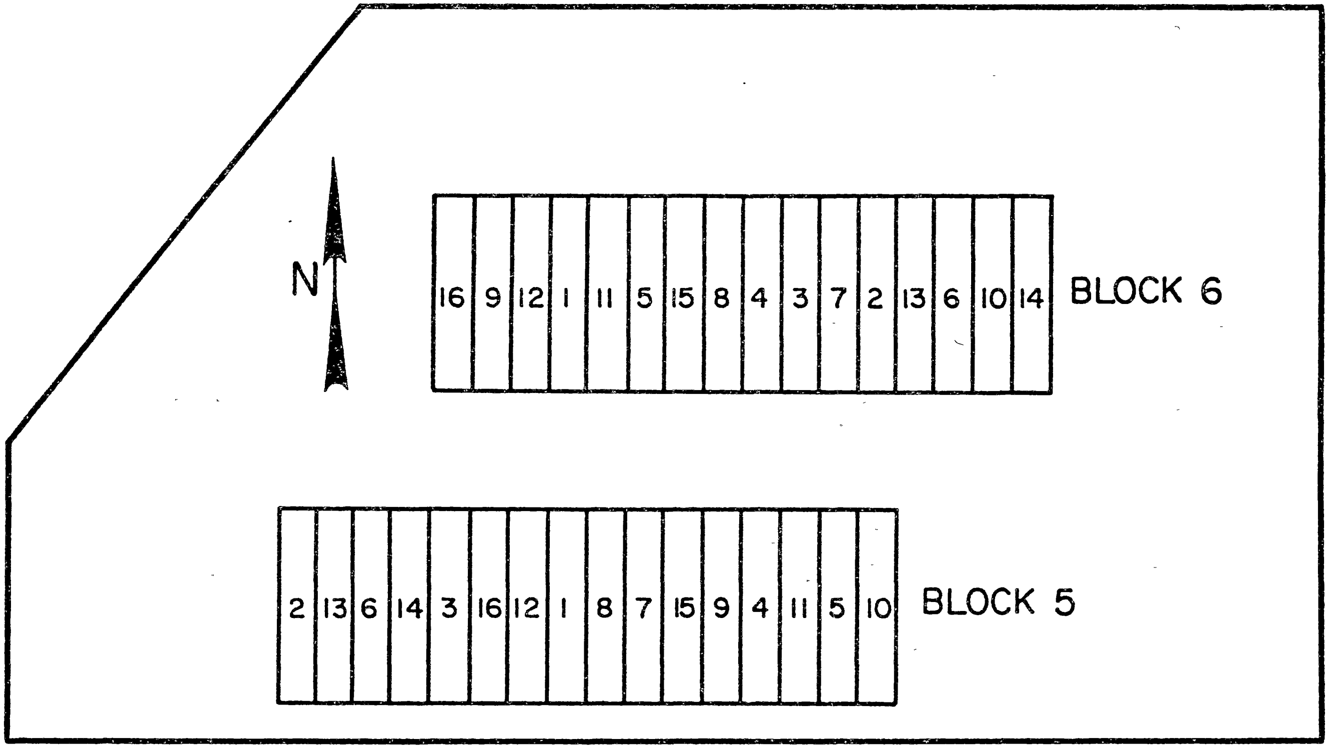

Figure 16. Arrangement of Blocks Five and Six

index per plot by determining an integrated average, using the rectangular rule, over the depth of tillage.

After cone index data were collected, draft and vertical force measurements were collected while operating at the specified depth and velocity. For ease in performing the experiment, all operations of equal depth were performed at one time. Since two force measurements were taken in each plot for each tool, two values of Π_1 exist for each plot.

The first three depths were completed for the four replications shown in Figure 15. The first two depths were completed for the two replications shown in Figure 16. Data collection stopped here because of data logger problems caused by the cold weather. It was determined that sufficient data had been collected to conduct the analysis.

After the data were gathered, depth of tillage was measured. Depth was measured using the ground surface in the gage wheel track as the zero reference.

CHAPTER IV

RESULTS AND DISCUSSION

Force data collected during field tests are listed in Appendix E and cone index, velocity and depth data are listed in Appendix F. Equations (3) and (4) were used to calculate Π_2 and Π_3 using these data. Three different expressions for Π_1 can be considered. These are:

$$\Pi_1 = \frac{F}{CI*D^2} \tag{5}$$

$$\Pi_1 = \frac{F}{CI*L^2} \tag{6}$$

$$\Pi_1 = \frac{F}{CI*L*D} \tag{7}$$

To determine the best form of Π_1, correlation matrices were formed between the three forms of Π_1 and the other two Π-terms. Correlations between Π_1 and Π_2 and between Π_1 and Π_3 are listed in Tables IV, V and VI. The form of Π_1 selected was the one having the highest correlation with Π_2 and Π_3. The form of Π_1 used in the remainder of the analysis is equation (5). Values of Π_1, Π_2 and Π_3 are listed in Appendix G.

The functional relationship between Π_1 and Π_2 is determined by holding Π_3 constant. The only variable that

TABLE IV

CORRELATIONS BETWEEN Π-TERMS AND Π_1
FOR DRAFT AND VERTICAL FORCE
CALCULATED BY EQUATION (5)

Tool	Force Component	Π_2			Π_3			
		Depth 1	Depth 2	Depth 3	Vel. 1	Vel. 2	Vel. 3	Vel. 4
Chisel	draft	0.065	0.367	0.340	0.814	0.667	0.907	0.841
	vertical	-0.189	-0.338	-0.432	0.918	0.874	0.716	0.892
Sweep	draft	-0.111	0.231	0.308	0.885	0.840	0.928	0.803
	vertical	0.066	-0.066	-0.544	0.722	0.518	0.291	0.644
Coulter	draft	-0.081	0.236	-0.224	0.803	0.607	0.777	0.663
	vertical	0.273	0.170	-0.350	0.859	0.762	0.653	0.831
Disk	draft	0.044	0.362	0.053	0.783	0.837	0.922	0.752
	vertical	-0.133	0.141	-0.084	0.632	0.131	0.358	0.448

TABLE V

CORRELATIONS BETWEEN Π-TERMS AND Π_1 FOR DRAFT AND VERTICAL FORCE CALCULATED BY EQUATION (6)

Tool	Force Component	Π_2			Π_3			
		Depth 1	Depth 2	Depth 3	Vel. 1	Vel. 2	Vel. 3	Vel. 4
Chisel	draft	0.065	0.367	0.340	-0.631	-0.689	-0.679	-0.875
	vertical	-0.189	-0.338	-0.432	0.766	0.640	0.701	0.834
Sweep	draft	-0.111	0.231	0.308	-0.488	-0.449	-0.691	-0.646
	vertical	0.066	-0.066	-0.544	0.827	0.733	0.751	0.860
Coulter	draft	-0.081	0.236	-0.224	-0.062	0.077	-0.099	-0.057
	vertical	0.273	0.170	-0.350	-0.010	0.080	-0.122	0.411
Disk	draft	0.044	0.362	0.053	-0.506	-0.724	-0.682	-0.751
	vertical	-0.133	0.141	-0.084	-0.661	-0.751	-0.612	-0.763

TABLE VI

CORRELATIONS BETWEEN Π-TERMS AND Π_1
FOR DRAFT AND VERTICAL FORCE
CALCULATED BY EQUATION (7)

Tool	Force Component	Π_2			Π_3			
		Depth 1	Depth 2	Depth 3	Vel. 1	Vel. 2	Vel. 3	Vel. 4
Chisel	draft	0.065	0.367	0.340	0.410	0.212	0.405	0.116
	vertical	-0.189	-0.338	-0.432	0.890	0.796	0.735	0.894
Sweep	draft	-0.111	0.231	0.308	0.685	0.609	0.406	0.348
	vertical	0.066	-0.066	-0.544	0.798	0.654	0.596	0.775
Coulter	draft	-0.081	0.236	-0.224	0.665	0.473	0.607	0.474
	vertical	0.273	0.170	-0.350	0.527	0.436	0.214	0.668
Disk	draft	0.044	0.362	0.053	0.349	0.307	0.423	0.125
	vertical	-0.133	0.141	-0.084	0.091	-0.388	-0.126	-0.205

changed in Π_3 was depth of tillage. However, the actual depths of tillage were not equal to the design values. Table VII shows the actual values and design values of depth.

TABLE VII

ACTUAL VALUES AND DESIGN VALUES OF DEPTH

Design Depth (cm)	Actual Depth (cm)
5.1	5.1
10.2	10.2
15.2	12.7
20.3	*

*The fourth depth was omitted from the experiment because the temperature dropped below the operational limits of the data logger.

The relationship between Π_1 and Π_3 is determined by holding Π_2 constant. The variable used to vary Π_2 was velocity. The velocity was to be maintained by the tractor. Due to changing soil conditions and depths of tillage the velocity did not remain constant for all depths. Therefore, the relationship between Π_1 and Π_3 was determined for each gear the tractor was operated in.

Graphs of Π_1 versus Π_2 and Π_1 versus Π_3 were made (Figures 17 through 32) for both forces acting on each tool. Regression equations were developed for each Π_1 versus Π_2 and Π_1 versus Π_3 using an IBM PC and Plotrax 2 by Engineering Science, Inc. This regression analysis software was used because it offered an easy wasy to fit the data to several different mathematical models. Based on the coefficient of determination, the models which best explained the variance are linear relationships for both Π_1 versus Π_2 and Π_1 versus Π_3. The equations are of the form:

$$\Pi_1 = A + B\Pi_2 \tag{8}$$

$$\Pi_1 = C + D\Pi_3 \tag{9}$$

Final regressions of the component equations were made using a general linear model procedure available in the Statistical Analysis System on the Oklahoma State University IBM 3081D computer. Regression equations are listed in Tables VIII and IX.

Analysis of the component equations (Tables VIII and IX) shows that Π_1 is more highly correlated to Π_2 than to Π_3. Correlation coefficients for Π_1 versus Π_3 range from 0.130 to 0.920. No value greater than 0.544 is observed for the correlation coefficient between Π_1 and Π_2. This indicates that tool forces are not strongly related to velocity in this analysis, but they are dependent on depth of tillage. The graphs of Π_1 versus Π_2 show more scatter at the largest value of Π_3 than for the other two values of Π_3. The largest value of Π_3 corresponds to the shallowest

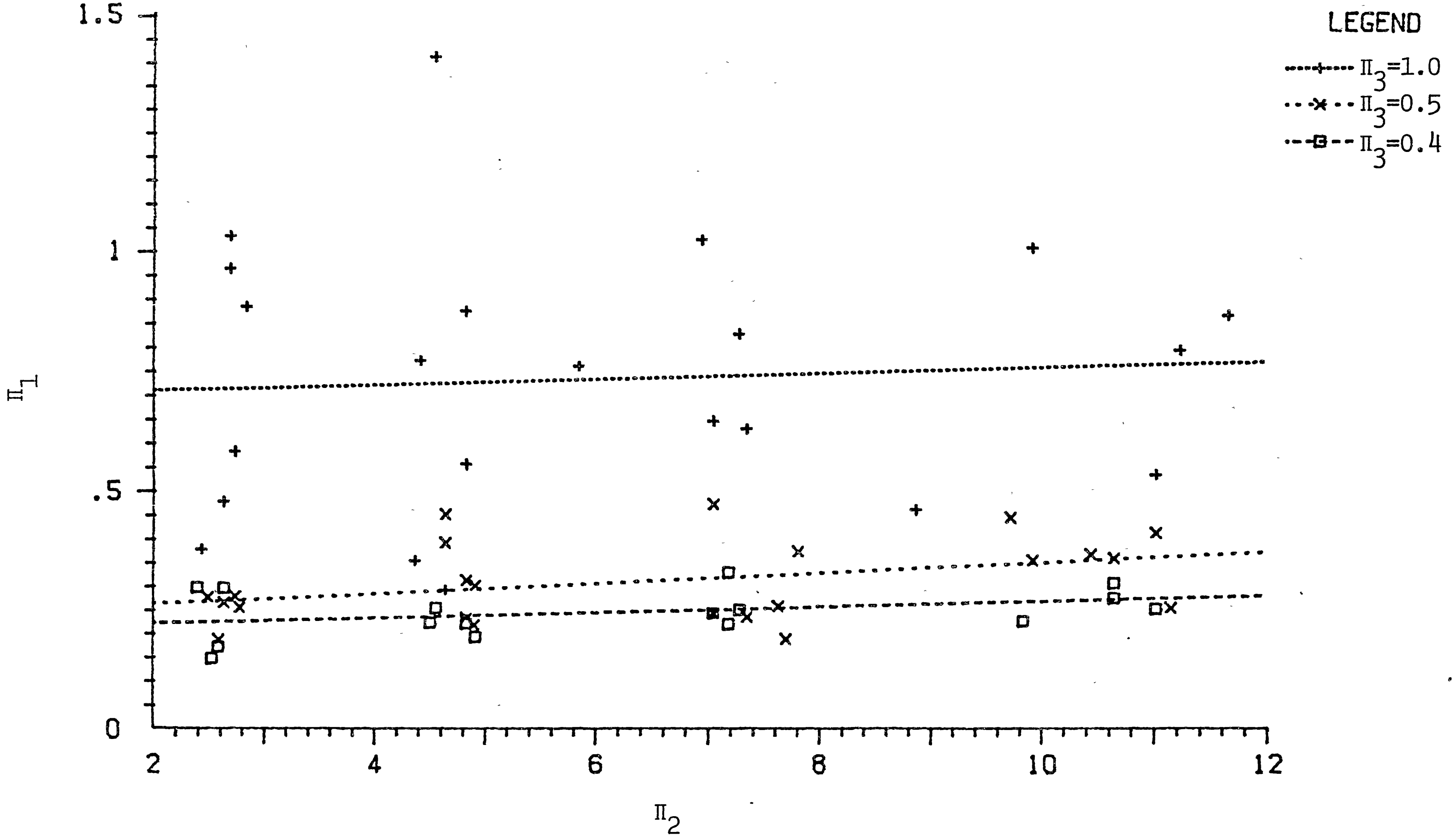

Figure 17. Π_1 versus Π_2 for the Chisel using Draft to Calculate Π_1

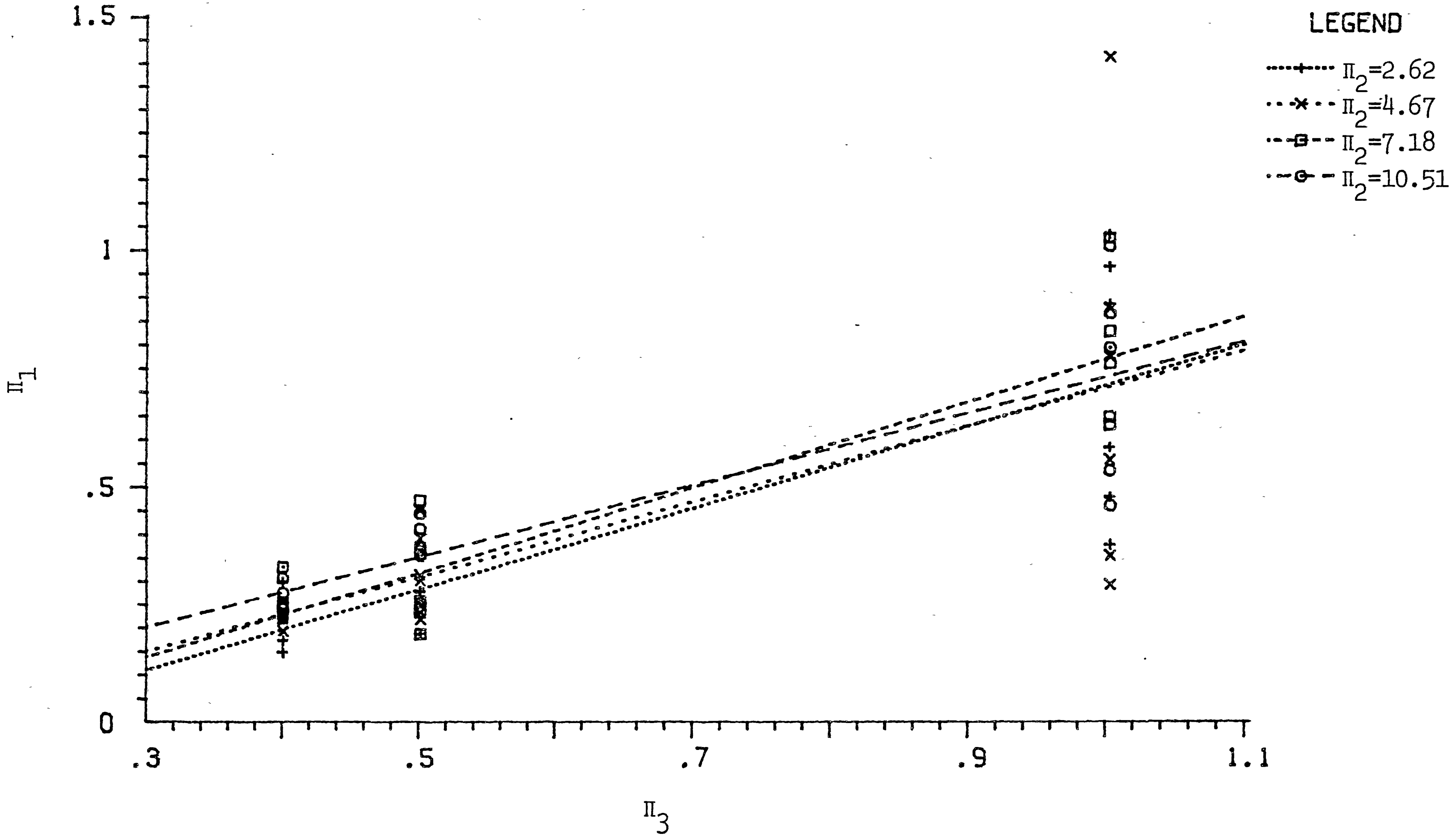

Figure 18. Π_1 versus Π_3 for the Chisel using Draft to Calculate Π_1

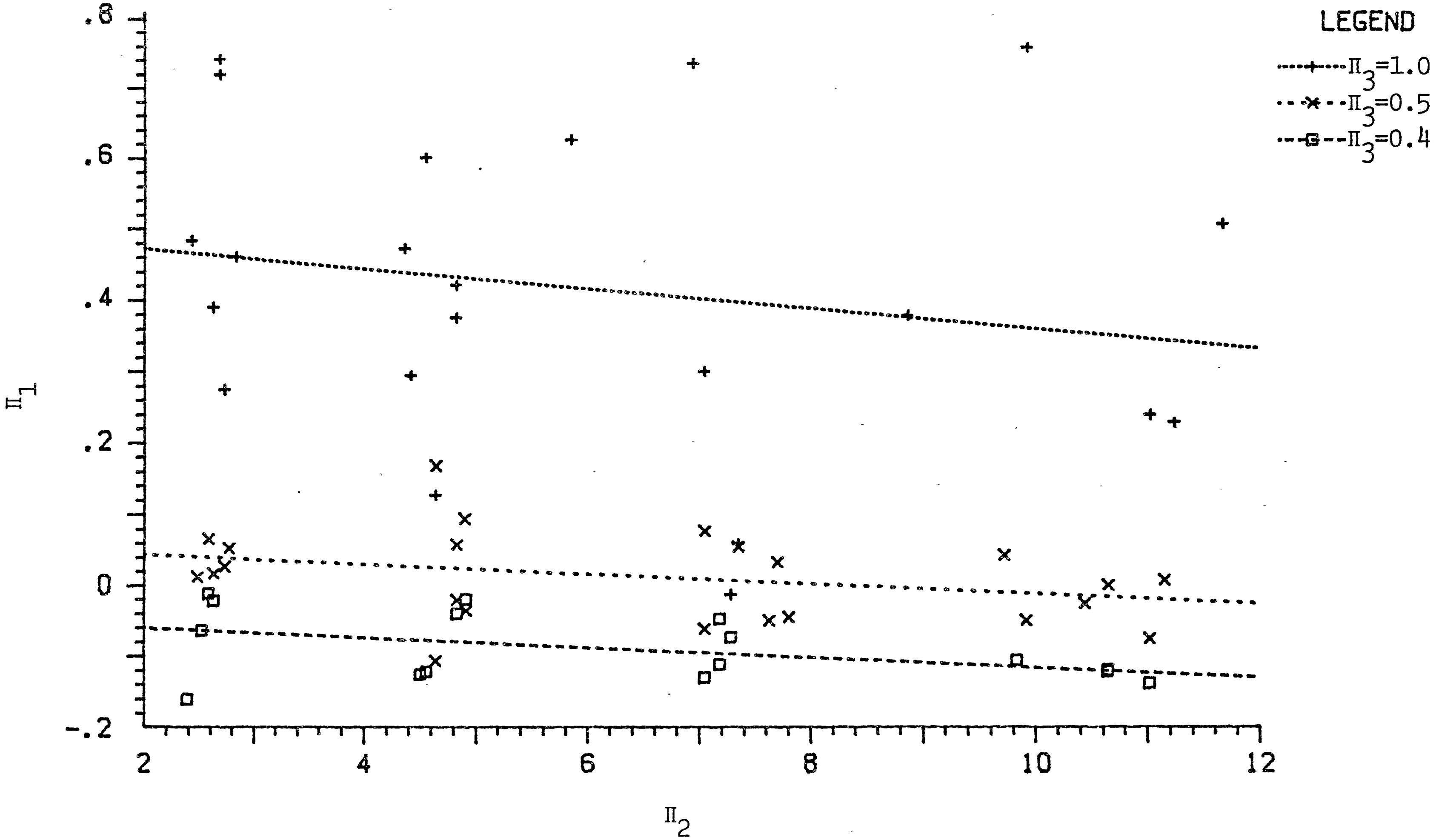

Figure 19. Π_1 versus Π_2 for the Chisel using Vertical Force to Calculate Π_1

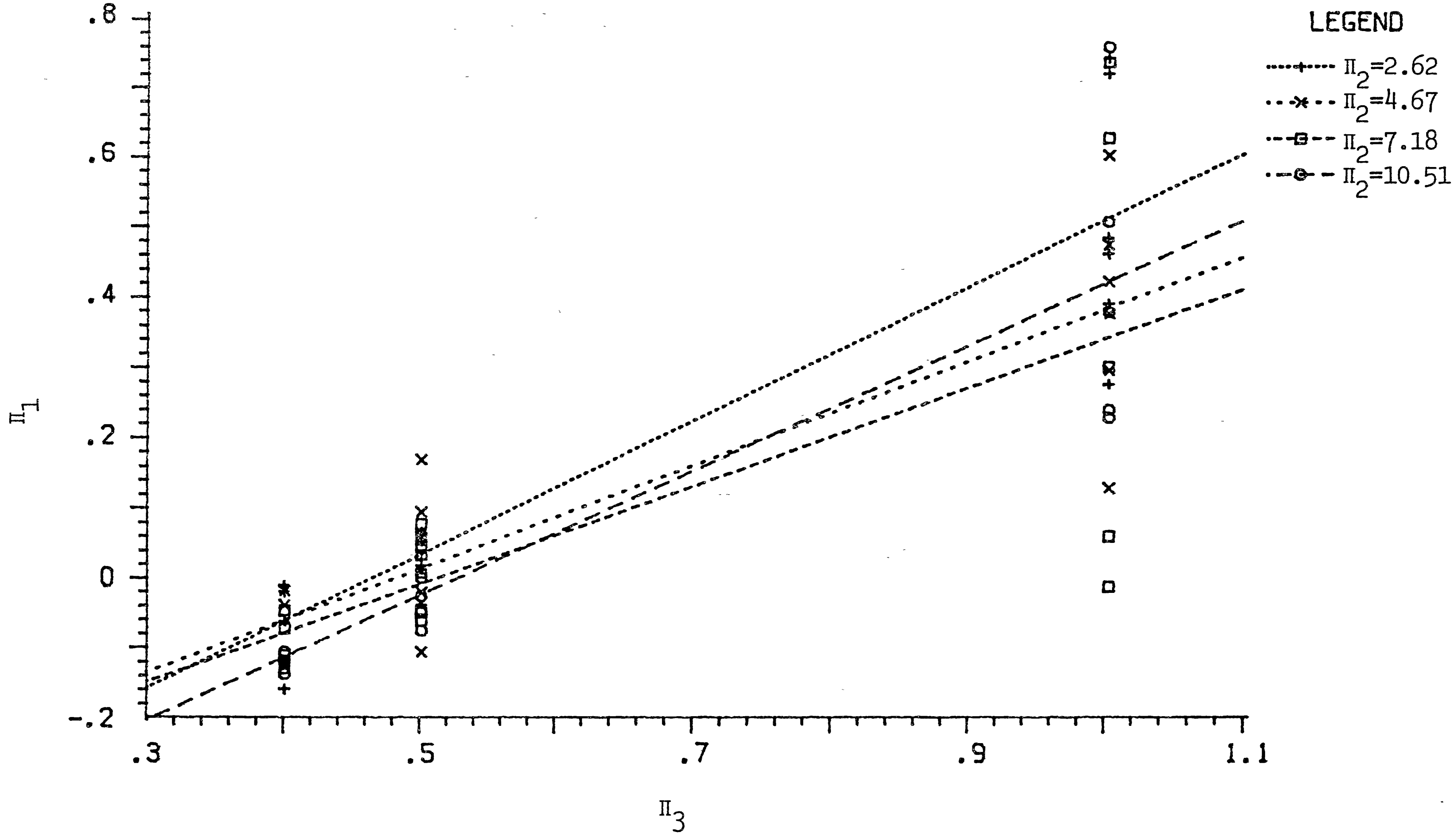

Figure 20. Π_1 versus Π_3 for the Chisel using Vertical Force to Calculate Π_1

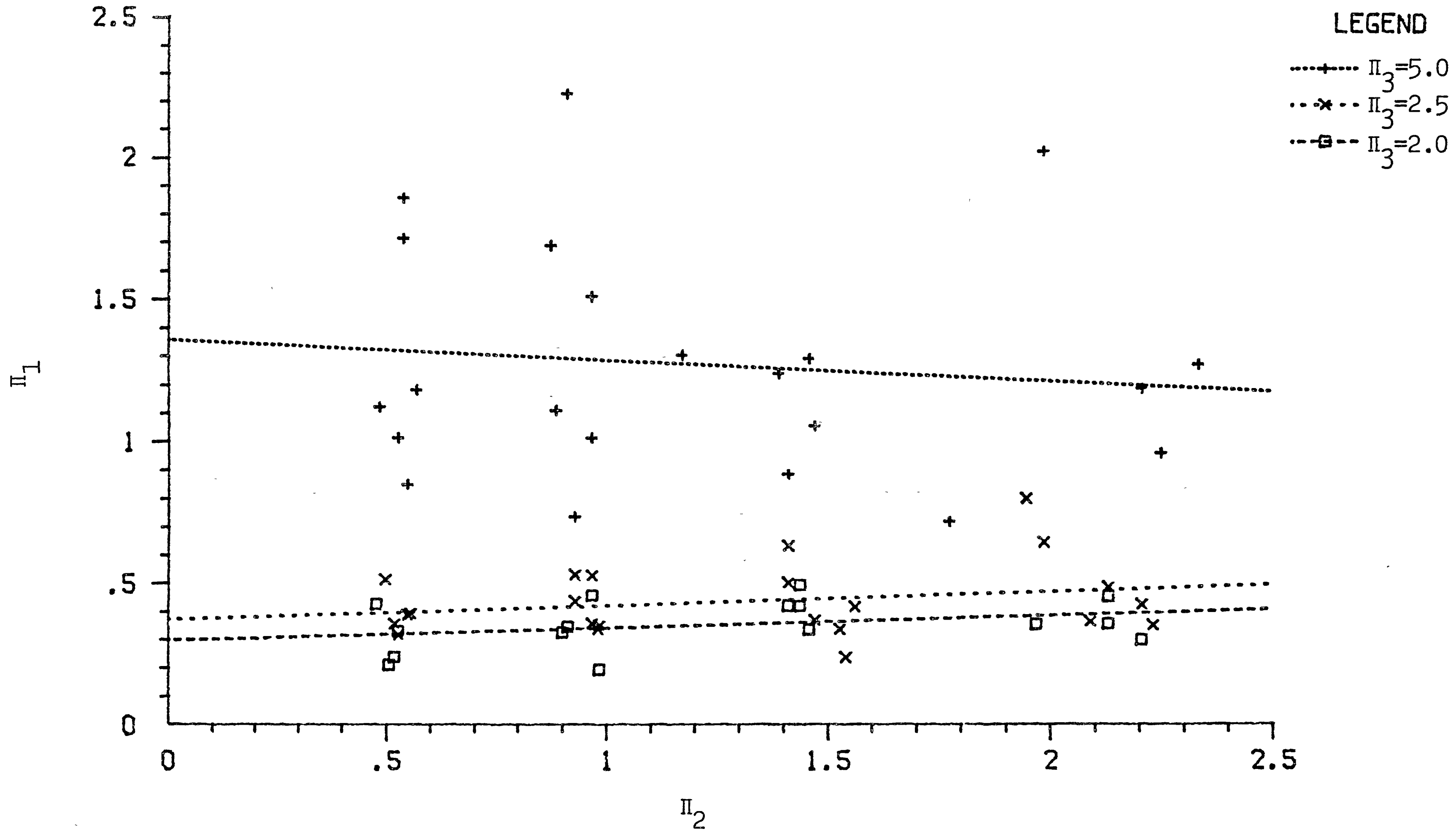

Figure 21. Π_1 versus Π_2 for the Sweep using Draft to Calculate Π_1

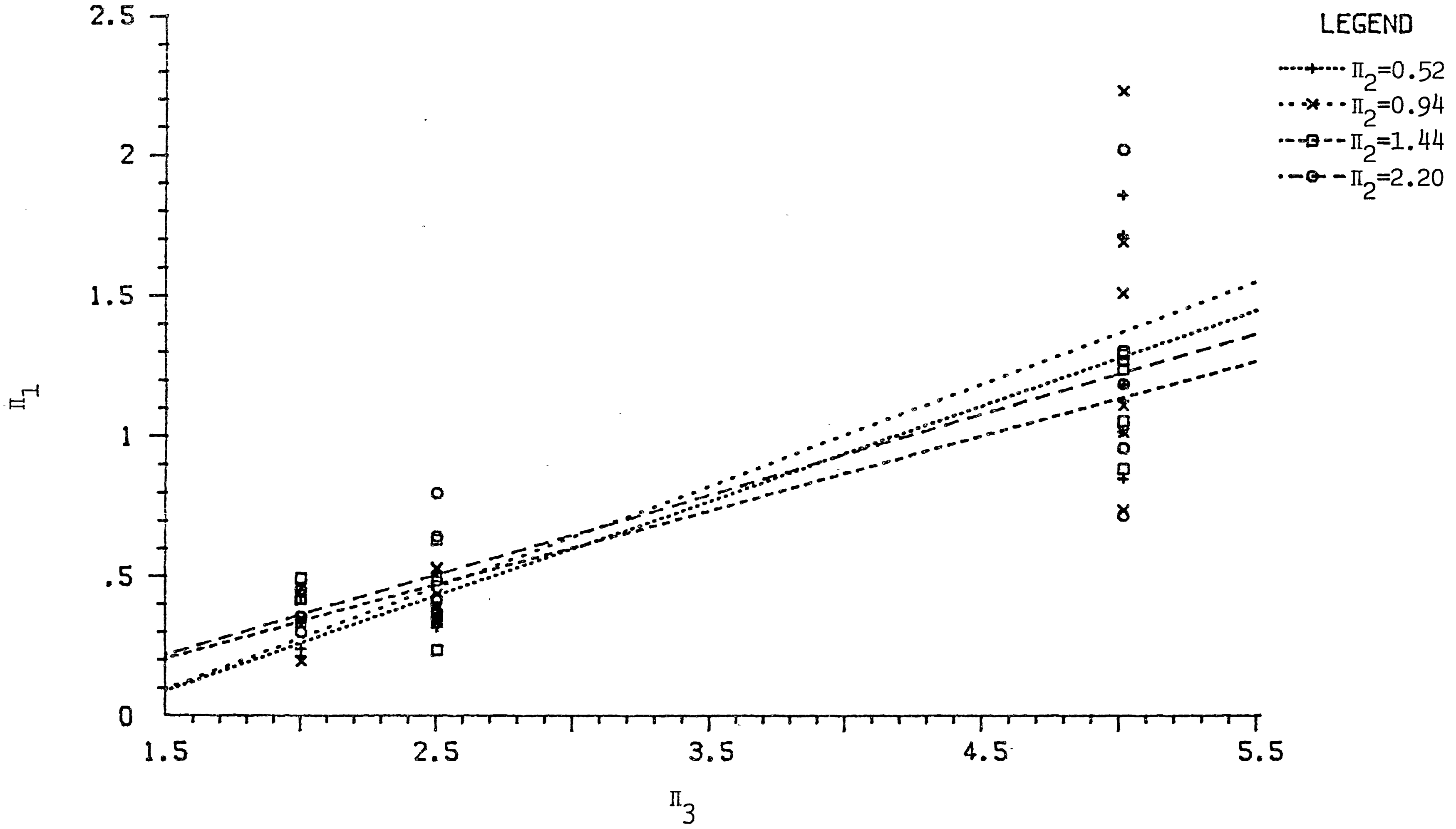

Figure 22. Π_1 versus Π_3 for the Sweep using Draft to Calculate Π_1

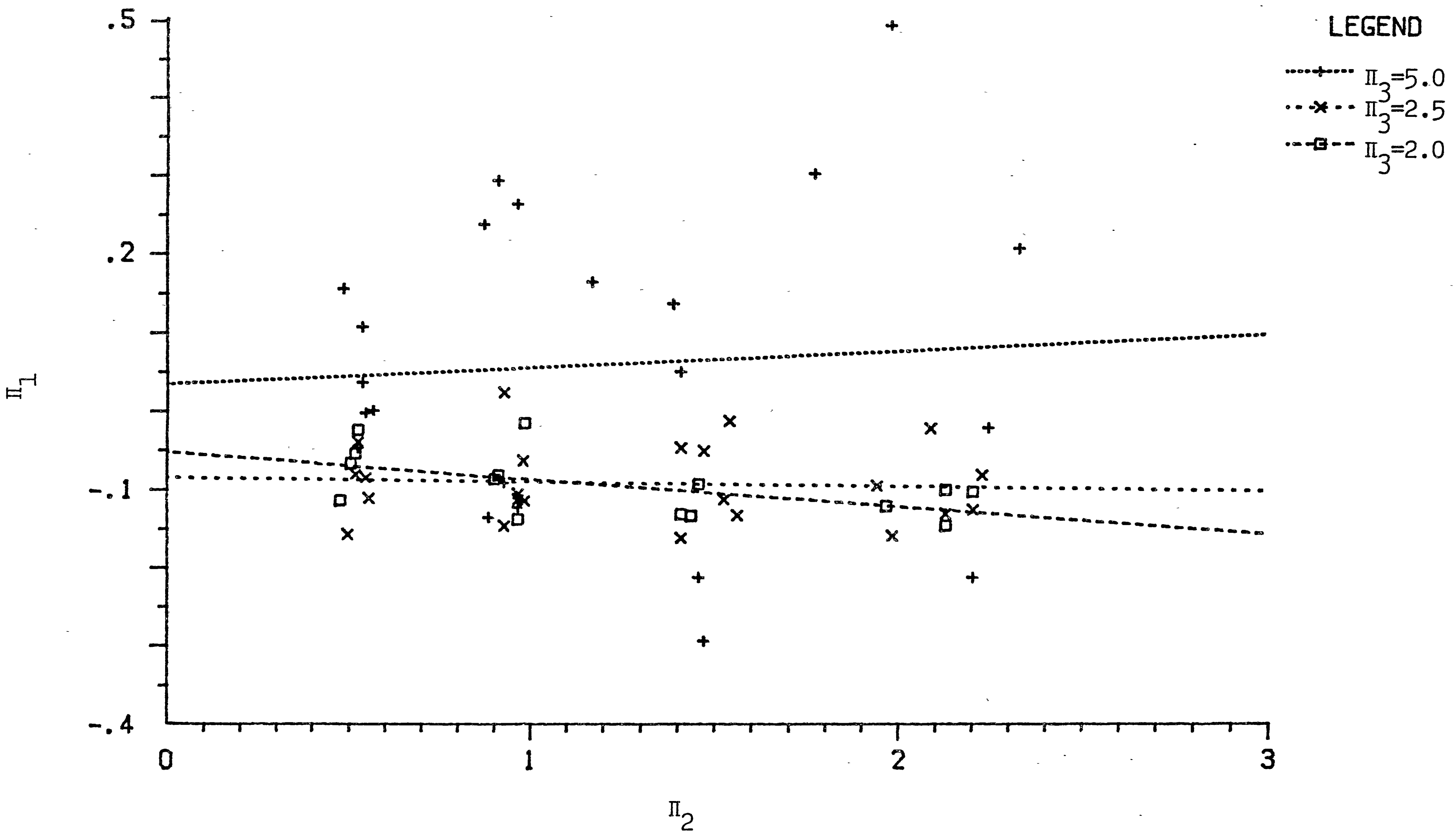

Figure 23. Π_1 versus Π_2 for the Sweep using Vertical Force to Calculate Π_1

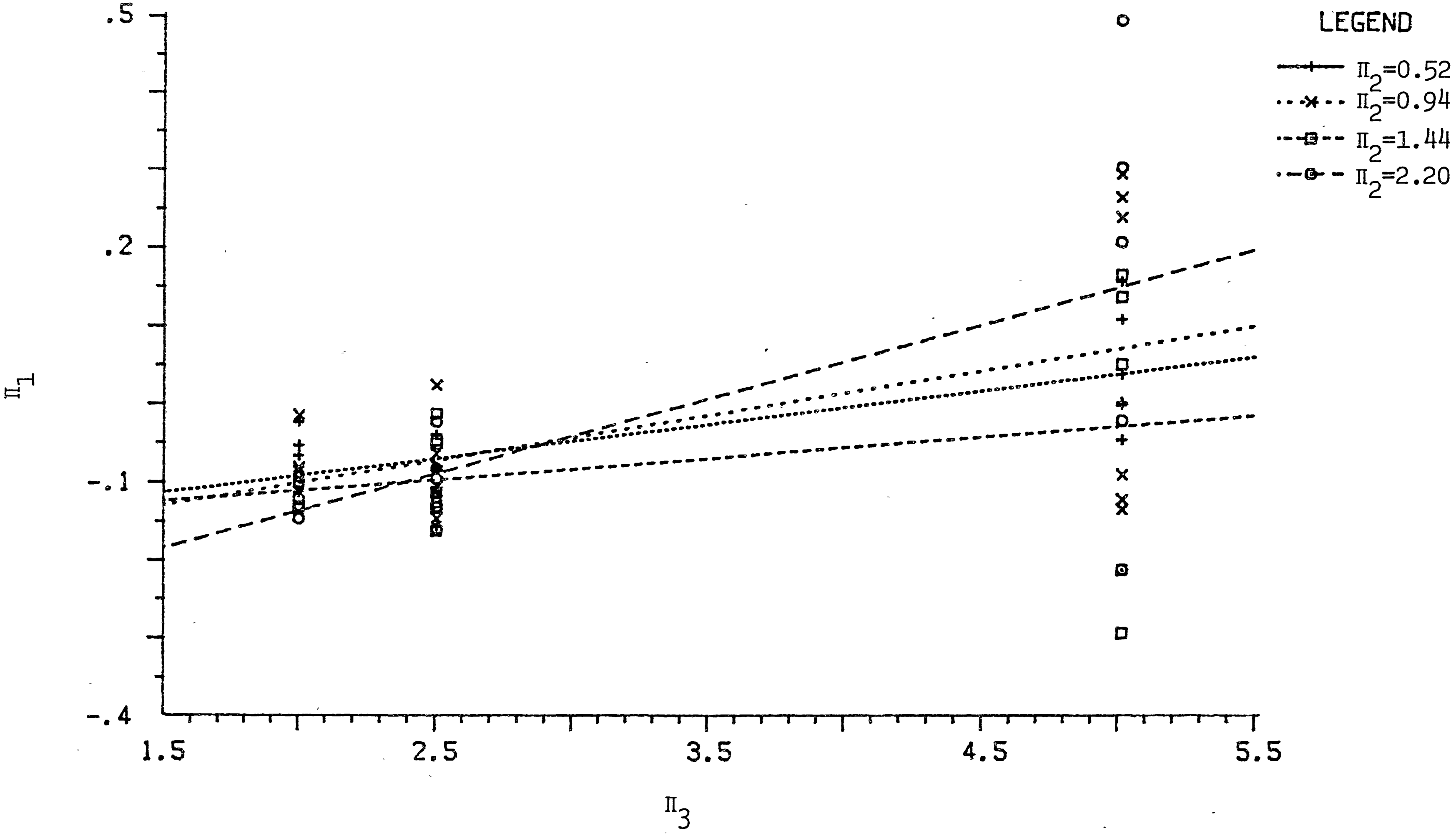

Figure 24. Π_1 versus Π_3 for the Sweep using Vertical Force to Calculate Π_1

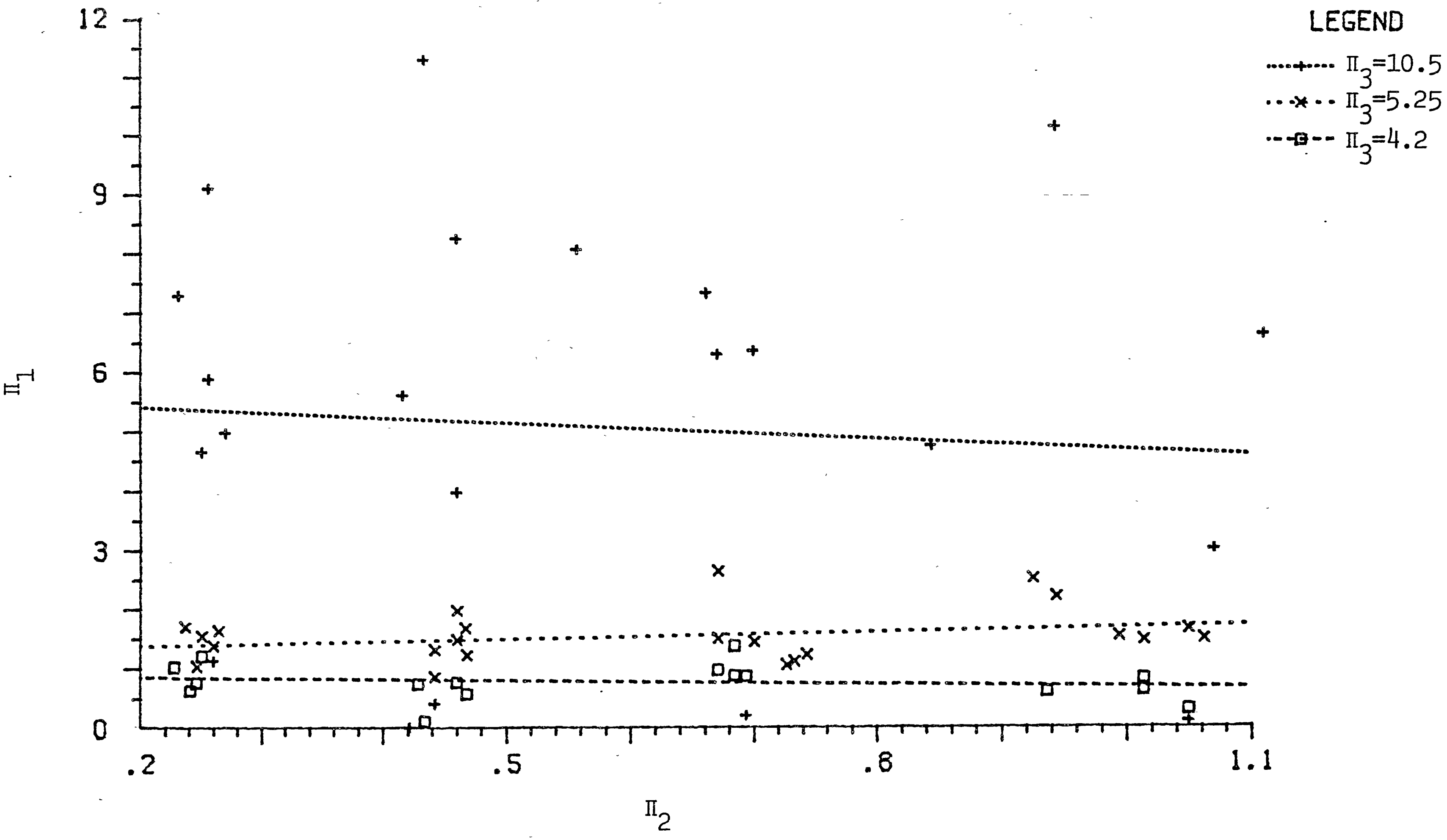

Figure 25. Π_1 versus Π_2 for the Coulter using Draft to Calculate Π_1

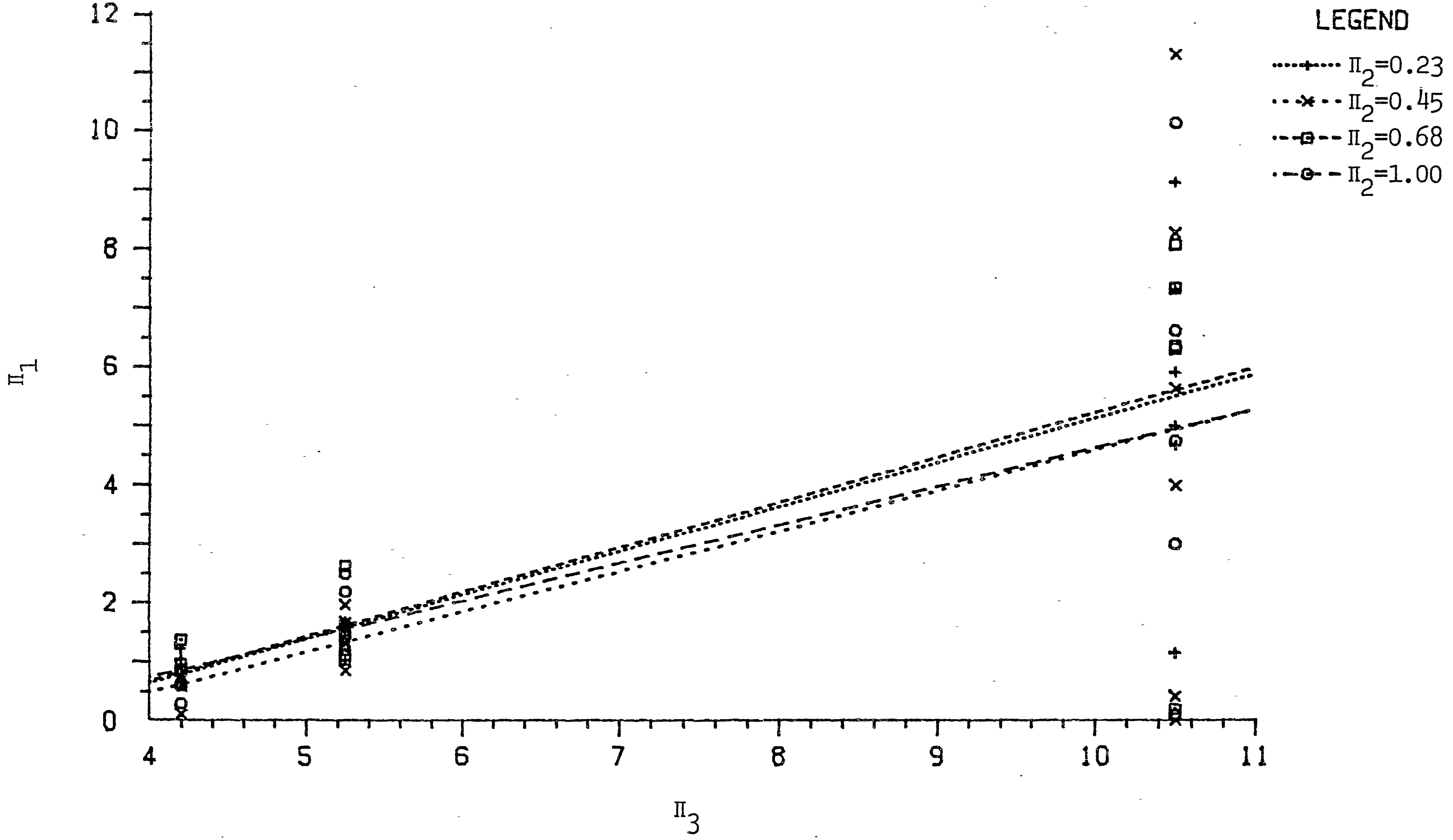

Figure 26. Π_1 versus Π_3 for the Coulter using Draft to Calculate Π_1

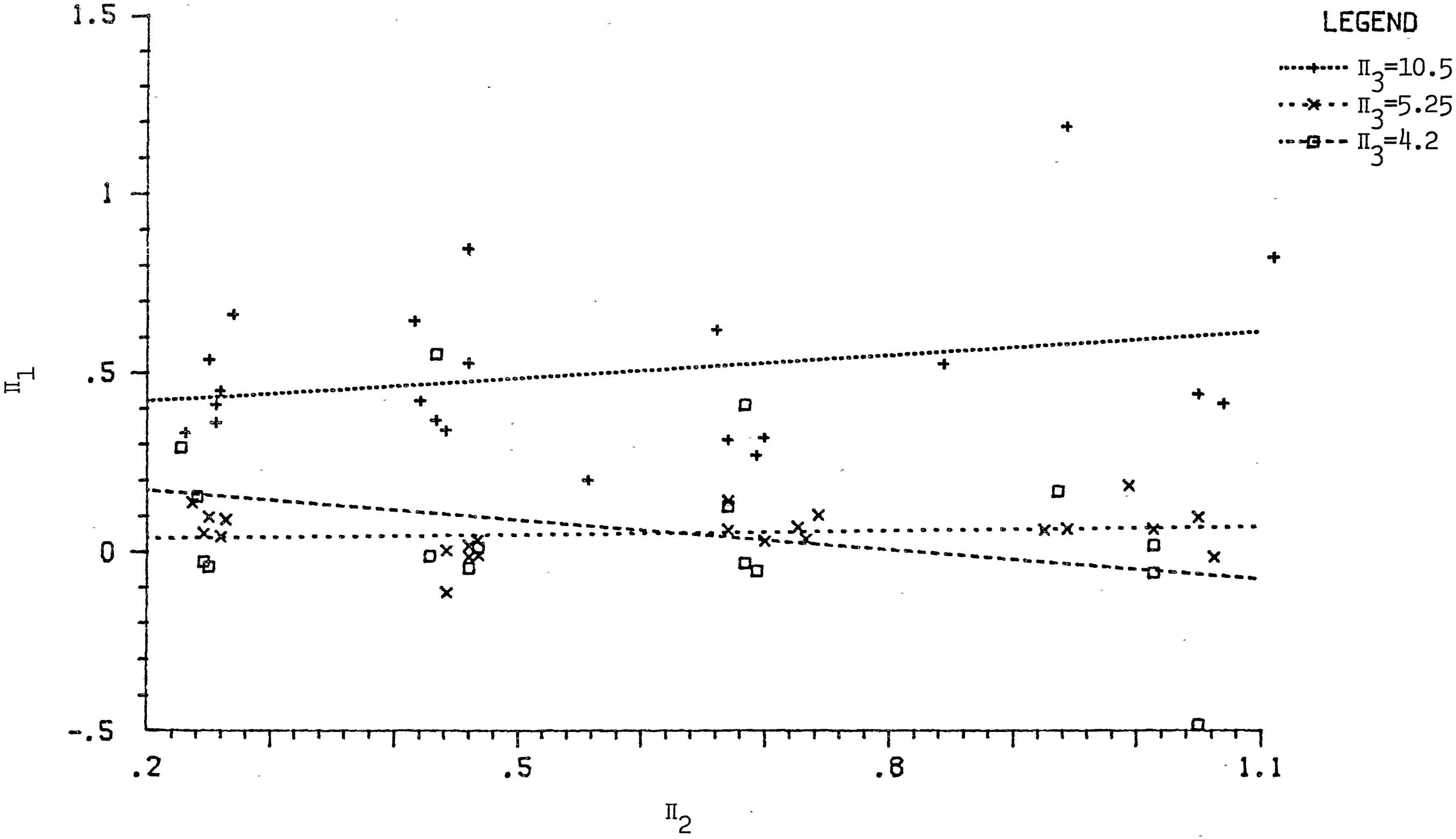

Figure 27. Π_1 versus Π_2 for the Coulter using Vertical Force to Calculate Π_1

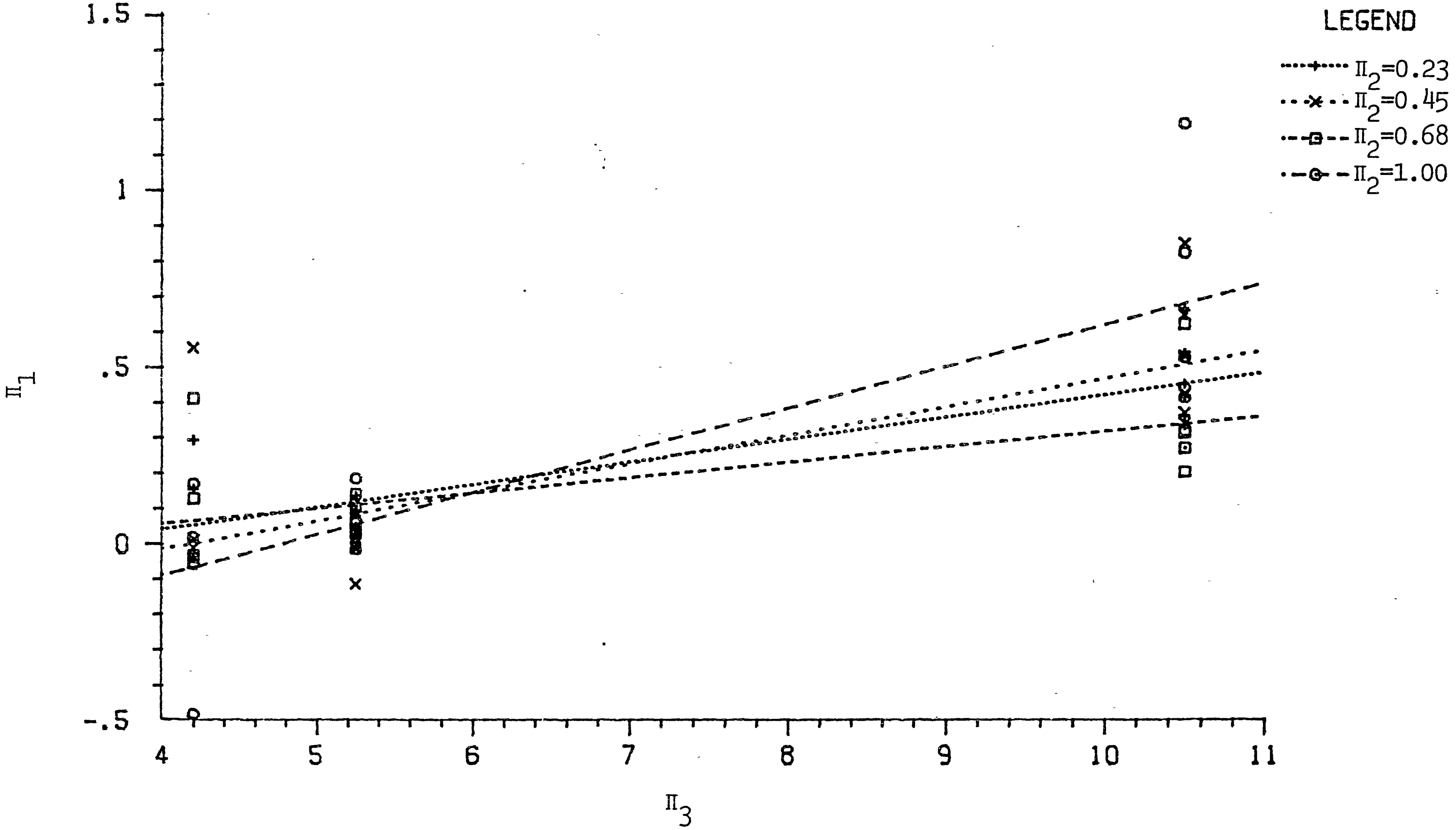

Figure 28. Π_1 versus Π_3 for the Coulter using Vertical Force to Calculate Π_1

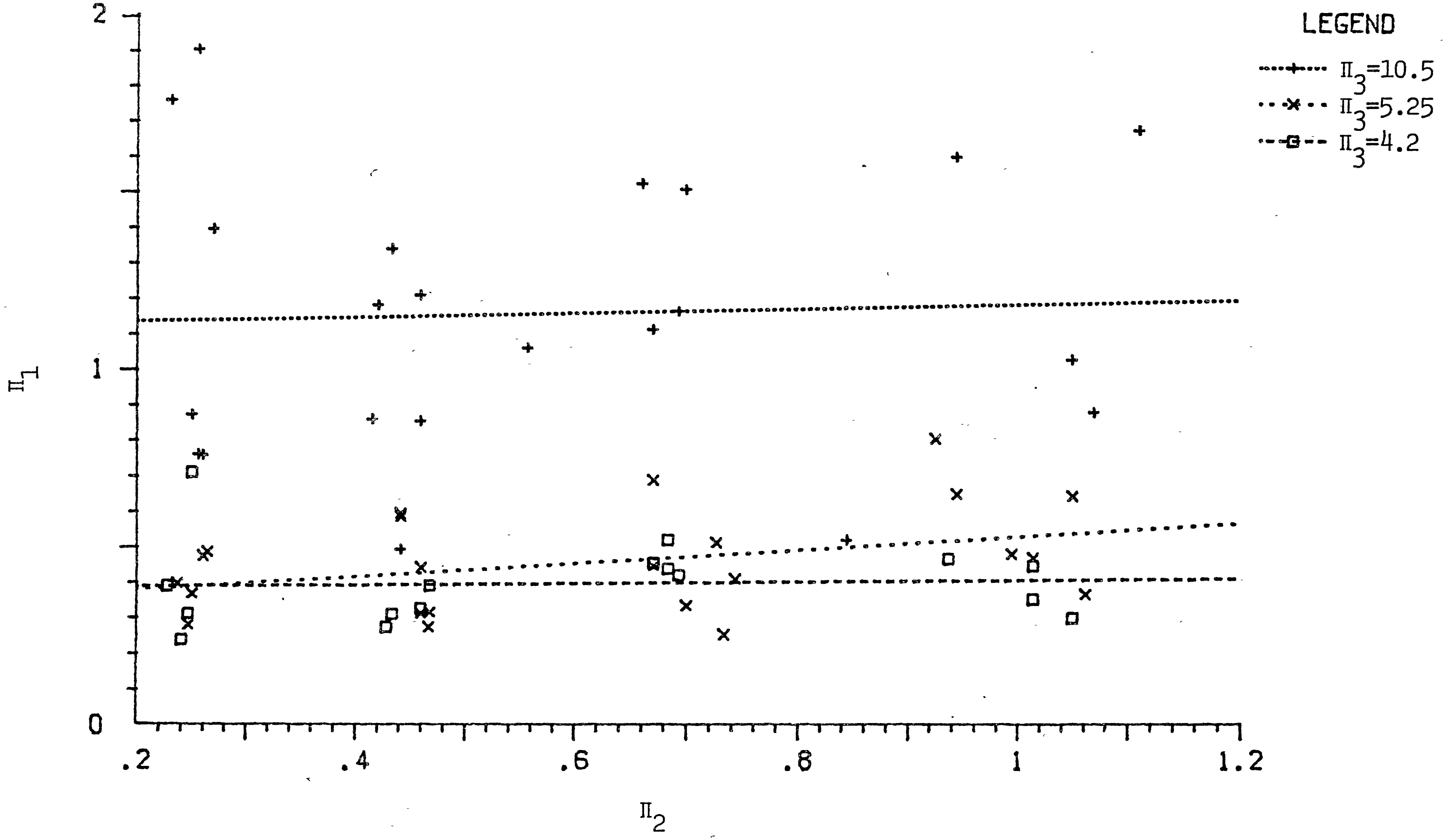

Figure 29. Π_1 versus Π_2 for the Disk using Draft to Calculate Π_1

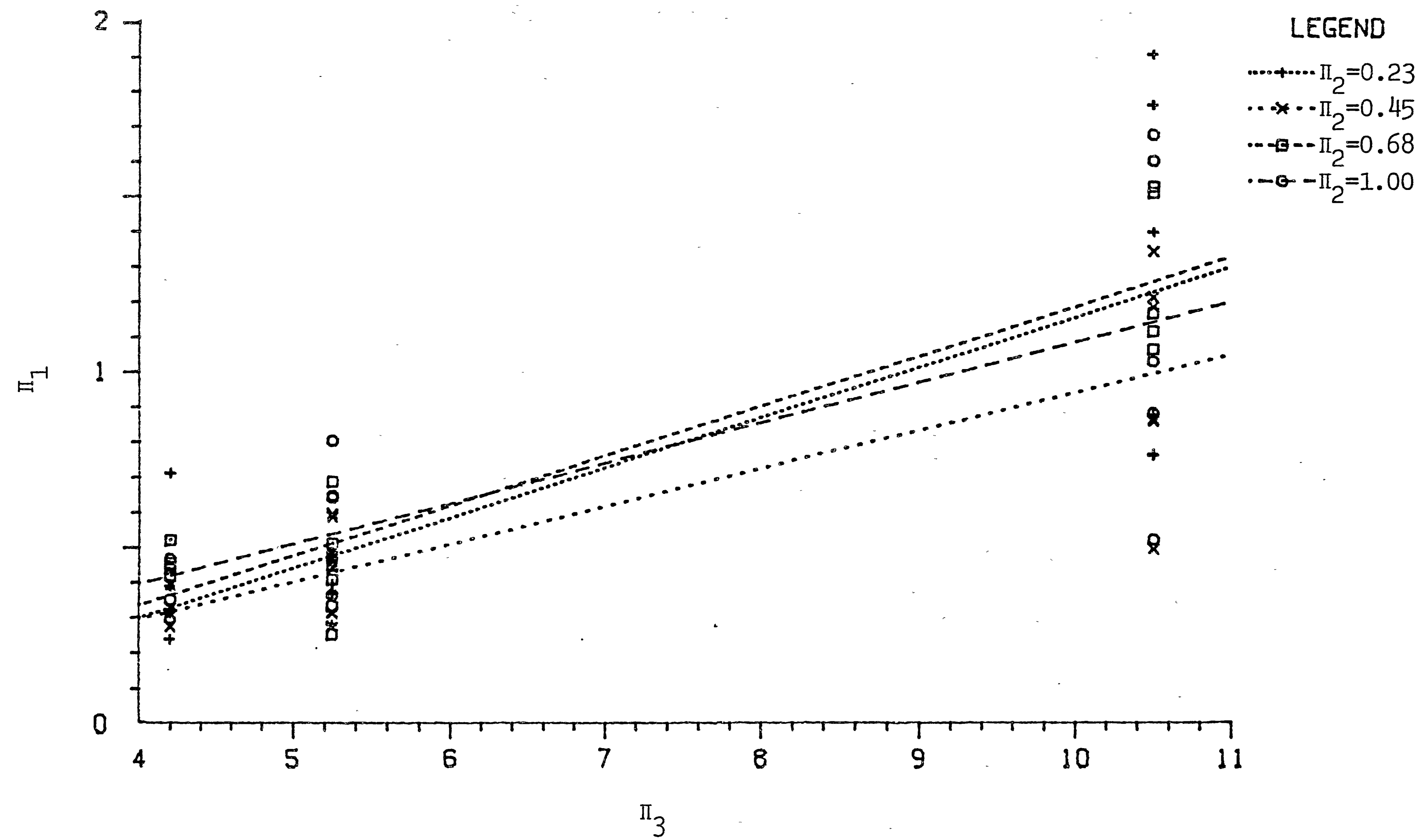

Figure 30. Π_1 versus Π_3 for the Disk using Draft to Calculate Π_1

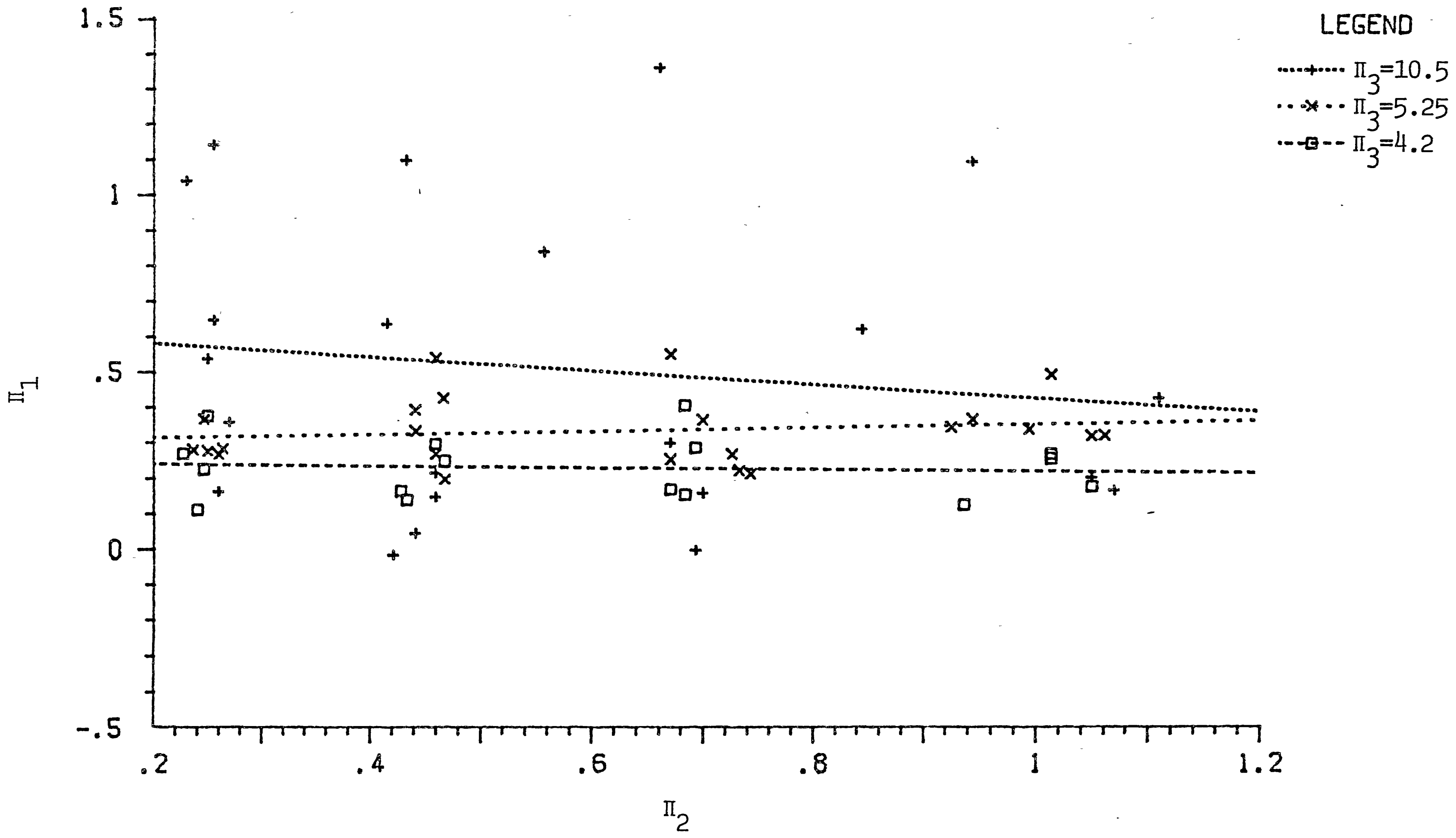

Figure 31. Π_1 versus Π_2 for the Disk using Vertical Force to Calculate Π_1

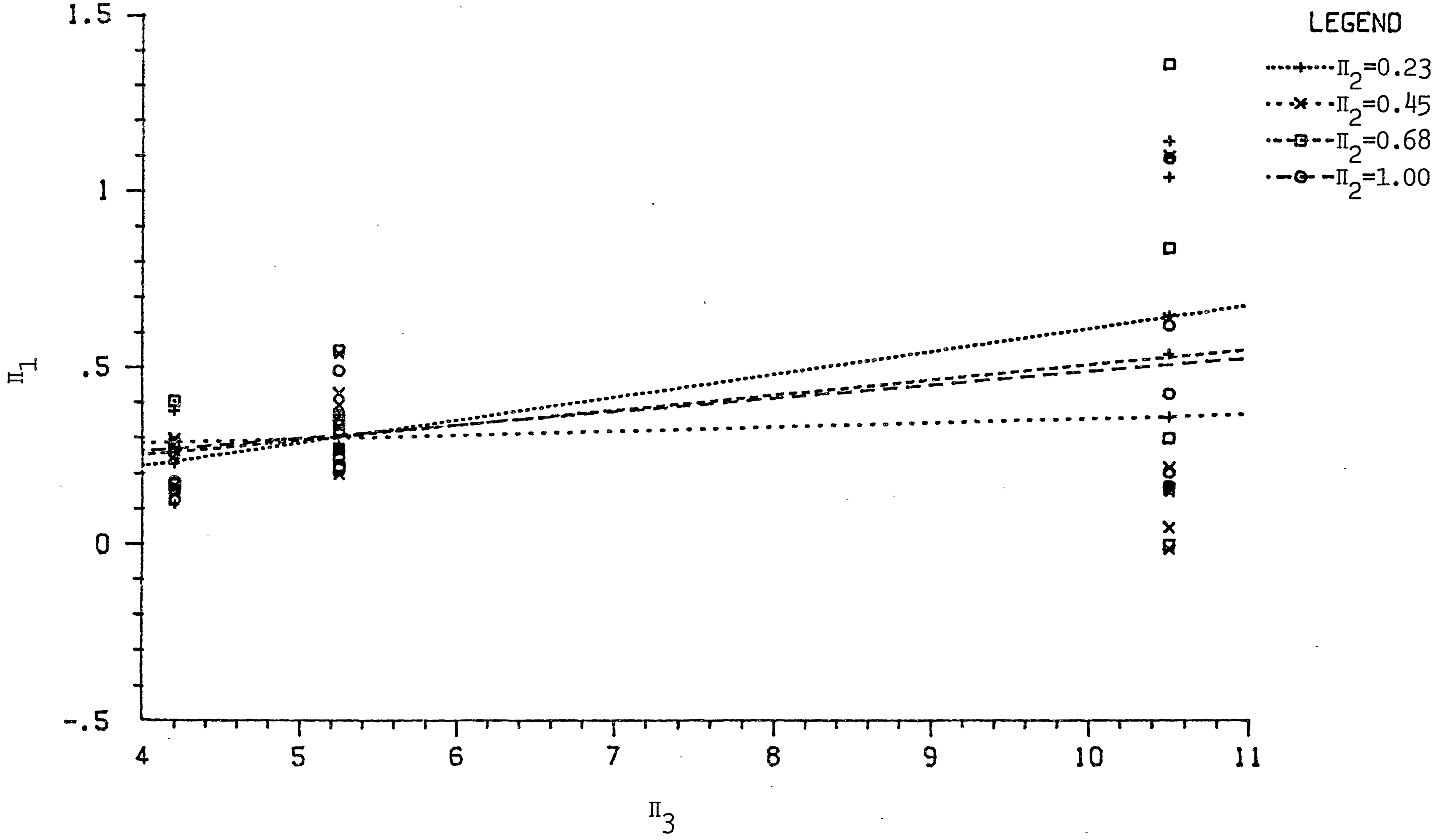

Figure 32. Π_1 versus Π_3 for the Disk using Vertical Force to Calculate Π_1

TABLE VIII

REGRESSION OF Π_1 ONTO Π_2

$$\Pi_1 = A + B\Pi_2$$

Tool	Force Component	Π_3	A	B	r^2	PR>F
Chisel	draft	1.0	0.696	0.006	0.004	.7746
	vertical	1.0	0.494	-0.014	0.036	.3990
	draft	0.5	0.241	0.011	0.134	.0852
	vertical	0.5	0.055	-0.007	0.114	.1149
	draft	0.4	0.209	0.006	0.116	.0948
	vertical	0.4	-0.048	-0.007	0.187	.0948
Sweep	draft	5.0	1.356	-0.075	0.012	.6236
	vertical	5.0	0.033	0.021	0.004	.7719
	draft	2.5	0.371	0.050	0.053	.2892
	vertical	2.5	-0.086	-0.006	0.004	.7637
	draft	2.0	0.297	0.044	0.095	.2454
	vertical	2.0	-0.054	-0.035	0.296	.0292

TABLE VIII (Continued)

Tool	Force Component	Π_3	A	B	r^2	Pr>F
Coulter	draft	10.5	5.576	-0.940	0.007	.7186
	vertical	10.5	0.375	0.216	0.075	.2188
	draft	5.25	1.300	0.368	0.056	.2775
	vertical	5.25	0.028	0.038	0.029	.4369
	draft	4.2	0.896	-0.238	0.050	.4050
	vertical	4.2	0.225	-0.277	0.123	.1838
Disk	draft	10.5	1.120	0.060	0.002	.8466
	vertical	10.5	0.615	-0.195	0.018	.5546
	draft	5.25	0.342	0.187	0.131	.0900
	vertical	5.25	0.301	0.048	0.020	.5219
	draft	4.2	0.383	0.021	0.003	.8451
	vertical	4.2	0.242	-0.025	0.007	.7574

TABLE IX

REGRESSION OF Π_1 ONTO Π_3

$$\Pi_1 = C + D\Pi_3$$

Tool	Force Component	Π_2	C	D	r^2	PR>F
Chisel	draft	2.62	-0.148	0.862	0.663	.0002
	vertical	2.62	-0.443	0.949	0.843	.0001
	draft	4.67	-0.089	0.798	0.445	.0047
	vertical	4.67	-0.357	0.737	0.763	.0001
	draft	7.18	-0.133	0.903	0.823	.0001
	vertical	7.18	-0.359	0.698	0.513	.0027
	draft	10.51	-0.025	0.757	0.708	.0001
	vertical	10.51	-0.469	0.887	0.796	.0001
Sweep	draft	0.52	-0.419	0.340	0.783	.0001
	vertical	0.52	-0.178	0.043	0.521	.0024
	draft	0.94	-0.448	0.364	0.706	.0001
	vertical	0.94	-0.215	0.057	0.268	.0400
	draft	1.44	-0.193	0.266	0.862	.0001
	vertical	1.44	-0.165	0.027	0.085	.2923
	draft	2.20	-0.210	0.287	0.645	.0003
	vertical	2.20	-0.327	0.095	0.414	.0096

TABLE IX (Continued)

Tool	Force Component	Π_2	C	D	r^2	PR>F
Coulter	draft	0.23	-2.343	0.745	0.644	.0003
	vertical	0.23	-0.212	0.063	0.738	.0001
	draft	0.45	-2.245	0.682	0.369	.0126
	vertical	0.45	-0.336	0.080	0.581	.0006
	draft	0.68	-2.359	0.757	0.604	.0007
	vertical	0.68	-0.115	0.043	0.427	.0082
	draft	1.00	-1.849	0.646	0.440	.0071
	vertical	1.00	-0.564	0.118	0.691	.0001
Disk	draft	0.23	-0.269	0.142	0.613	.0006
	vertical	0.23	-0.041	0.065	0.399	.0115
	draft	0.45	-0.133	0.107	0.701	.0001
	vertical	0.45	0.233	0.012	0.017	.6285
	draft	0.68	-0.229	0.141	0.849	.0001
	vertical	0.68	0.077	0.043	0.128	.1898
	draft	1.00	-0.060	0.114	0.565	.0012
	vertical	1.00	0.107	0.038	0.201	.0938

depth of tillage. The scatter at this value of Π_3 is caused by uneveness in the ground surface and most likely by the root system of the weed cover on the field.

Because the component equations are linear in arithmetic coordinates, they combine additively. The final form of the prediction equation is:

$$\Pi_1 = E + F\Pi_2 + G\Pi_3 \qquad (10)$$

The prediction equations for both draft and vertical force on each tool are listed in Table X. The chisel exhibits the highest correlation between Π-terms when the vertical force acting on the chisel is used as the force for calculating Π_1. The coefficient of determination for this relationship is 0.727. The disk exhibits the worst correlation between Π-terms when the disk vertical force is used to calculate Π_1. Coefficient of determination for this relationship is 0.154.

Another source of variation in addition to ground cover and surface roughness is the tillage history of each field. Analysis of the Π-terms listed in Appendix G reveals that Π_3 tends to be larger for replications five and six. This is due to smaller values of cone index for for these two replications. Since the observed forces acting on the tillage tools were equal for all six replications it appears that these forces were more dependent on field surface cover than on soil properties. This indicates that the list of pertinent quantities was not sufficient to describe the tool-penetrometer systems for conditions as tested.

TABLE X

PREDICTION EQUATION

$$\Pi_1 = E + F\Pi_2 + G\Pi_3$$

Tool	Force Componenet	E	F	G	r^2	PR>F
Chisel	draft	-0.145	0.007	0.831	0.628	.0001
	vertical	-0.348	-0.009	0.817	0.727	.0001
Sweep	draft	-0.323	0.001	0.317	0.724	.0001
	vertical	-0.215	-0.004	0.055	0.266	.0001
Coulter	draft	-2.028	-0.267	0.705	0.495	.0001
	vertical	-0.314	0.012	0.076	0.565	.0001
Disk	draft	-0.227	0.091	0.126	0.652	.0001
	vertical	0.130	-0.056	0.039	0.154	.0079

A polynomial regression was done to determine if any correlation between cone index and tillage tool force exists. Only the first order equation was statisticaly significant. These equations are listed in Table XI. Analysis of these equations shows that no more than 30 percent of the variation in tool force is explained by the change in cone index. This indicates that the initial assumption, soil properties affect cone index and tool forces similarly, is not valid and a measurement of draft or vertical force acting on the tillage tools tested cannot be used to predict cone index for conditions as tested.

TABLE XI

REGRESSION EQUATION
$F = H + J(CI)$

Tool	Force Component	H	J	r^2	PR<F
Chisel	draft	98.93	26.39	0.296	.0001
	vertical	735.38	-20.09	0.233	.0001
Sweep	draft	445.97	31.37	0.251	.0001
	vertical	327.59	-16.50	0.250	.0001
Coulter	draft	4135.81	24.66	0.020	.2726
	vertical	260.11	2.04	0.001	.8548
Disk	draft	242.45	38.74	0.234	.0001
	vertical	101.48	24.43	0.175	.0008

CHAPTER V

SUMMARY AND CONCLUSIONS

Equations were developed to predict soil cone index from tillage tool forces in order to determine the feasibility of using a tillage tool as a mobile penetrometer. Prediction equations were developed for four different tillage tools using draft and vertical force. Tools used were a chisel, sweep, rolling coulter, and disk. Literature indicates pertinent variables are velocity, depth of tillage, and characteristic length of the tool. The range of velocities and depths used in this research covers the range of velocities and depths used in most tillage operations. Soil properties were omitted from this analysis based on the assumption that they affect tool forces and cone index similarly. Cone index data were collected at six locations in each plot prior to force measurement. A single value of cone index was calculated by averaging data from the six locations together and determining an integrated average over the depth of tillage. Experimental data were then combined into three Π-terms. The functional relationship between the three Π-terms was determined for each tool. A regression was also performed to determine if a direct correlation exists between tool forces and cone index.

Conclusions derived from this research are:

1. For the chisel, sweep, coulter, and disk tested, it is not feasible to predict cone index from tool forces for soil with high moisture content and surface cover.

2. The pertinent quantities, cone index, force, velocity, depth, and characteristic length did not adequately describe the tool-penetrometer systems.

3. Analysis of the developed prediction equations indicates:

A. Tool forces are highly correlated to depth of tillage.

B. Correlation between tool forces and velocity of tillage is low for high soil moisture conditions.

C. Tool forces and soil cone index are poorly correlated for the conditions tested.

D. The assumption that soil properties affect tool forces and cone index similarly is not valid for the conditions tested.

CHAPTER VI

SUGGESTIONS FOR FURTHER RESEARCH

Further research should be conducted in three areas:

1. Different field conditions
2. Different tools
3. Soil-cone index relationships

Relationships between tool forces and cone index should be investigated for soil with no ground cover and a lower moisture content. This will allow prediction equations to cover a more complete range of tillage operating conditions.

Other tools might provide a better correlation between forces and cone index. One tool which should be tested is a horizontal penetrometer. This would be the standard cone mounted horizontally and operated at some depth in the soil parallel with the soil surface.

Studies should be conducted to increase knowledge about soil cone index. Currently, interpretation of cone index as a measurement of soil strength can only be made for pure clay or sand.

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APPENDIX A

MACHINE LANGUAGE SUBROUTINE

FOR DATA COLLECTION

Data Storage Locations

Force Data Starts at	5000 (Hex)	20480 (Decimal)	
Ends at	67FF (Hex)	26623 (Decimal)	

$5000	Chisel Vertical
$5001	Chisel Draft
$5002	Sweep Vertical
$5003	Sweep Draft
$5004	Coulter Vertical
$5005	Coulter Draft
$5006	Disk Vertical
$5007	Disk Draft
$5008	Chisel Vertical
$5009	Chisel Draft
$500A	Sweep Vertical
$500B	Sweep Draft
$500C	Coulter Vertical
$500D	Coulter Draft
$500E	Disk Vertical
$500F	Disk Draft
	Etc.

High RPM count stored at	6800 (Hex)	26624 (Decimal)
Low RPM count stored at	6801 (Hex)	26625 (Decimal)

Computer Program

Address	Op Code	Operand	Label	Mnemonic	Operand	Remarks
7200	A9	7F		LDA	#$7F	DISABLE VIA TIMER INTERRUPTS
7202	8D	2E90		STA	$902E	

```
7205   A9    00        LDA   #$00      INPUT CONFIGURATION
7207   8D  2290        STA   $9022     PORT B
720A   A9    20        LDA   #$20      SET BIT 5 FOR PULSE
                                       COUNTING
720C   8D  2B90        STA   $902B     ACR FOR VIA TIMER 2
                                       (COUNTS NEG. PULSES)
720F   A9    FF        LDA   #$FF      LOW BYTE FOR TIMER 2
7211   8D  2890        STA   $9028     ADDRESS FOR LOW BYTE
7214   A9    FF        LDA   #$FF      HIGH BYTE FOR TIMER
                                       /COUNTER 2
7216   8D  2990        STA   $9029     HIGH BYTE ADDRESS, STARTS
                                       DEC. RPM COUNT
7219   A9    00        LDA   #$00      BAL FOR DATA ADDRESSING
721B   85    E0        STA   E0        ADDRESS FOR BAL
721D   A9    50        LDA   #$50      BAH FOR DATA ADDRESSING
721F   85    E1        STA   $E1       ADDRESS FOR BAH
7221   A9    03        LDA   #$03      SET INDEX FOR 3 DATA
                                       SETS PER PLOT
7223   85    E6        STA   $E6       STORE INDEX AT $00E6
7225   A9    01    D   LDA   #$01      "DATA" COUNT (BLOCKS
                                       OF 256,DECIMAL)
7227   85    E2        STA   $E2       ADDRESS FOR "DATA" INDEX
7229   A0    00        LDY   #$00      ZERO Y REGISTER FOR DATA
                                       ADDRESS INDEXING
722B   A2    00    A   LDX   #$00      SET DATA INDEX TO 100
722D   A9    00    B   LDA   #$00      SET MUX CHANNEL TO FORCE
                                       ONE
722F   20  0073        JSR   FR        GO TO FORCE READING
                                       SUBROUTINE
7232   A9    01        LDA   #$01      SET MUX CHANNEL TO FORCE
                                       TWO
7234   20  0073        JSR   FR        GO TO FORCE READING
                                       SUBROUTINE
7237   A9    02        LDA   #$02      SET MUX CHANNEL TO FORCE
                                       THREE
7239   20  0073        JSR   FR        GO TO FORCE READING
                                       SUBROUTINE
723C   A9    03        LDA   #$03      SET MUX CHANNEL TO FORCE
                                       FOUR
723E   20  0073        JSR   FR        GO TO FORCE READING
                                       SUBROUTINE
7241   A9    04        LDA   #$04      SET MUX CHANNEL TO FORCE
                                       FIVE
7243   20  0073        JSR FR          GO TO FORCE READING
                                       SUBROUTINE
7246   A9    05        LDA   #$05      SET MUX CHANNEL TO FORCE
                                       SIX
7248   20  0073        JSR   FR        GO TO FORCE READING
                                       SUBROUTINE
724B   A9    06        LDA   #$06      SET MUX CHANNEL TO FORCE
                                       SEVEN
724D   20  0073        JSR   FR        GO TO FORCE READING
                                       SUBROUTINE
7250   A9    07        LDA   #$07      SET MUX CHANNEL TO FORCE
```

```
                                           EIGHT
7252   20   0073       JSR   FR            GO TO FORCE READING
                                           SUBROUTINE
7255   CA              DEX
7256   D0     D5       BNE   B             GO TO B IF 100 FORCE SETS
                                           NOT TAKEN
7258   C6     E2       DEC   $E2
725A   D0     CF       BNE   A             GO TO A  IF NOT ENOUGH
                                           DATA BLOCKS TAKEN
725C   A9     02       LDA   #$02          DELAY PARAMETERS
725E   85     E9       STA   $E9
7260   A9     00    M  LDA   #$00
7262   85     E7       STA   $E7
7264   A9     00    L  LDA   #$00
7266   85     E8       STA   $E8
7268   C6     E8    K  DEC   $E8
726A   D0     FC       BNE   K
726C   C6     E7       DEC   $E7
726E   D0     F4       BNE   L
7270   C6     E9       DEC   $E9
7272   D0     EC       BNE   M             END OF DELAY
7274   C6     E6       DEC   $E6
7276   D0     AD       BNE   D
7278   AD   2990       LDA   $9029         READ RPM COUNTER HIGH
                                           ORDER BYTE
727B   91     E0       STA   [$E0],Y       STORE DATA
727D   20   9073       JSR   AI            DATA ADDRESS INCREASING
                                           SUBROUTINE
7280   AD   2890       LDA   $9028         READ RPM COUNTER LOW
                                           ORDER BYTE
7283   91     E0       STA   [$E0],Y       STORE DATA
7285   60              RTS
7300   8D   FA9F   FR  STA   $9FFA         SET MUX CHANNEL
7303   A9     00       LDA   #$00
7305   8D   0BA0       STA   $A00B         ACR SET FOR ONE TIME
                                           PULSE ON TIMER 2
7308   A9     26       LDA   #$26          LOW ORDER BYTE OF TIME
                                           (CLOCK CYCLES)
730A   8D   08A0       STA   $A008         LOW ORDER BYTE ADDRESS
730D   A9     00       LDA   #$00          HIGH ORDER BYTE OF TIME
730F   8D   09A0       STA   $A009         HIGH ORDER BYTE ADDRESS,
                                           START TIMER 2
7312   A9     20       LDA   #$20          SET BIT 5 OF ACCUMULATOR
7314   2C   0DA0    E  BIT   $A00D         TEST TIME OUT SIGNAL
7317   F0     FB       BEQ   E             TEST AGAIN IF NOT SET YET
7319   AD   08A0       LDA   $A008         CLEAR TIMER 2 TIME OUT
                                           SIGNAL
731C   8D   FB9F       STA   $9FFB         START A/D CONVERSION
731F   A9     02       LDA   #$02          START OF 26*E-6 SECOND
                                           DELAY
7321   85     E4       STA   $E4
7323   C6     E4    F  DEC   $E4
7325   D0     FC       BNE   F             END OF DELAY LOOP
7327   EA              NOP
```

```
7328   EA                  NOP
7329   EA                  NOP              END OF DELAY
732A   AD   FF9F           LDA   $9FFF      READ DATA
732D   91     E0           STA   [$E0],Y    STORE DATA
732F   20   9073           JSR   AI         DATA ADDRESS INCREASING
                                            SUBROUTINE
7332   60                  RTS
7390   18             AI   CLC              CLEAR CARRY
7391   A5     E0           LDA   $E0        ADL OF DATA ADDRESS
7393   69     01           ADC   #$01       INCREMENT DATA ADDRESS
7395   85     E0           STA   $E0        STORE DATA ADL
7397   A5     E1           LDA   $E1        ADH OF DATA ADDRESS
7399   69     00           ADC   #$00       INCREMENT ADL IF
                                            NECESSAARY
739B   85     E1           STA   $E1        STORE DATA ADH
739D   60                  RTS
```

APPENDIX B

BASIC PROGRAM FOR DATA MANIPULATION

Variable Description

A1$(1) - A5$(3)	=	computer display variable names
M1 - M8	=	regression equation constants
AA$	=	dummy variable name for computer display
ZL	=	display line number
A$	=	the letter "S"
P(J)	=	zeroing subroutine force name
RT$	=	block and treatment number
ZV	=	dummy variable
CV	=	chisel vertical force
CD	=	chisel draft
SV	=	sweep vertical force
SD	=	sweep draft
WV	=	coulter vertical force
WD	=	coulter draft
DV	=	disk vertical force
DD	=	disk draft
RP	=	velocity in rev/s
VE	=	velocity in cm/s
XZ	=	dummy variable name
AT$	=	repeat test variable name

Computer Program

```
 10 POKE 4,176
 20 POKE 5,222
 30 A1$(1)="THIS IS CRAIG'S FORCE DATA PROGRAM      "
 40 A1$(2)="START OF DATA AQUISTION                 "
 50 A1$(3)="ENTER REP AND TRT AS XXX                "
 60 A1$(4)="PRESS S TO START DATA COLLECTION        "
 70 A1$(5)="DO YOU WANT TO MAKE ANOTHER TEST? (Y/N) "
 80 A1$(6)="                                        "
 90 A1$(7)="ENTER TAPE FILE NAME AS XX              "
100 A2$(1)="CHIS VERT="
110 A2$(2)=" CHIS DRAFT="
120 A2$(3)="        "
```

```
130 A3$(1)="SWEEP VERT="
140 A3$(2)=" SWEEP DRAFT="
150 A3$(3)="       "
160 A4$(1)="COLT VERT"
170 A4$(2)=" COLT DRAFT="
180 A4$(4)=" TRT="
190 A5$(1)="DISC VERT="
200 A5$(2)=" DISC DRAFT="
210 A5$(3)=" S="
220 M1=116.5
230 M2=7.8
240 M3=96.5
250 M4=3.4
260 M5=108.6
270 M6=7.3
280 M7=129.0
290 M8=21.0
300 F1=0
310 F2=0
320 F3=0
330 F4=0
340 F5=0
350 F6=0
360 F7=0
370 F8=0
380 AA$=A1$(1)
390 ZL=0
400 GOSUB 1880
410 AA$=A1$(6)
420 ZL=1
430 GOSUB 1880
440 FOR II=1 TO 1000
450 NEXT
460 ZL=0
470 AA$=A1$(6)
480 GOSUB 1880
490 AA$=A1$(7)
500 ZL=1
510 GOSUB 1880
520 INPUT A$
530 POKE 42030,ASC(LEFT$(A$,1))
540 POKE 42031,ASC(LEFT$(A$,2,1))
550 POKE 42010,0
560 POKE 42011,112
570 POKE 42012,46
580 POKE 42013,112
590 FOR J=0 TO 7
600 POKE 40954,J
610 FOR I=0 TO 100
620 NEXT I
630 POKE 40955,0
640 FOR I=0 TO 100
650 NEXT I
655 P(J)=0
```

```
 656 FOR JJ=1 TO 100
 660 P(J)=P(J)+PEEK(40959)
 661 NEXT JJ
 662 P(J)=P(J)/100
 670 NEXT J
 680 AA$=A1$(3)
 690 ZL=1
 700 GOSUB 1880
 710 INPUT RT$
 720 AA$=A1$(6)
 730 GOSUB 1880
 740 AA$=A1$(4)
 750 ZL=0
 760 GOSUB 1880
 770 GET A$: IF A$<>"S" GOTO 770
 780 AA$=A1$(2)
 790 ZL=0
 800 GOSUB 1880
 810 POKE 4,0
 820 POKE 5,114
 830 ZV=USR(WD)
 840 POKE 4,176
 850 POKE 5,222
 860 AA$=A1$(6)
 870 ZL=0
 880 GOSUB 1880
 890 PRINT "DONE"
 900 FOR I=0 TO 767
 910 F1=F1+PEEK(20480+8*I)
 920 F2=F2+PEEK(20481+8*I)
 930 F3=F3+PEEK(20482+8*I)
 940 F4=F4+PEEK(20483+8*I)
 950 F5=F5+PEEK(20484+8*I)
 960 F6=F6+PEEK(20485+8*I)
 970 F7=F7+PEEK(20486+8*I)
 980 F8=F8+PEEK(20487+8*I)
 990 NEXT I
1000 CV=M1*(FI/768-P(0))*16
1010 CD=M2*(F2/768-P(1))*16/3
1020 SV=M3*(F3/768-P(2))*16
1030 SD=M4*(F4/768-P(3))*16/1.184
1040 WV=M5*(F5/768-P(4))*16
1050 WD=M6*(F6/768-P(5))*16/2.6
1060 DV=M7*(F7/768-P(6))*16
1070 DD=M8*(F8/768-P(7))*16/2.69
1080 RP=(65535-PEEK(26624)*256-PEEK(26625))/184.869135
1090 VE=RP*203.5
1100 CV$=STR$(INT(CV+.5))
1110 IF LEN(CV$)<2 THEN CV$="    "+CV$
1120 IF LEN(CV$)<3 THEN CV$="   "+CV$
1130 IF LEN(CV$)<4 THEN CV$="  "+CV$
1131 IF LEN(CV$)<5 THEN CV$=" "+CV$
1140 CD$=STR$(INT(CD+.5))
1150 IF LEN(CD$)<2 THEN CD$="    "+CD$
```

```
1160 IF LEN(CD$)<3 THEN CD$="   "+CD$
1170 IF LEN(CD$)<4 THEN CD$="  "+CD$
1171 IF LEN(CD$)<5 THEN CD$=" "+CD$
1180 SV$=STR$(INT(SV+.5))
1190 IF LEN(SV$)<2 THEN SV$="    "+SV$
1200 IF LEN(SV$)<3 THEN SV$="   "+SV$
1210 IF LEN(SV$)<4 THEN SV$="  "+SV$
1211 IF LEN(SV$)<5 THEN SV$=" "+SV$
1220 SD$=STR$(INT(SD+.5))
1230 IF LEN(SD$)<2 THEN SD$="    "+SD$
1240 IF LEN(SD$)<3 THEN SD$="   "+SD$
1250 IF LEN(SD$)<4 THEN SD$="  "+SD$
1251 IF LEN(SD$)<5 THEN SD$=" "+SD$
1260 WV$=STR$(INT(WV+.5))
1270 IF LEN(WV$)<2 THEN WV$="    "+WV$
1280 IF LEN(WV$)<3 THEN WV$="   "+WV$
1290 IF LEN(WV$)<4 THEN WV$="  "+WV$
1291 IF LEN(WV$)<5 THEN WV$=" "+WV$
1300 WD$=STR$(INT(WD+.5))
1310 IF LEN(WD$)<2 THEN WD$="    "+WD$
1320 IF LEN(WD$)<3 THEN WD$="   "+WD$
1330 IF LEN(WD$)<4 THEN WD$="  "+WD$
1331 IF LEN(WD$)<5 THEN WD$=" "+WD$
1340 DV$=STR$(INT(DV+.5))
1350 IF LEN(DV$)<2 THEN DV$="    "+DV$
1360 IF LEN(DV$)<3 THEN DV$="   "+DV$
1370 IF LEN(DV$)<4 THEN DV$="  "+DV$
1371 IF LEN(DV$)<5 THEN DV$=" "+DV$
1380 DD$=STR$(INT(DD+.5))
1390 IF LEN(DD$)<2 THEN DD$="    "+DD$
1400 IF LEN(DD$)<3 THEN DD$="   "+DD$
1410 IF LEN(DD$)<4 THEN DD$="  "+DD$
1411 IF LEN(DD$)<5 THEN DD$=" "+DD$
1420 VE$=STR$(INT(VE*100+.5)/100)
1421 IF LEN(VE$)<2 THEN VE$="    "+VE$
1422 IF LEN(VE$)<3 THEN VE$="   "+VE$
1423 IF LEN(VE$)<4 THEN VE$="  "+VE$
1424 IF LEN(VE$)<5 THEN VE$=" "+VE$
1430 FOR J=1 TO 5
1440 POKE 28671+J,ASC(MID$(CV$,J,1))
1450 POKE 28676+J,ASC(MID$(CD$,J,1))
1460 POKE 28681+J,ASC(MID$(SV$,J,1))
1470 POKE 28686+J,ASC(MID$(SD$,J,1))
1480 POKE 28691+J,ASC(MID$(WV$,J,1))
1490 POKE 28696+J,ASC(MID$(WD$,J,1))
1500 POKE 28701+J,ASC(MID$(DV$,J,1))
1510 POKE 28706+J,ASC(MID$(DD$,J,1))
1520 POKE 28711+J,ASC(MID$(VE$,J,1))
1530 NEXT J
1531 FOR J=1 TO 3
1532 POKE 28716+J,ASC(MID$(RT$,J,1))
1533 NEXT J
1540 A6$(0)=A2$(1)+CV$+A2$(2)+CD$+A2$(3)
1550 A6$(1)=A3$(1)+SV$+A3$(2)+SD$+A3$(3)
```

```
1560 A6$(2)=A4$(1)+WV$+A4$(2)+WD$+A4$(4)+RT$
1570 A6$(3)=A5$(1)+DV$+A5$(2)+DD$+A5$(3)+VE$
1580 FOR ZL=0 TO 3
1590 AA$=A6$(ZL)
1600 GOSUB 1880
1610 NEXT ZL
1620 POKE 4,0
1630 POKE 5,221
1640 XZ=USR(YZ)
1650 FOR ZL=0 TO 3
1660 PRINT A6$(ZL)
1670 NEXT
1680 POKE 4,176
1690 POKE 5,222
1700 AA$=A1$(6)
1710 FOR ZL=0 TO 3
1720 GOSUB 1880
1730 NEXT
1740 AA$=A1$(5)
1750 ZL=1
1760 GOSUB 1880
1770 INPUT AT$
1780 IF AT$="Y" GOTO 1810
1790 IF AT$="N" GOTO 1870
1800 GOTO 1740
1810 AA$=A1$(6)
1820 ZL=0
1830 GOSUB 1880
1840 FOR I=1 TO 1000
1850 NEXT
1860 F1=0
1861 F2=0
1862 F3=0
1863 F4=0
1864 F5=0
1865 F6=0
1866 F7=0
1867 F8=0
1868 GOTO 680
1870 END
1880 FOR ZR=0 TO 39
1890 ZZ$=MID$(AA$,ZR+1,1)
1900 ZX=USR((128+ASC(ZZ$))*256+ZL*64+ZR)
1910 NEXT
1920 RETURN
```

APPENDIX C

MACHINE LANGUAGE PROGRAM FOR DATA TRANSFER TO MAINFRAME COMPUTER

Address	Op Code	Operand	Label	Mnemonic	Operand	Remarks
0200	A9	00		LDA	#$00	LOAD 00 INTO ACCUM.
0202	8D	01AC		STA	$AC01	RESET CHANNEL 1 OF ACIA
0205	8D	05AC		STA	$AC05	RESET CHANNEL 2 OF ACIA
0208	A9	38		LDA	#$38	SET UP CONTROL REGISTER
020A	8D	03AC		STA	$AC03	SETS BAUD, WORD LENGTH, CLOCK SOURCE, STOP BITS
020D	A9	6B		LDA	#$6B	SET UP COMMAND REGISTER
020F	8D	020C		STA	$AC02	
0212	A2	C0		LDX	#$C0	START DISPLAY INDEX AT BOTTOM LINE
0214	A9	52		LDA	#$52	ASCII R
0216	20	7BEF		JSR	$EF7B	DISPLAY SUBROUTINE
0219	E8			INX		INCREMENT DISPLAY INDEX
021A	A9	45		LDA	#$45	ASCII E
021C	20	7BEF		JSR	$EF7B	DISPLAY SUBROUTINE
021F	E8			INX		INCREMENT DISPLAY INDEX
0220	A9	44		LDA	#$44	ASCII D
0222	20	7BEF		JSR	$EF7B	DISPLAY SUBROUTINE
0225	E8			INX		INCREMENT DISPLAY INDEX
0226	A9	49		LDA	#$49	ASCII I
0228	20	7BEF		JSR	$EF7B	DISPLAY SUBROUTINE
022B	E8			INX		INCREMENT DISPLAY INDEX
022C	A9	41		LDA	#$41	ASCII A
022E	20	7BEF		JSR	$EF7B	DISPLAY SUBROUTINE
0231	E8			INX		INCREMENT DISPLAY INDEX
0232	A9	4C		LDA	#$4C	ASCII L
0234	20	7BEF		JSR	$EF7B	DISPLAY SUBROUTINE
0237	20	E303		JSR	DS	GO TO DSR SUBROUTINE
023A	A2	C0		LDX	#$C0	SET DISPLAY INDEX TO START OF FOURTH LINE
023C	A9	20		LDA	#$20	ASCII CARRIAGE RETURN
023E	20	7BEF		JSR	$EF7B	

```
0241   E8              INX
0242   20   7BEF       JSR   $EF7B
0245   E8              INX
0246   20   7BEF       JSR   $EF7B
0249   E8              INX
024A   20   7BEF       JSR   $EF7B
024D   E8              INX
024E   20   7BEF       JSR   $EF7B
0251   E8              INX
0252   20   7BEF       JSR   $EF7B
0255   A2     00  A1   LDX   #$00     SET DISPLAY LOCATION TO
                                      START
0257   20   E303  LO   JSR   DS       GO TO DSR SUBROUTINE
025A   A9     08       LDA   #$08     SET BIT 3
025C   2C   01AC       BIT   $AC01    CHECK TO SEE IF ACIA
                                      RDR IS FULL
025F   F0     0C       BEQ   WR       IF NOT, GO TO WR
0261   AD   00AC  A6   LDA   $AC00    IF IS, READ RDR
0264   20   7BEF  A3   JSR   $EF7B    GO TO DISPLAY SUBROUTINE
0267   20   F203       JSR   IN       GO TO DISPLAY INDEX
                                      SUBROUTINE
026A   4C   5702       JMP   LO       GO TO LO
026D   20   E303  WR   JSR   DS       GO TO DSR SUBROUTINE
0270   A9     10       LDA   #$10     SET BIT 4
0272   2C   01AC       BIT   $AC01    CHECK TO SEE IF ACIA
                                      TDR IS FULL
0275   F0     F6       BEQ   WR       IF FULL, GO TO WR
0277   98              TYA            IF NOT, MOVE Y TO ACCUM
0278   48              PHA
0279   8A              TXA
027A   48              PHA
027B   20   07E9       JSR   $E907    SCAN KEYBOARD
027E   8D   1005       STA   $0510    STORE LETTER
0281   68              PLA
0282   AA              TAX
0283   68              PLA
0284   A8              TAY
0285   AD   1005  C9   LDA   $0510    GET LETTER
0288   C9     FF       CMP   #$FF     COMPARE WITH NULL
                                      CHARACTER
028A   F0     CB       BEQ   LO       IF IS, GO TO LO
028C   C9     2D       CMP   #$2D     IF NOT, COMPARE WITH A
                                      NEGATIVE SIGN
028E   F0     35       BEQ   TD       IF IS, GO TO TAPE DUMP
                                      ROUTINE
0290   C9     3B       CMP   #$3B     IF NOT, COMPARE WITH A
                                      SEMI-COLON
0292   D0     03       BNE   D2       IF NOT, GO TO D2
0294   4C   2203       JMP   MD       IF IS, GO TO MEMEORY
                                      DUMP ROUTINE
0297   C9     3A  D2   CMP   #$3A     COMPARE WITH A COLON
0299   D0     03       BNE   C8       IF NOT, GO TO C8
029B   4C   D103       JMP   BR       IF IS, GO TO BREAK
                                      ROUTINE
```

```
029E   C9    2F   C8   CMP   #$2F     COMPARE WITH SLASH
02A0   D0    08        BNE   D4       IF NOT, GO TO D4
02A2   A9    20        LDA   #$20     IF IS, LOAD ACCUM WITH
                                      ASCII SPACE
02A4   8D   1005       STA   $0510    STORE AT LETTER LOCATION
02A7   4C   B302       JMP   D3       GO TO D3
02AA   C9    7F   D4   CMP   #$7F     COMPARE WITH DEL
02AC   D0    05        BNE   D3       IF NOT, GO TO D3
02AE   A9    3D        LDA   #$3D     IF IT IS, LOAD ACCUM WITH
                                      ASCII EQUALS
02B0   8D   1005       STA   $0510    STORE AT LETTER LOCATION
02B3   20   E303  D3   JSR   DS       GO TO DSR SUBROUTINE
02B6   AD   1005       LDA   $0510    GET LETTER
02B9   8D   00AC       STA   $AC00    SEND TO ACIA TDR
02BC   20   7BEF       JSR   $EF7B    DISPLAY LETTER
02BF   20   F203       JSR   IN       GO TO DISPLAY INDEX
                                      SUBROUTINE
02C2   4C   5702       JMP   LO       GO TO LO
02C5   A2    01   TD   LDX   #$01     SET DISPLAY INDEX
02C7   A9    54        LDA   #$54     ASCII T
02C9   20   7BEF       JSR   $EF7B    DISPLAY SUBROUTINE
02CC   E8              INX            INCREASE DISPLAY INDEX
02CD   A9    41        LDA   #$41     ASCII A
02CF   20   7BEF       JSR   $EF7B    DISPLAY SUBROUTINE
02D2   E8              INX            INCREASE DISPLAY INDEX
02D3   A9    50        LDA   #$50     ASCII P
02D5   20   7BEF       JSR   $EF7B    DISPLAY SUBROUTINE
02D8   E8              INS            INCREASE DISPLAY INDEX
02D9   A9    45        LDA   #$45     ASCII E
02DB   20   7BEF       JSR   $EF7B    DISPLAY SUBROUTINE
02DE   E8              INX            INCREASE DISPLAY INDEX
02DF   A9    2C        LDA   #$2C     ASCII COMMA
02E1   20   7BEF       JSR   $EF7B    DISPLAY SUBROUTINE
02E4   E8              INX            INCREASE DISPLAY INDEX
02E5   A9    20        LDA   #$20     ASCII SPACE
02E7   20   7BEF       JSR   $EF7B    DISPLAY SUBROUTINE
02EA   E8              INX            INCREASE DISPLAY INDEX
02EB   A9    4E        LDA   #$4E     ASCII N
02ED   20   7BEF       JSR   $EF7B    DISPLAY SUBROUTINE
02F0   E8              INX            INCREASE DISPLAY INDEX
02F1   A9    41        LDA   #$41     ASCII A
02F3   20   7BEF       JSR   $EF7B    DISPLAY SUBROUTINE
02F6   E8              INX            INCREASE DISPLAY INDEX
02F7   A9    4D        LDA   #$4D     ASCII M
02F9   20   7BEF       JSR   $EF7B    DISPLAY SUBROUTINE
02FC   E8              INX            INCREASE DISPLAY INDEX
02FD   A9    45        LDA   #$45     ASCII E
02FF   20   7BEF       JSR   $EF7B    DISPLAY SUBROUTINE
0302   E8              INX            INCREASE DISPLAY INDEX
0303   A9    3D        LDA   #$3D     ASCII EQUALS SIGN
0305   20   7BEF       JSR   $EF7B    DISPLAY SUBROUTINE
0308   E8              INX            INCREMENT DISPLAY INDEX
0309   20   83FE       JSR   $FE83    READ FROM KEYBOARD TO
                                      ACCUM
```

```
030C   20   7BEF        JSR   $EF7B     DISPLAY ROUTINE
030F   E8               INX             INCREMENT DISPLAY INDEX
0310   8D   2EA4        STA   $A42E     PUT FIRST LETTER OF FILE
                                        NAME IN $A42E
0313   20   83FE        JSR   $FE83     READ FROM DEYBOARD TO
                                        ACCUM
0316   20   7BEF        JSR   $EF7B     DISPLAY ROUTINE
0319   8D   2FA4        STA   $A42F     PUT SECOND LETTER OF FILE
                                        NAME IN $A42F
031C   20   1004        JSR   $0410     LOAD TAPE TO MEMORY
031F   4C   5702        JMP   LO        GO TO LO
0322   A5     FD   MD   LDA   $FD       GET LENGTH OF LAST BLOCK
                                        READ FROM TAPE
0324   18               CLC             CLEAR CARRY
0325   65     FE        ADC   $FE       ADD ADL OF START OF LAST
                                        BLOCK
0327   8D   0E05        STA   $050E     STORE AT $050E
032A   A5     FF        LDA   $FF       GET ADH OF START OF LAST
                                        BLOCK
032C   69     00        ADC   #$00      ADD CARRY IF ANY
032E   8D   0D05        STA   $050D     STORE AT $050D
0331   A0     00        LDY   #$00      CLEAR Y
0333   A9     00        LDA   #$00      LOAD LOW ORDER BYTE OF
                                        START ADDRESS
0335   85     00        STA   $00       STORE AT $0000
0337   A9     70        LDA   #$70      LOAD HIGH ORDER BYTE OF
                                        START ADDRESS
0339   85     01        STA   $01       STORE AT $0001
033B   A9     0B        LDA   #$0B      $0B IN ACCUM
033D   8D   0F05        STA   $050F     STORE $050F (ELEVEN
                                        NUMBERS PER DATA LINE)
0340   20   E303        JSR   DS        GO TO DSR SUBROUTINE
0343   4C   5703        JMP   C1        GO TO C1 ON FIRST TIME
                                        THROUGH
0346   20   E303   E0   JSR   DS        GO TO DSR SUBROUTINE
0349   A9     08        LDA   #$08      SET BIT 3
034B   2C   01AC        BIT   $AC01     CHECK TO SEE IF ACIA RDR
                                        IS FULL
034E   F0     F6        BEQ   E0        IF NOT, GO TO E0
0350   AD   00AC        LDA   $AC00     READ DATA FROM ACIA RDR
0353   C9     20        CMP   #$20      COMPARE WITH ASCII BLANK
0355   D0     EF        BNE   E0        IF NOT, GO TO E0
0357   A9     02   C1   LDA   #$02      IS THIS ONE OF THE FIRST
                                        NINE NUMBERS
0359   CD   0F05        CMP   $050F
035C   B0     05        BCS   A2        IF NOT, GO TO A2
035E   A2     05        LDX   #$05      IF IS, THERE ARE 5 DIGITS
0360   4C   7103        JMP   C6        GO TO C6
0363   A9     02   A2   LDA   #$02      IS THIS THE TENTH NUMBER
0365   CD   0F05        CMP   $050F
0368   D0     05        BNE   A4        IF NOT, GO TO A4
036A   A2     01        LDX   #$01      IF IS THERE IS 1 DIGIT
036C   4C   7103        JMP   C6        GO TO C6
036F   A2     02   A4   LDX   #$02      THERE ARE 2 DIGITS
```

```
0371   A9   10   C6   LDA   #$10       SET BIT 4
0373   2C   01AC      BIT   $AC01      CHECK TO SEE IF ACIA TDR
                                       IS FULL
0376   F0   F9        BEQ   C6         IF IT IS, GO TO C6
0378   B1   00        LDA   [$00],Y    LOAD ONE BYTE ASCII DATA
                                       TO ACCUM
037A   8D   00AC B1   STA   $AC00      SEND TO ACIA TDR
037D   A9   10   C2   LDA   #$10       SET BIT 4
037F   2C   01AC      BIT   $AC01      CHECK TO SEE IF ACIA TDR
                                       IS FULL
0382   F0   F9        BEQ   C2         IF IT IS, GO TO C2
0384   20   E303      JSR   DS         IF NOT, GO TO DSR
                                       SUBROUTINE
0387   A5   01        LDA   $01        HIGH BYTE OF CURRENT DATA
                                       ADDRESS
0389   CD   0D05      CMP   $050D      COMPARE WITH HIGH BYTE OF
                                       DATA ENDING ADDRESS
038C   90   0A        BCC   B3         IF NOT, GO TO B3
038E   A5   00        LDA   $00        LOW BYTE OF CURRENT DATA
                                       ADDRESS
0390   CD   0E05      CMP   $050E      COMPARE WITH LOW BYTE OF
                                       DATA ENDING ADDRESS
0393   90   03        BCC   B3         IF NOT, GO TO B3
0395   4C   BF03      JMP   C5         GO TO C5
0398   A5   00   B3   LDA   $00        CURRENT DATA ADL
039A   18             CLC              CLEAR CARRY
039B   69   01        ADC   #$01       INCREMENT DATA ADDRESS
039D   85   00        STA   $00        STORE NEXT DATA ADL
039F   A5   01        LDA   $01        HIGH BYTE OF CURRENT DATA
                                       ADDRESS
03A1   69   00        ADC   #$00       ADD CARRY IF ANY
03A3   85   01        STA   $01        STORE NEST DATA ADH
03A5   CA             DEX              DECREMENT BYTE COUNTER
03A6   D0   C9        BNE   C6         IF NOT ENOUGH BYTES READ,
                                       GO TO C6
03A8   A9   10   C3   LDA   #$10       SET BIT 4
03AA   2C   01AC      BIT   $AC01      CHECK TO SEE IF ACIA TDR
                                       IS FULL
03AD   F0   F9        BEQ   C3         IF IT IS, GO TO C3
03AF   20   E303      JSR   DS         IF NOT, GO TO DSR
                                       SUBROUTINE
03B2   A9   20        LDA   #$20       ASCII SPACE
03B4   8D   00AC      STA   $AC00      SEND TO TDR
03B7   CE   0F05      DEC   $050F      DECREMENT NUMBER COUNT
03BA   F0   03        BEQ   C5         IF 9 NUMBERS HAVE BEEN
                                       SENT, GO TO C5
03BC   4C   5703      JMP   C1         IF NOT, GO TO C1
03BF   A9   10   C5   LDA   #$10       SET BIT 4
03C1   2C   01AC      BIT   $AC01      CHECK TO SEE IF ACIA TDR
                                       IS FULL
03C4   F0   F9        BEQ   C5         IF IT IS, GO TO C5
03C6   20   E303      JSR   DS         GO TO DSR SUBROUTINE
03C9   A9   0D        LDA   #$0D       ASCII CARRIAGE RETURN
03CB   8D   00AC      STA   $AC00      SEND TO ACIA TDR
```

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03CE    4C   5702        JMP   LO         GO TO LO
03D1    A9     10   BR   LDA   #$10       SET BIT 4
03D3    2C   01AC        BIT   $AC01      CHECK TO SEE IF ACIA TDR
                                          IS FULL
03D6    F0     F9        BEQ   BR         IF IT IS, GO TO BR
03D8    20   E303        JSR   DS         IF NOT, GO TO DSR
                                          SUBROUTINE
03DB    A9     01        LDA   #$01       ASCII "BREAK"
03DD    8D   00AC        STA   $AC00      SEND TO ACIA TDR
03E0    4C   5702        JMP   LO         GO TO LO
03E3    AD   01AC   DS   LDA   $AC01      READ ACIA STATUS REGISTER
03E6    29     20        AND   #$20       CHECK BIT 5 TO SEE IF
                                          DCD IS ON
03E8    D0     F9        BNE   DS         IF ON, GO TO DS
03EA    AD   01AC        LDA   $AC01      READ ACIA STATUS REGISTER
03ED    29     40        AND   #$40       CHECK BIT 6 FOR DSR ON
03EF    D0     F2        BNE   DS         IF NOT ON, GO TO DS
03F1    60               RTS              RETURN TO MAIN PROGRAM
03F2    E8          IN   INX              INCREMENT X
03F3    E0     28        CPX   #$28       IS DISPLAY AT END OF
                                          FIRST LINE
03F5    F0     0D        BEQ   I1         IF IS, GO TO I1
03F7    E0     68        CPX   #$68       IS DISPLAY AT END OF
                                          SECOND LINE
03F9    F0     09        BEQ   I1         IF IS, GO I1
03FB    E0     A8        CPX   #$A8       IS DISPLAY AT END OF
                                          THIRD LINE
03FD    F0     05        BEQ   I1         IF IS, GO TO I1
03FF    E0     E8        CPX   #$E8       IS DISPLAY AT END OF
                                          FOURTH LINE
0401    F0     07        BEQ   I2         IF IS, GO TO I2
0403    60               RTS              RETURN TO MAIN PROGRAM
0404    8A          I1   TXA              MOVE X TO ACCUM
0405    18               CLC              CLEAR CARRY
0406    69     18        ADC   #$18       MOVE DISPLAY INDEX TO
                                          START OF NEXT LINE
0408    AA               TAX              MOVE X FROM ACCUM TO X
0409    60               RTS              RETURN TO MAIN PROGRAM
040A    A2     00   I2   LDX   #$00       MOVE DISPLAY INDES TO
                                          START
040C    60               RTS              RETURN TO MAIN PROGRAM
0410    A9     00        LDA   #$00
0412    48               PHA
0413    48               PHA
0414    4C   A4E3        JMP   $E3A4
0417    60               RTS              RETURN TO MAIN PROGRAM
```

APPENDIX D

BULK DENSITY AND MOISTURE CONTENT DATA

Block	Trt	Moisture content (%,Dry Basis)	Bulk density (g/cc)
1	1	23.7	2.10
	2	23.8	2.11
	3	21.8	1.99
	4	21.8	2.20
	5	22.6	2.12
	6	19.5	1.97
	7	20.1	2.19
	8	21.9	2.09
	9	19.3	1.99
	10	22.0	2.07
	11	19.9	1.82
	12	19.9	1.98
2	1	21.2	1.71
	2	22.1	2.07
	3	20.6	1.85
	4	24.6	1.87
	5	23.2	1.94
	6	21.7	2.06
	7	22.1	1.99
	8	23.2	2.00
	9	21.9	2.00
	10	21.2	1.39
	11	20.5	1.25
	12	22.0	2.07
3	1	21.3	1.78
	2	21.7	1.81
	3	19.5	2.08
	4	21.7	2.01
	5	20.9	1.97
	6	19.5	2.00
	7	21.1	1.74
	8	20.5	1.96
	9	19.3	2.01
	10	19.8	1.99
	11	19.8	2.02
	12	19.8	2.02

APPENDIX D (Continued)

Block	Trt	Moisture content (%,Dry Basis)	Bulk density (g/cc)
4	1	19.9	2.04
	2	21.7	1.86
	3	18.3	2.18
	4	18.9	2.44
	5	21.5	2.21
	6	20.9	1.50
	7	19.3	2.10
	8	20.6	1.86
	9	20.6	2.01
	10	19.2	2.08
	11	20.7	1.99
	12	21.3	2.26
5	1	23.2	2.38
	2	21.6	2.27
	3	23.6	1.65
	4	25.4	1.62
	5	24.2	1.94
	6	24.0	2.28
	7	22.8	2.42
	8	23.6	1.98
6	1	21.0	1.85
	2	20.7	2.12
	3	20.0	2.07
	4	20.7	1.87
	5	20.2	2.09
	6	19.8	2.04
	7	19.4	2.04
	8	19.3	1.96

APPENDIX E

FORCE DATA

Block	Trt	CV (N)	CD (N)	SV (N)	SD (N)	WV (N)	WD (N)	DV (N)	DD (N)
1	1	315	646	-4	987	520	1317	187	881
	2	169	396	-124	997	454	538	58	668
	3	-13	721	-187	1126	231	160	-4	1015
	4	258	912	-27	1099	472	3444	187	1010
	5	102	1157	-356	1602	164	5700	1095	1967
	6	-214	1682	-645	1949	-67	6733	1095	1749
	7	-236	1873	-672	2078	503	6039	1050	2047
	8	-120	1606	-107	1584	801	6586	1460	2092
	9	-120	1593	-512	2216	-267	7089	2074	2875
	10	-200	1753	-156	1762	111	5126	2261	3573
	11	-267	1807	-734	2697	-178	7436	2207	2852
	12	-956	2158	-1157	2795	-463	4802	2078	2750
2	1	347	672	0	899	503	3787	271	1059
	2	218	579	-102	832	316	0	-13	886
	4	249	565	-227	1255	463	85	214	1086
	5	62	1099	-169	1308	396	6341	1126	1522
	6	-445	1606	-605	1789	4	5300	1602	2439
	7	-289	1442	-641	1869	383	5745	1473	2861
	8	-316	1673	-516	1709	383	6577	1277	2603
	9	-134	1722	-147	1927	-249	7031	2167	4125
	10	-289	1549	-970	2191	-325	5309	2056	2278
	11	-574	1922	-725	2568	-418	6568	2185	3226
	12	-748	1905	-632	2804	116	5015	1562	2768
3	1	387	481	-49	1019	538	4668	538	877
	2	227	534	160	921	516	5037	89	739
	3	271	592	45	810	285	5758	271	1019
	4	338	583	138	854	552	4446	285	1126
	5	307	894	-392	1709	240	4948	1744	1339
	6	196	1113	-378	1869	58	6978	1909	1571
	7	249	1104	-249	1727	134	6684	1709	1566
	8	-9	1469	-543	1985	249	5892	2007	1914
	9	-912	1695	-650	2412	1638	5798	1513	2207
	10	-1157	2020	-797	2959	-107	6653	1482	2474
	11	-886	1722	-1055	3275	3213	6742	1197	3449
	12	-877	1847	-1001	2879	1371	4753	1006	3827

APPENDIX E (Continued)

Block	Trt	CV (N)	CD (N)	SV (N)	SD (N)	WV (N)	WD (N)	DV (N)	DD (N)
4	1	418	565	62	1006	240	3449	378	445
	2	374	498	-111	908	472	3556	191	765
	3	53	587	-276	983	294	5919	147	1406
	6	378	903	-271	1388	125	6898	1762	1121
	7	191	1157	-89	1464	214	6800	1362	1558
	8	22	1135	-374	1558	-80	6515	1420	1629
	9	-663	1504	-690	2163	1562	6457	1117	2421
	10	-957	1980	-641	2683	4285	801	1072	2407
	11	-837	1549	-846	2679	805	6097	1068	2906
	12	-1193	2158	-890	2541	-4156	2421	1500	2537
5	1	401	316	129	939	276	6097	868	1469
	2	218	516	107	814	134	4125	401	490
	3	458	561	120	961	147	5945	619	783
	4	472	579	378	903	659	5945	779	654
	5	40	1095	-623	2020	530	6644	1090	1558
	6	401	1095	53	1291	-285	2047	801	1420
	7	294	952	-191	1962	231	5785	983	1753
	8	107	1166	-254	2096	151	6542	894	2100
6	1	365	512	18	921	178	4512	565	943
	2	512	387	258	1847	703	6032	694	939
	3	409	574	76	694	347	4098	761	854
	4	436	583	285	1170	685	5856	632	926
	5	160	805	-356	1246	280	5166	890	1540
	6	-102	1019	-498	1553	-67	6377	1161	1357
	7	-142	1055	-365	1411	312	5856	1224	1535
	8	-151	1041	-472	1891	182	6404	1068	1896

APPENDIX F

VELOCITY, CONE INDEX AND DEPTH DATA

Block	Trt	Cone Index (N/cm^2)	Velocity (cm/s)	Depth (cm)
1	1	45.2	117	5.1
	2	52.5	152	5.1
	3	33.9	190	5.1
	4	44.7	236	5.1
	5	40.2	117	10.2
	6	54.2	156	10.2
	7	48.7	197	10.2
	8	42.5	228	10.2
	9	57.4	114	12.7
	10	56.9	156	12.7
	11	34.0	189	12.7
	12	48.8	230	12.7
2	1	29.5	119	5.1
	2	29.1	148	5.1
	4	41.2	234	5.1
	5	40.1	114	10.2
	6	39.8	152	10.2
	7	54.4	194	10.2
	8	39.4	234	10.2
	9	36.0	114	12.7
	10	43.3	155	12.7
	11	47.7	190	12.7
	12	38.5	230	12.7
3	1	39.0	114	5.1
	2	23.7	155	5.1
	3	35.6	187	5.1
	4	26.1	241	5.1
	5	46.6	114	10.2
	6	34.5	155	10.2
	7	45.8	191	10.2
	8	39.8	230	10.2
	9	35.2	109	12.7
	10	56.5	150	12.7
	11	48.7	189	12.7
	12	50.9	221	12.7

APPENDIX F (Continued)

Block	Trt	Cone Index (N/cm^2)	Velocity (cm/s)	Depth (cm)
4	1	22.8	116	5.1
	2	34.8	155	5.1
	3	36.2	191	5.1
	6	40.3	156	10.2
	7	60.3	196	10.2
	8	43.4	236	10.2
	9	63.4	112	12.7
	10	48.3	151	12.7
	11	39.6	187	12.7
	12	53.2	234	12.7
5	1	32.5	110	5.1
	2	14.2	151	5.1
	3	28.7	171	5.1
	4	48.9	210	5.1
	5	38.3	111	10.2
	6	23.6	152	10.2
	7	38.1	187	10.2
	8	25.4	219	10.2
6	1	19.3	116	5.1
	2	42.5	148	5.1
	3	21.8	186	5.1
	4	22.5	222	5.1
	5	30.8	118	10.2
	6	42.5	155	10.2
	7	21.7	187	10.2
	8	28.5	222	10.2

APPENDIX G

Π -TERMS

Tool	Block	Trt	Π_1 Vertical	Π_1 Draft	Π_2	Π_3
Chisel	1	1	0.271	0.581	2.73	1.0
		2	0.125	0.292	4.63	1.0
		3	-0.015	0.825	7.28	1.0
		4	0.224	0.791	11.22	1.0
		5	0.025	0.279	2.73	0.5
		6	-0.038	0.300	4.91	0.5
		7	-0.047	0.373	7.80	0.5
		8	-0.027	0.366	10.43	0.5
		9	-0.013	0.172	2.58	0.4
		10	-0.022	0.191	4.91	0.4
		11	-0.049	0.330	7.18	0.4
		12	-0.123	0.274	10.64	0.4
	2	1	0.456	0.882	2.84	1.0
		2	0.290	0.770	4.42	1.0
		4	0.235	0.532	11.01	1.0
		5	0.015	0.265	2.63	0.5
		6	-0.108	0.391	4.64	0.5
		7	-0.052	0.257	7.62	0.5
		8	-0.078	0.412	11.01	0.5
		9	-0.023	0.297	2.63	0.4
		10	-0.041	0.221	4.83	0.4
		11	-0.075	0.250	7.28	0.4
		12	-0.120	0.307	10.64	0.4
	3	1	0.384	0.477	2.63	1.0
		2	0.371	0.872	4.83	1.0
		3	0.300	0.644	7.04	1.0
		4	0.501	0.863	11.65	1.0
		5	0.064	0.186	2.57	0.5
		6	0.055	0.312	4.83	0.5
		7	0.053	0.233	7.35	0.5
		8	-0.002	0.358	10.64	0.5
		9	-0.161	0.299	2.39	0.4
		10	-0.127	0.222	4.50	0.4
		11	-0.113	0.219	7.18	0.4

APPENDIX G (Continued)

Tool	Block	Trt	Π_1 Vertical	Π_1 Draft	Π_2	Π_3
Chisel	4	1	0.721	0.962	2.69	1.0
		2	0.416	0.551	4.83	1.0
		3	0.057	0.628	7.35	1.0
		6	0.091	0.217	4.90	0.5
		7	0.031	0.186	7.69	0.5
		8	0.005	0.253	11.14	0.5
		9	0.065	0.147	2.53	0.4
		10	-0.123	0.254	4.55	0.4
		11	-0.131	0.242	7.04	0.4
		12	-0.139	0.252	11.01	0.4
	5	1	0.478	0.377	2.43	1.0
		2	0.595	1.408	4.55	1.0
		3	0.619	0.758	5.85	1.0
		4	0.374	0.458	8.85	1.0
		5	0.010	0.277	2.49	0.5
		6	0.165	0.450	4.64	0.5
		7	0.075	0.242	7.04	0.5
		8	0.041	0.444	9.71	0.5
	6	1	0.734	1.029	2.69	1.0
		2	0.467	0.353	4.37	1.0
		3	0.729	1.022	6.94	1.0
		4	0.751	1.003	9.90	1.0
		5	0.050	0.254	2.77	0.5
		6	-0.023	0.232	4.83	0.5
		7	-0.064	0.471	7.04	0.5
		8	-0.051	0.354	9.90	0.5
Sweep	1	1	-0.004	0.847	0.54	5.0
		2	-0.092	0.735	0.92	5.0
		3	-0.214	1.288	1.46	5.0
		4	-0.023	0.954	2.24	5.0
		5	-0.086	0.386	0.55	2.5
		6	-0.115	0.348	0.98	2.5
		7	-0.134	0.413	1.56	2.5
		8	-0.024	0.361	2.09	2.5
		9	-0.055	0.239	0.52	2.0
		10	-0.017	0.192	0.98	2.0
		11	-0.134	0.492	1.44	2.0
		12	-0.147	0.355	2.13	2.0
	2	1	0.0	1.180	0.57	5.0
		2	-0.136	1.107	0.88	5.0
		4	-0.214	1.182	2.20	5.0
		5	-0.041	0.316	0.53	2.5
		6	-0.147	0.435	0.93	2.5
		7	-0.114	0.333	1.52	2.5
		8	-0.127	0.420	2.20	2.5
		9	-0.025	0.332	0.53	2.0

APPENDIX G (Continued)

Tool	Block	Trt	Π_1 Vertical	Π_1 Draft	Π_2	Π_3
Sweep	2	10	-0.139	0.456	0.97	2.00
		11	-0.094	0.333	1.46	2.00
		12	-0.102	0.451	2.13	2.00
	3	1	-0.049	1.011	0.53	5.00
		2	0.262	1.504	0.97	5.00
		3	0.048	0.882	1.41	5.00
		4	0.204	1.265	2.33	5.00
		5	-0.081	0.355	0.52	2.50
		6	-0.106	0.525	0.95	2.50
		7	-0.053	0.365	1.47	2.50
		8	-0.132	0.484	2.12	2.50
		9	-0.114	0.425	0.48	2.00
		10	-0.087	0.325	0.90	2.00
		11	-0.134	0.417	1.44	2.00
		12	-0.122	0.351	1.97	2.00
	4	1	0.106	1.711	0.54	5.00
		2	-0.124	1.010	0.96	5.00
		3	-0.295	1.052	1.47	5.00
		6	-0.065	0.334	0.98	2.50
		7	-0.014	0.235	1.54	2.50
		8	-0.083	0.347	2.23	2.50
		9	-0.067	0.211	0.51	2.00
		10	-0.082	0.345	0.91	2.00
		11	-0.132	0.419	1.41	2.00
		12	-0.104	0.296	2.20	2.00
	5	1	0.154	1.120	0.49	5.00
		2	0.291	2.222	0.91	5.00
		3	0.162	1.299	1.17	5.00
		4	0.300	0.716	1.77	5.00
		5	-0.157	0.511	0.50	2.50
		6	0.022	0.531	0.93	2.50
		7	-0.049	0.499	1.41	2.50
		8	-0.097	0.798	1.94	2.50
	6	1	0.036	1.852	0.54	5.00
		2	0.236	1.686	0.87	5.00
		3	0.135	1.235	1.39	5.00
		4	0.490	2.015	1.98	5.00
		5	-0.112	0.392	0.55	2.50
		6	-0.114	0.354	0.97	2.50
		7	-0.163	0.630	1.41	2.50
		8	-0.160	0.643	1.98	2.50
Coulter	1	1	0.447	1.131	0.26	10.50
		2	0.335	0.397	0.44	10.50
		3	0.265	0.183	0.69	10.50
		4	0.409	2.988	1.07	10.50
		5	0.040	1.373	0.26	5.25

APPENDIX G (Continued)

Tool	Block	Trt	Π_1		Π_2	Π_3
			Vertical	Draft		
Coulter	1	6	-0.012	1.203	0.47	5.25
		7	0.100	1.201	0.74	5.25
		8	0.183	1.502	0.99	5.25
		9	-0.029	0.765	0.25	4.20
		10	0.012	0.559	0.47	4.20
		11	-0.032	1.357	0.68	4.20
		12	-0.059	0.610	1.01	4.20
	2	1	0.660	4.970	0.27	10.50
		2	0.420	0.000	0.42	10.50
		4	0.436	0.080	1.05	10.50
		5	0.096	1.530	0.25	5.25
		6	0.001	1.289	0.44	5.25
		7	0.068	1.023	0.73	5.25
		8	0.094	1.618	1.05	5.25
		9	-0.043	1.211	0.25	4.20
		10	-0.046	0.759	0.46	4.20
		11	-0.054	0.853	0.69	4.20
		12	0.019	0.807	1.01	4.20
	3	1	0.534	4.633	0.25	10.50
		2	0.843	8.226	0.46	10.50
		3	0.310	6.269	0.67	10.50
		4	0.817	6.582	1.11	10.50
		5	0.050	1.028	0.25	5.25
		6	0.016	1.959	0.46	5.25
		7	0.028	1.413	0.70	5.25
		8	0.061	1.436	1.01	5.25
		9	0.288	1.021	0.23	4.20
		10	-0.013	0.730	0.43	4.20
		11	0.409	0.859	0.68	4.20
		12	0.167	0.580	0.94	4.20
	4	1	0.409	5.869	0.26	10.50
		2	0.525	3.954	0.46	10.50
		3	0.314	6.330	0.70	10.50
		6	0.030	1.659	0.47	5.25
		7	0.034	10.92	0.73	5.25
		8	-0.018	1.453	1.06	5.25
		9	0.153	0.631	0.24	4.20
		10	0.551	0.103	0.43	4.20
		11	0.126	0.954	0.67	4.20
		12	-0.485	0.282	1.05	4.20
	5	1	0.329	7.271	0.23	10.50
		2	0.364	11.254	0.43	10.50
		3	0.198	8.034	0.56	10.50
		4	0.522	4.711	0.84	10.50
		5	0.134	1.680	0.24	5.25
		6	-0.117	0.842	0.44	5.25

APPENDIX G (Continued)

Tool	Block	Trt	Π_1 Vertical	Π_1 Draft	Π_2	Π_3
Coulter	5	7	0.059	1.470	0.67	5.25
		8	0.058	2.490	0.92	5.25
	6	1	0.358	9.073	0.26	10.50
		2	0.642	5.597	0.41	10.50
		3	0.618	7.294	0.66	10.50
		4	1.180	10.082	0.94	10.50
		5	0.088	1.627	0.26	5.25
		6	-0.015	1.454	0.46	5.25
		7	0.139	2.615	0.67	5.25
		8	0.062	2.177	0.94	5.25
Disk	1	1	0.160	0.756	0.26	10.50
		2	0.043	0.492	0.44	10.50
		3	-0.005	1.161	0.69	10.50
		4	0.162	0.876	1.07	10.50
		5	0.264	0.474	0.26	5.25
		6	0.196	0.312	0.47	5.25
		7	0.209	0.407	0.74	5.25
		8	0.333	0.477	0.99	5.25
		9	0.224	0.310	0.25	4.20
		10	0.247	0.390	0.47	4.20
		11	0.403	0.520	0.68	4.20
		12	0.264	0.349	1.01	4.20
	2	1	0.356	1.390	0.27	10.50
		2	-0.018	1.178	0.42	10.50
		4	0.201	1.022	1.05	10.50
		5	0.272	0.367	0.25	5.25
		6	0.390	0.593	0.44	5.25
		7	0.262	0.509	0.73	5.25
		8	0.314	0.640	1.05	5.25
		9	0.373	0.710	0.25	4.20
		10	0.294	0.326	0.46	4.20
		11	0.284	0.419	0.69	4.20
		12	0.251	0.445	1.01	4.20
	3	1	0.534	0.870	0.25	10.50
		2	0.145	1.206	0.46	10.50
		3	0.296	1.109	0.67	10.50
		4	0.422	1.667	1.11	10.50
		5	0.363	0.278	0.25	5.25
		6	0.536	0.441	0.46	5.25
		7	0.361	0.331	0.70	5.25
		8	0.489	0.466	1.01	5.25
		9	0.266	0.389	0.23	4.20
		10	0.163	0.272	0.43	4.20
		11	0.152	0.439	0.68	4.20
		12	0.123	0.467	0.94	4.20
	4	1	0.644	0.757	0.26	10.50

APPENDIX G (Continued)

Tool	Block	Trt	Π_1		Π_2	Π_3
			Vertical	Draft		
Disk	4	2	0.213	0.851	0.46	10.50
		3	0.157	1.504	0.70	10.50
		6	0.424	0.270	0.47	5.25
		7	0.219	0.250	0.73	5.25
		8	0.317	0.363	1.06	5.25
		9	0.109	0.237	0.24	4.20
		10	0.138	0.309	0.43	4.20
		11	0.167	0.455	0.67	4.20
		12	0.175	0.296	1.05	4.20
	5	1	1.035	1.751	0.23	10.50
		2	1.093	1.335	0.43	10.50
		3	0.836	1.058	0.56	10.50
		4	0.617	0.518	0.84	10.50
		5	0.276	0.394	0.24	5.25
		6	0.329	0.584	0.44	5.25
		7	0.250	0.445	0.67	5.25
		8	0.341	0.800	0.92	5.25
	6	1	1.136	1.897	0.26	10.50
		2	0.634	0.857	0.42	10.50
		3	1.354	1.520	0.66	10.50
		4	1.088	1.594	0.94	10.50
		5	0.280	0.485	0.26	5.25
		6	0.265	0.309	0.46	5.25
		7	0.546	0.686	0.67	5.25
		8	0.363	0.645	0.94	5.25

VITA 2

Craig Clayton Reisbeck

Candidate for the Degree of

Master of Science

Thesis: FEASIBILITY OF USING A TILLAGE TOOL AS A MOBILE PENETROMETER

Major Field: Agricultural Engineering

Biographical:

Personal Data: Born in Julesburg, Colorado, January 30, 1959, the son of Robert F. and Sandra Reisbeck.

Education: Graduated from C. E. Donart High School, Stillwater, Oklahoma, in May, 1977; recieved Bachelor of Science degree in Agricultural Engineering from Oklahoma State University in December, 1983; completed requirements for the Master of Science degree at Oklahoma State University in May, 1985.

Professional Experience: Teaching Assistant, Department of Agricultural Engineering, Oklahoma State University, January, 1984 to May, 1984; Research Assistant, Department of Agricultural Engineering, Oklahoma State University, May 1984 to May, 1985.