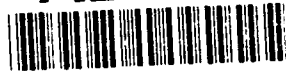


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Report SE-91-03

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**IN-PROCESS INSPECTION STUDY (IPIS)
FOR
ABRASIVE MACHINING (HONING)**

Manufacturing Methods and Technology Project 6XX8250

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FINAL REPORT

MMT 6XX8250, IMPROVED FABRICATION OF RECOIL COMPONENTS
CONTRACT NO.: DAAA08-89-C-0084



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REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
1a. REPORT SECURITY CLASSIFICATION Unclassified			1b. RESTRICTIVE MARKINGS		
2a. SECURITY CLASSIFICATION AUTHORITY			3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution is unlimited.		
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE					
4. PERFORMING ORGANIZATION REPORT NUMBER(S) NPN-A31			5. MONITORING ORGANIZATION REPORT NUMBER(S) SE-91-03		
6a. NAME OF PERFORMING ORGANIZATION Babcock & Wilcox Manufactured & Systems Tech. Div.		6b. OFFICE SYMBOL (If applicable)		7a. NAME OF MONITORING ORGANIZATION SMCRI-SEM-T Rock Island Arsenal	
6c. ADDRESS (City, State, and ZIP Code) P.O. Box 785 Lynchburg VA 24505			7b. ADDRESS (City, State, and ZIP Code) Rock Island IL 61299-5000		
8a. NAME OF FUNDING / SPONSORING ORGANIZATION		8b. OFFICE SYMBOL (If applicable)		9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER DAAA08-89-C-0084	
8c. ADDRESS (City, State, and ZIP Code)			10. SOURCE OF FUNDING NUMBERS		
			PROGRAM ELEMENT NO. DE 62	PROJECT NO. 6XX8250	TASK NO.
11. TITLE (Include Security Classification) In-process Inspection Study (IPIS) for Abrasive Machining (Honing)					
12. PERSONAL AUTHOR(S) Michael A. Paul, V. Ed Stubbs, Michael W. Minnick, and Donald G. Eitzen					
13a. TYPE OF REPORT Final		13b. TIME COVERED FROM Jun 89 to Sep 90		14. DATE OF REPORT (Year, Month, Day) 1990 November 09	
15. PAGE COUNT 271					
16. SUPPLEMENTARY NOTATION Destroy this report when no longer needed. Do not return to the originator.					
17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)		
FIELD	GROUP	SUB-GROUP			
13	08		1. Detectors		
12	09		2. Inspection		
			3. Honing		
			4. In-process		
			5. Eddy Current		
19. ABSTRACT (Continue on reverse if necessary and identify by block number) This study was to prove the feasibility of in-process inspection of parts being honed on the inside diameter. Capacitance and inductive (eddy current) sensors were bench tested for accuracy and for the sensitivities of these measurements to honing oil. Unlike capacitance sensing, eddy current sensing was insensitive to the oil, so a honing machine was set up that had two eddy current sensors diagonally opposed to each other in a fixture screwed to the honing head. The wires were fed through flexible coupling to a slip ring, where the signals were routed through a signal conditioner to a 12 bit analog voltage to digital conversion (data acquisition) board in a computer. A lookup table was automatically used to correct for deviations from linearity of the sensors. A color monitor enabled graphical displays of individual readings in real time. The data acquisition rate was 33 readings per second. The three sigma diameter accuracies for one part were 0.00072 inch, 0.00066 inch and 0.00033 inch for no averaging, averaging two points, and averaging 16 points, respectively, all normally sufficient for diameter inspection. (Continued)					
20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS			21. ABSTRACT SECURITY CLASSIFICATION Unclassified		
22a. NAME OF RESPONSIBLE INDIVIDUAL RICHARD KALKAN, JR.			22b. TELEPHONE (Include Area Code) (309)782-7873		22c. OFFICE SYMBOL SMCRI-SEM-T

19. ABSTRACT (Continued)

A calculated bias of 0.0002 inch was consistent with thermal expansion. A second part had corresponding accuracies of 0.00099, 0.00093 and 0.00060. The three sigma repeatabilities of diameters without averaging was 0.00042 inch. The data acquisition board introduced a ± 0.0005 inch error from an 11 degree rotation between the readings of the two opposed sensors. Using truly differential gaging and sensors that match the full voltage range of the data acquisition board, more accurate roundness determinations could be made. Bench tests showed potentials of fiber optic and ultrasonic sensors to automatically measure surface finish of a wiped or coolant coupled part, respectively, on a honing machine and to detect large changes in surface finish in real time, as when a breaking stone would cause a flaw.

ACKNOWLEDGMENTS

Evans, Douglas H.
 Ferguson, Calvin R.
 Franklin, Joe O.
 Gossler, E. Thomas
 Myers, Steve J.

Babcock & Wilcox

Kalkan, Richard G.
 Moriarty, John

Rock Island Arsenal



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Table of Contents

Section	Page
Table of Figures	ix
List of Tables	xi
1.0 INTRODUCTION	1-1
1.1 Background	1-1
1.2 Objectives	1-2
1.3 Summary	1-2
2.0 TECHNICAL APPROACH - DIMENSIONAL INSPECTION	2-1
2.1 Two-Phased Approach	2-1
2.2 Open Loop System	2-1
2.3 Choice of Sensors	2-1
2.4 Sensor Fixturing	2-2
2.5 Tooling Modifications	2-4
2.6 Summary	2-4
3.0 BENCH TESTING - DIMENSIONAL INSPECTION	3-1
3.1 Capacitance Sensor Testing	3-1
3.1.1 Test Apparatus	3-1
3.1.2 Test Description	3-6
3.1.3 Test Results	3-6
3.1.4 Test Conclusions	3-8
3.2 Inductive (Eddy Current) Sensor Testing	3-9
3.2.1 Test Apparatus	3-11
3.2.2 Test Descriptions	3-14
3.2.3 Test Results	3-14
3.2.4 Test Conclusions	3-21
4.0 MACHINE TESTING - DIMENSIONAL INSPECTION	4-1
4.1 Mechanical System Description	4-1
4.1.1 Honing Machine	4-1
4.1.2 Hone Tooling	4-4
4.1.3 Test Materials	4-4
4.1.4 Expendables	4-4
4.1.5 Part Fixturing	4-5
4.1.6 Sensor Fixturing	4-5
4.2 Data Acquisition System Description	4-6

4.2.1	Equipment	4-6
4.2.2	System Schematic	4-11
4.2.3	Software Design	4-12
4.3	Calibration Procedure	4-14
4.3.1	Sensor Characterization	4-14
4.3.2	Offset Determination	4-15
4.4	Test Procedure	4-19
4.5	Test Results, Analysis & Discussions	4-20
4.5.1	System Resolution & Electrical Noise	4-22
4.5.2	Data Acquisition Rate / Phase Shift Error	4-22
4.5.3	Thermal Effects	4-24
4.5.4	Bore Profiles	4-26
4.5.5	Statistical Error Analysis	4-28
4.5.6	Stone Pressure & Roughness Effects	4-32
5.0	BENCH TESTING - SURFACE FINISH INSPECTION	5-1
5.1	Technical Approach	5-1
5.2	Optical Sensor Testing	5-1
5.2.1	Test Apparatus	5-1
5.2.2	Test Procedure	5-4
5.2.3	Test Results	5-7
5.2.4	Test Conclusions	5-10
5.3	Ultrasonic Sensor With Stream Coupling Testing	5-10
6.0	CONCLUSIONS	6-1
6.1	Dimensional Inspection	6-1
6.1.1	Sensors	6-1
6.1.2	System Resolution	6-1
6.1.3	Data Acquisition Rate	6-2
6.1.4	Phase Shift Reading Errors	6-2
6.1.5	Temperature Effects	6-2
6.1.6	Accuracies	6-3
6.1.7	Practical Application of Data	6-3
6.2	Surface Finish Inspection	6-4
7.0	RECOMMENDATIONS	7-1
7.1	Proposed Open-Loop Retrofit System	7-1
7.1.1	Sensor & Equipment Fixturing	7-1
7.1.2	Data Acquisition Equipment / Operator Interface	7-6
7.2	Closed-Loop System	7-7

Drawings	Appendix I
Source Code	Appendix II
Bench Testing Capacitance Sensor Data	Appendix III
Bench Testing Inductive Sensor Data	Appendix IV
Offset Standard Zeiss Inspection Data	Appendix V
Machine Testing Data	Appendix VI
Error Analysis Tables	Appendix VII
Bench Testing Optical Sensor Data	Appendix VIII
Computer Screens	Appendix IX
Vendor List	Appendix X

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Table Of Figures

No.	Description	Page
1-1	Basic Honing Machine	1-1
2-1	Honing Head Centering	2-2
2-2	Diameter Determination	2-3
2-3	Ideal Retrofit Concept	2-5
3-1	Bench Testing Sensors	3-2
3-2	Capacitance Sensor Gage Setup	3-3
3-3	Capacitance Sensor Oil Setup	3-4
3-4	Fluids Tested	3-5
3-5	Capacitance Sensor Oil Bath	3-7
3-6	Plot of Capacitance Sensor Data	3-8
3-7	Eddy Current Sensor Schematic	3-10
3-8	Keyence Sensor Gage Setup	3-12
3-9	Omron Sensor Gage Setup	3-13
3-10	Keyence Sensor Oil Setup	3-15
3-11	Omron Sensor Oil Setup	3-16
3-12	Keyence Sensor Errors	3-17
3-13	Keyence Sensor Errors	3-18
3-14	Keyence Sensor Errors	3-18
3-15	Keyence Sensor Data Wet vs. Dry	3-19
3-16	Omron Sensor Errors	3-19
3-17	Omron Sensor Errors	3-20
3-18	Omron Sensor Errors	3-20
3-19	Omron Sensor Errors	3-21
4-1	Demonstration/Study Machine	4-2
4-2	#3 Barnes Horizontal Honing Machine Photo 900857-12	4-3
4-3	Custom Sensor Fixturing	4-6
4-4	Custom Sensor Fixturing	4-7
4-5	Sensor Fixturing Modifications	4-8
4-6	Thermistor Setup	4-10
4-7	Electrical System Schematic	4-12
4-8	Calibration Setup	4-16
4-9	Calibration Fixture	4-17
4-10	Offset Calibration	4-18

4-11 Test Piece Station Layout	4-21
4-12 System A/D Noise Resolution	4-23
4-13 Honing Head Wobble Effects	4-25
4-14 Phase Shift Reading Error	4-26
4-15 Variation In Hone Head Wobble	4-27
4-16 RIA Test Part 1 Bore Profile	4-29
4-17 RIA Test Part 1 Bore Profile	4-30
5-1 Photonic Sensor Calibration Set-up	5-2
5-2 Photonic Sensor Calibration Fixture	5-3
5-3 Photonic Sensor Calibration Curve	5-4
5-4 Photonic Sensor Test Set-up	5-5
5-5 Photonic Sensor Testing	5-6
5-6 Photonic Sensor Results For Dry Surface Finish Testing	5-7
5-7 Photonic Sensor Results For Oil Film Surface Finish Testing	5-8
5-8 Photonic Sensor Results For Oil Medium Surface Finish Testing	5-9
5-9 Photonic Sensor Results For Oil Medium Surface Finish Testing With a New Offset	5-10
7-1 Proposed Retrofit System	7-2
7-2 Proposed Retrofit System Honing Head	7-3
7-3 Alternate Proposed retrofit System Honing Head	7-4
7-4 Proposed Retrofit Machine Modifications	7-5

LIST OF TABLES

Description	Page
Oil Comparisons (Effects on Sensors)	3-22
Error Analysis Results - Accuracy	4-31
Error Analysis Results - Repeatability	4-32
Ultrasonic Sensor With Water Coupling Data (For Surface Finish)	5-12
Bench Testing Capacitance Sensor Data.	A3-1
Bench Testing Inductive Sensor Data - Omron 0.000 to .250 inches.	A4-1
Bench Testing Inductive Sensor Data - Keyence 0.000 to .200 inches.	A4-4
Bench Testing Inductive Sensor Data - Omron 0.020 to .080 inches (High Sensitivity)	A4-7
Bench Testing Inductive Sensor Data - Omron 0.020 to .080 inches (Low Sensitivity)	A4-8
Bench Testing Inductive Sensor Data - Keyence 0.000 to .200 inches (Wet Vs. Dry)	A4-9
Machine Testing Data - Part 1, Roughing Stones (Stations 1 & 2)	A6-1
Machine Testing Data - Part 2, Finishing Stones (Stations 1 to 5)	A6-9
Machine Testing Data - Part 1 Bore Profile, Roughing Stones.	A6-40
Error Analysis Tables - Accuracy Analysis, Part 1, Roughing Stones.	A7-1
Error Analysis Tables - Accuracy Analysis, Part 2, Finishing Stones.	A7-3
Error Analysis Tables - Repeatability Analysis, Part 1, Roughing Stones.	A7-6
Bench Testing Optical Sensor Data - Voltage vs. Displacement	A8-1
Bench Testing Optical Sensor Data - Voltage vs. Surface Finish	A8-7

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1.0 INTRODUCTION

This report represents the work performed and results obtained by Babcock & Wilcox (B&W) in completing contract DAAA08-89-R-0084, In Process Inspection Study (IPIS) for abrasive machining, for the Rock Island Arsenal (RIA). Recommendations are made to apply the developed technology on a RIA honing machine in a factory floor environment.

1.1 Background

Abrasive machining, more specifically honing, historically has been a slow, non-automated, un-monitored process where very limited advances have been made in the past 40 years. RIA's desire for high quality, less costly parts inspired this study to determine a method for obtaining real-time (in-process) inspection data that can ultimately be used to control the honing machine process parameters (stroke, hydraulic pressure, machine time), in a manner that will aid the operator to produce a more accurate part, with minimal operator intervention, ultimately, eliminating the need for post operation inspection altogether.

Inherent factors which imposed constraints pursuing this particular project were as follows (refer to Figure 1-1 for basic honing machine terminology):

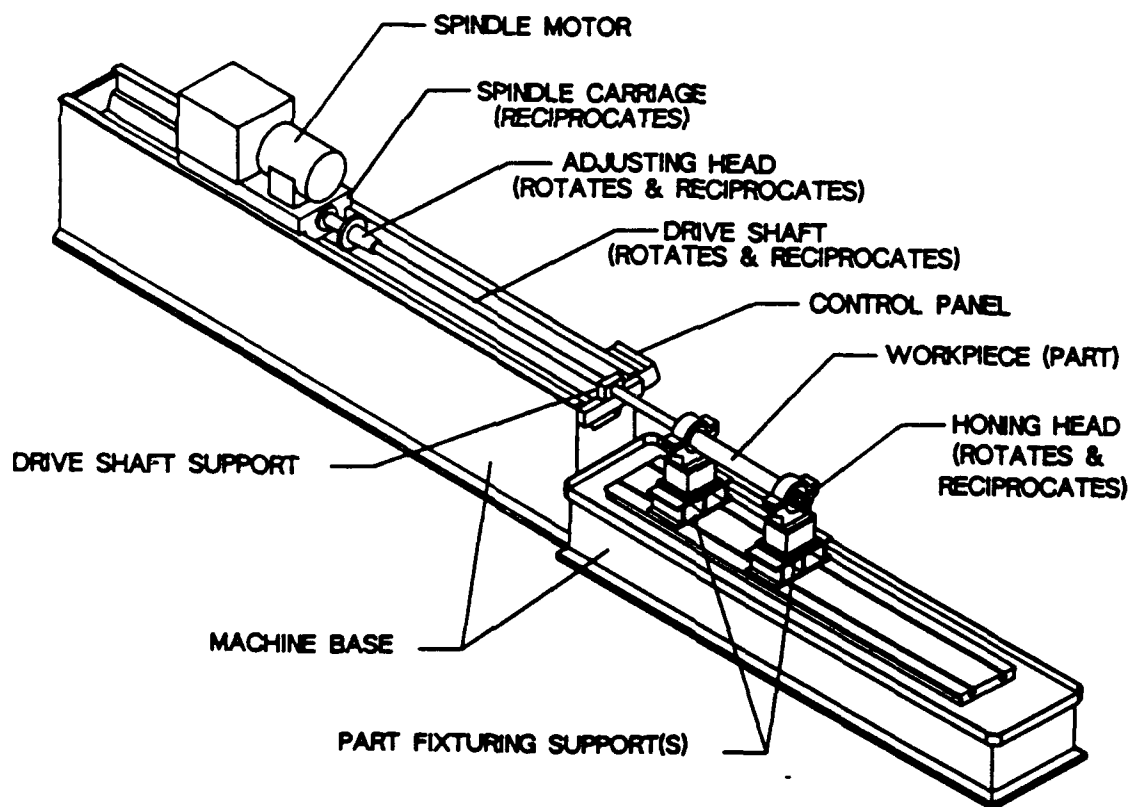


Figure 1-1, Basic Honing Machine

- **Cutting Dynamics** - The nature of the honing operation involves a relatively fast reciprocating motion, in comparison to most machining and welding operations. This motion implies that whatever sensing device(s) are used, the sensors must also be moved rapidly over the surface of the part - along with the honing head. This imposes various constraints with respect to the speed at which data can be taken and processed, as well as other electromechanical fixturing complications involved with probing the part (e.g. contacting the part surface, sensor fixturing).
- **Presence of Honing Fluid** - Honing requires that a large amount of cutting oil flood the bore in order to produce a smooth surface finish and to remove the cutting fines. The desire for an extremely smooth surface finish coupled with the dynamics of the honing operation imply that contact sensing devices should be avoided, and the presence of the fluid naturally eliminates many types of non-contact sensing technologies, leaving only a few candidates with a potential for success.
- **Part Holding** - Honing is a centerless machining operation, where the abrasive stones (honing head) rotate about a center that is defined by the workpiece, in lieu of rotating about the machine center (spindle), the latter producing a new center of the part. The centerless machining is permitted by coupling the abrasives to the spindle via a drive shaft and two U-joints. This implies that a part does not require precise fixturing to the machine (i.e. the part is not parallel to the machine base and spindle), since the honing head is free to orient itself to follow the part center. However, for dimensional sensing, orientation and relative sensor positioning with respect to the part is extremely important, where it is necessary to have a common reference datum for both the part and sensors to the machine. The absence of a common reference datum complicates the inspection process and reduces the inspection accuracy that can be expected.

These factors played a major role in directing the *evolution of the methodologies* and the techniques utilized and presented in this report.

1.2 Objectives

The primary objectives of the IPIS were twofold. The first objective was to "determine the most appropriate sensing technology for inspecting various dimensional bore attributes (diameter, roundness, cylindricity) during the honing operation". The second objective was to "demonstrate the capabilities of the chosen sensor technology on a representative honing machine utilizing anticipated mechanical, electrical and programming techniques".

A secondary objective was to "evaluate sensor technologies for potential use in determining surface finish of a part during a honing operation". (This objective was later added to the original workscope and is presented separately throughout this report.)

1.3 Summary

B&W's generic philosophy and technical approach maintained throughout the project was based on the anticipation that the techniques developed by the IPIS would eventually be incorporated on a production honing machine, with a closed loop control system to monitor and control the machine parameters. Hence, the ultimate goal to automatically monitor and control the operation(s), in real-time, was always considered in the decision making process utilized throughout this study.

The sensing technologies investigated by this study in a laboratory environment (bench testing) included capacitance and eddy current (inductive) sensors for dimensional inspections, and optical and ultrasonic sensors for surface finish inspections. The eddy current sensors were chosen for the honing application, retrofitted on a representative horizontal honing machine at B&W, tested, and evaluated for the feasibility of application to production honing processes in general.

The data obtained from the various tests performed in the study was compiled and analyzed by B&W and is presented herein. The results of the machine testing indicated that eddy current sensors could be utilized in this set-up for in-process inspection with real-time data feedback (while honing) with repeatabilities and accuracies for diameters measurements on the order of .001 inches, while accuracies as low as .0004 inches should be achievable in the proposed retrofit system.

The discussions that follow in Sections 2.0, 3.0, 4.0 and 7.0, are specific to the goals of the original workscope, related solely to dimensional (diameter related) attribute determinations. The surface finish workscope is presented in Section 5.0. Section 6.0 summarizes the conclusions and recommendations for the entire workscope - both dimensional and surface finish determinations.

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2.0 TECHNICAL APPROACH - DIMENSIONAL INSPECTION

Several up-front conclusions were drawn and general philosophies were adopted on "what" and "how" to proceed with the study. A general plan-of-attack and schedule resulted. The purpose of this plan was to establish a manageable direction towards meeting the objections of the IPIS. In order to specify direction, several decisions were made. The remainder of this section identifies the assumed conclusions and initial decisions.

2.1 Two-Phased Approach

The objectives of this study naturally eluded to dividing the study into two phases. The first phase was bench testing and the second phase was machine testing. The purpose of the first phase was to meet the first objective of RIA; to determine the best sensing technology to be utilized with honing operation(s). The purpose of the second phase was to demonstrate the chosen sensing technology from Phase I on a honing machine, by developing fixturing and software techniques necessary to determine the capabilities of in-process inspection with real-time feedback of the data.

2.2 Open Loop System

B&W's initial concept was based on the philosophy that for the purposes of this project, it was not necessary to complete a closed loop system where the inspection data would be used to control the process parameters of the machine tool. The real unknown, high risk problem was to determine how to obtain reliable, usable data. Once a methodology for obtaining data was developed, closing the control loop became a low risk (but higher cost) task, since it encompassed incorporating known technologies (*logical decision making software and control system equipment and circuitry*) into an existing system. In addition, closing the loop would have incurred a significant increase of unnecessary expenses. Therefore, this project was based on the goal of obtaining data only and not controlling the honing operations automatically in real-time.

2.3 Choice of Sensors

In order to control the project costs, certain sensors were prioritized for testing while others were eliminated from contention. These decisions were based on past experience and knowledge of various sensor technologies and evaluation of the current RIA honing operations.

The first decision was to utilize non-contact sensor technology in lieu of a contact type. This was simply due to the fact that a rapidly reciprocating honing head and respective contact probe may score the bore surface during the final passes, which is counterproductive to a primary reason for honing - to leave an extremely smooth surface finish (micro-inches).

The second decision was to eliminate any types of non-contact sensors which typically are effected by the presence of a liquid, such as the cutting oil. The nature of honing results in a widely changing amount of oil - from flooding at the bottom of the bore, to an inconsistent film thickness over the remainder of the bore surface. This eliminated ultrasonic and any type of optical sensor since the reflective characteristics of the unknown amounts of oil would have an unpredictable effect on the sensor readings. B&W did consider leading the sensor with a

wiping device, but chose not to pursue it due to the concerns of dragging the cutting fines around the tube and over the dry surface.

These conclusions prompted B&W to pursue the use of capacitive and inductive (eddy current) sensors for the monitoring of real-time diameter feedback from a rotating head. The capacitance sensor was chosen as the number one candidate due to B&W's extensive experience in the manufacture and production of high accuracy capacitance sensors. B&W currently produces custom sensors with ranges varying from 0.005 inches up to 3 inches with accuracies on the order of 0.0001 inches for a sensor with a range of 0.125 inches. The inductive sensor was chosen as a backup but not initially tested due the larger inaccuracies inherent in an eddy current system (i.e. accuracy of 0.001 inches for a sensor with a range of 0.200 inches).

2.4 Sensor Fixturing

Honing is a centerless machining operation and thereby has no common reference datum between the part surface and the machine other than the cutting abrasives themselves (refer to Section 1.1). Therefore, it was decided that the sensors be fixtured to the honing head body, since the honing head's inherent design (refer to Figure 2-1 and the General Hone drawing, G10D116, provided in Appendix I) is such that the head will be theoretically centered within the bore when the abrasive stones are expanded against the wall of the tube. U-joints in the

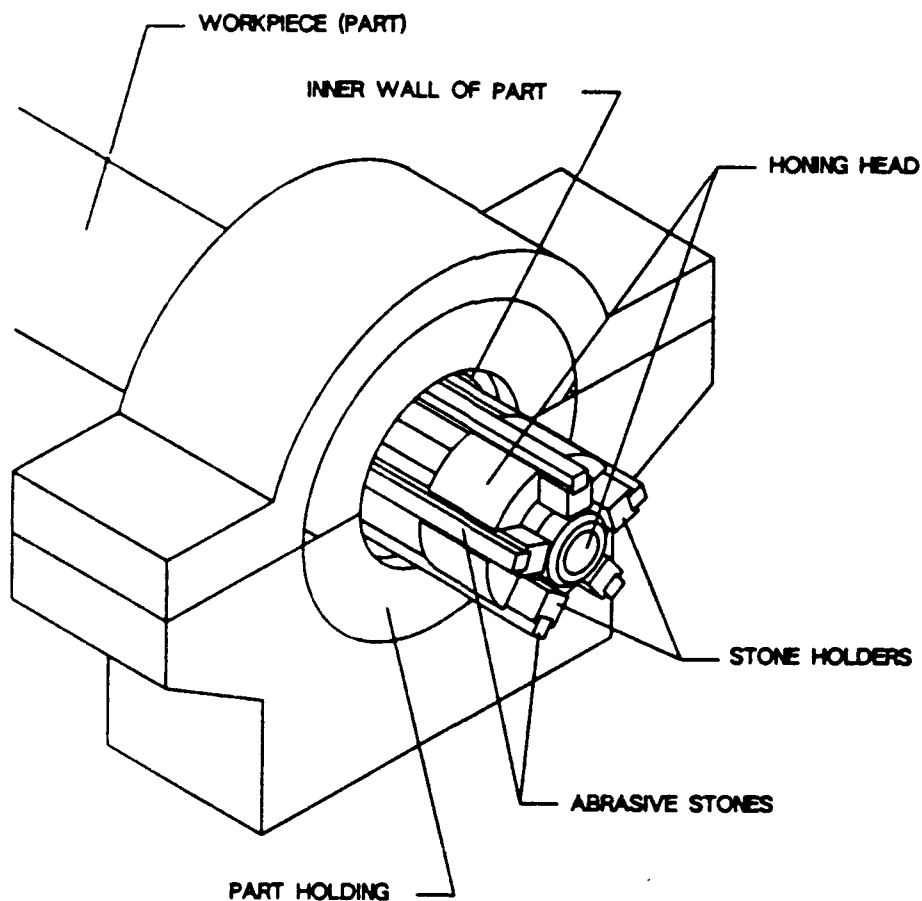


Figure 2-1, Honing Head Centering

drive shaft permit the honing head to orient itself parallel with the part. This creates the optimum scenario for diameter readings where when mounted to the honing head, the sensors would be inspecting the diameters along the best known axis of the bore diameter.

Figure 2-2 shows how the diameter is determined from two oppositely fixed sensors attached to the honing head. The two sensors read the gap distance between the sensor faces and the part surfaces such that when summed with the known (previously calibrated) offset distance between the two sensor faces, equals the diameter of the part.

However, while attaching the sensors to the honing head does eliminate the problem of a common reference in the X and Y axis of the bore (refer to Figure 2-2), it does not eliminate the problem of having no common reference datum in the Z (longitudinal) axis of the part. This implies that inspecting the bore for the true TIR of the Z axis centerline is not possible with this setup. It would only be possible with a mandrel concept (refer to B&W's proposal CP-459 in response to solicitation DAA08-89-R-0018), where the sensors are attached to a mandrel probe that surrounds the drive shaft and is rigidly fixed to the machine's spindle. However, upon further evaluation of honing and the needs of RIA, this concept was deemed infeasible for in-process inspection. First, because the mandrel would interfere with the drive shaft supports and second, since the mandrel would have to be extremely long, the unsupported length would be susceptible to oscillations due to machine vibrations, resulting in poor

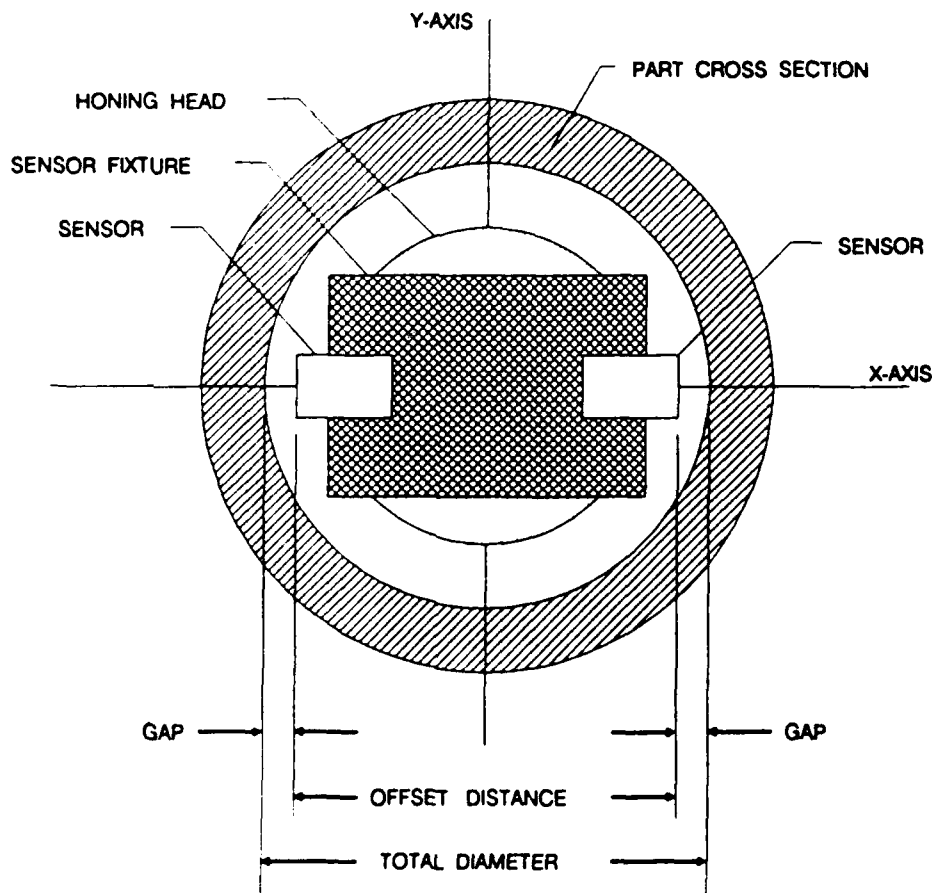


Figure 2-2, Diameter Determination

inspection repeatability. B&W and RIA concluded that it would be most beneficial to pursue imbedding/attaching the sensors to the honing head body.

B&W and RIA also concluded that it would be advantageous to allow the sensors to rotate with the honing head, in lieu of fixing them such that they do not rotate (i.e. with a bearing mount), since this would permit 100% rotational coverage of the part as required for diameter and roundness determinations. Rotating the sensors requires a slip ring to transmit the signals back to the signal conditioners and computer.

2.5 Tooling Modifications

B&W's original concept was based on the utilization of a rented hone and tooling in order to minimize expendable equipment and costs. The ideal retrofit concept for a production hone would be to imbed the sensors and wiring in the honing head and drive shaft respectively, and mount the slip ring to the machine spindle (refer to Figure 2-3), as to not interfere with the current operation of the machine. (This concept is further explained in section 7.0 of this report.) However, this would require modification to the tooling and would incur significant additional costs. Therefore, the design philosophy for the sensor fixturing was to avoid modifications to the rented honing equipment, without altering the capabilities of obtaining representative inspection data. This was done by mocking-up only the critical features of the ideal fixturing design, without modifying the rented tooling.

2.6 Summary

The technical approach was based on the following:

- Perform the study in two-distinct phases; a sensor study and a machine testing/demonstration.
- Do not close the loop. Mock-up only what is required to demonstrate the capabilities of in-process data collection.
- Utilize non-contact sensors.
- Do not test ultrasonic and optical sensors for dimensional measurement.
- Test capacitive displacement sensors first and utilize inductive proximity sensors as a contingency.
- Fixture the sensors to the honing head.
- Allow the sensors to rotate.
- For the machine study/demonstration, the sensor fixturing represents only the critical features of the ideal production fixturing concept necessary to adequately demonstrate the inspection capabilities of the sensors. Hence, for cost reduction purposes, the fixturing design was done without modification to the rented hone tooling.

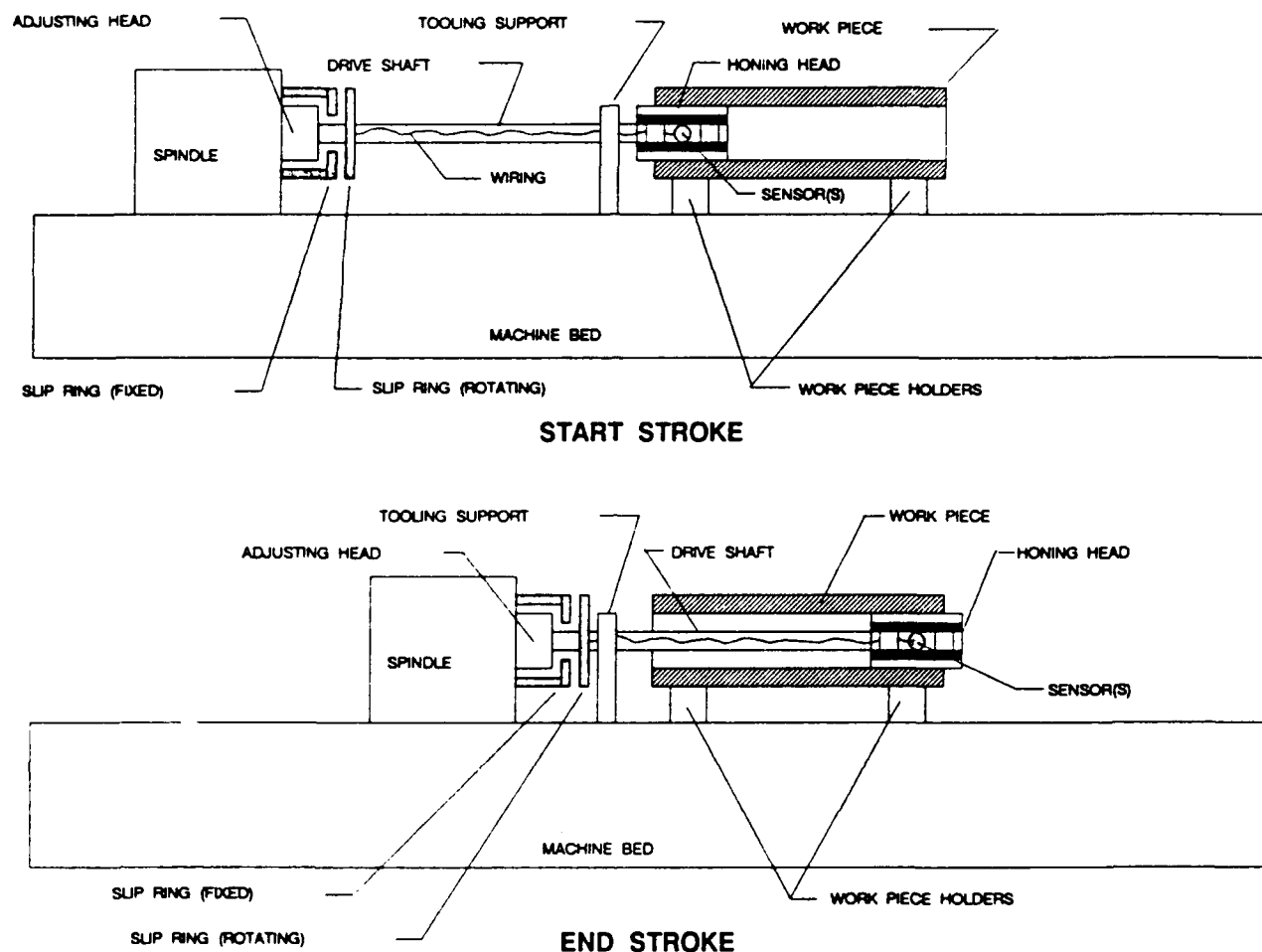


Figure 2-3, Ideal Retrofit Concept

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3.0 BENCH TESTING - DIMENSIONAL INSPECTION

Based on B&W's past experience with non-contact sensors for dimensional inspections, two technologies were chosen as the most likely candidates for testing; capacitive and inductive (eddy current) sensors. Capacitance sensors were the first choice due to the small non-linearity errors that can be obtained with signal conditioning over fairly large ranges (.050-.150 inches for example), in addition to exceptional repeatability. In a static state, accuracies of 0.0001 inches are easily achievable with capacitance sensors. Eddy current sensors however, typically yield larger non-linearity errors (0.001 inches for example over a 0.050-0.150 range) and require more software corrections (e.g. lookup tables, filtering, averaging, etc.) to obtain the accuracies desired by RIA (0.0005 inches to meet a +/- 0.001 inch overall system accuracy). Therefore, the eddy current sensors were chosen as a backup to be used only in the event that the accuracy of the capacitance sensors was significantly effected by the presence of the cutting fluid.

The bench testing setup apparatus, test description, results and conclusions are presented in the remainder of this section. Figure 3-1 represents the three sensors tested and their associated electronics as tested in B&W's metrology laboratory.

3.1 Capacitance Sensor Testing

Dimensional measurement testing was performed on a capacitance sensor which was designed and manufactured in B&W's Metrology laboratory. The capacitance sensor was chosen based on the probability that the sensor could accurately measure the dimensional attributes of a rotating metallic tube with an overall system accuracy of 0.001 inches. The sensor selected had a range of 0.000-0.125 inches and a linear output from the signal conditioner of 0-1.25 Volts. B&W manufactures custom capacitance sensors with distance ranges of 0.005 inches up to 3.000 inches depending on the application. Signal conditioners manufactured by Hitec were utilized to linearize the output of the sensor to achieve an accuracy of 0.0001 inches per sensor.

Capacitance sensors produce an analog voltage proportional to the distance between the sensor face and the electrically conductive surface connected to ground. The principle of the capacitance sensor is such that the capacitive reactance (X_c) is proportional to the spacing of a parallel plate capacitor, which in this application refers to the sensor head and the metallic target. The capacitive reactance is measured with the use of an AC constant current source and a low capacitance voltage preamplifier that measures the voltage loss across the sensor face. This sensor voltage is proportional to the sensor capacitive reactance, which is in turn proportional to the sensor spacing to the measuring surface. Since the sensor face is of a finite size, the sensor ceases to become a parallel plate capacitor at long distances. Additional signal conditioner compensation must be employed to maintain a linear output voltage proportional to the distance being measured. With air as a dielectric the sensor output is directly proportional to the distance between the sensor face and the metallic target.

3.1.1 Test Apparatus

A B&W capacitance sensor with a 1/8" spot size was connected to a Hitec Model 32004 amplifier with a digital readout in tenths of a mil (0.0001 inches). The Hitec signal conditioner was equipped with gain, offset, and linearization controls to achieve a 0.2% linearity and a

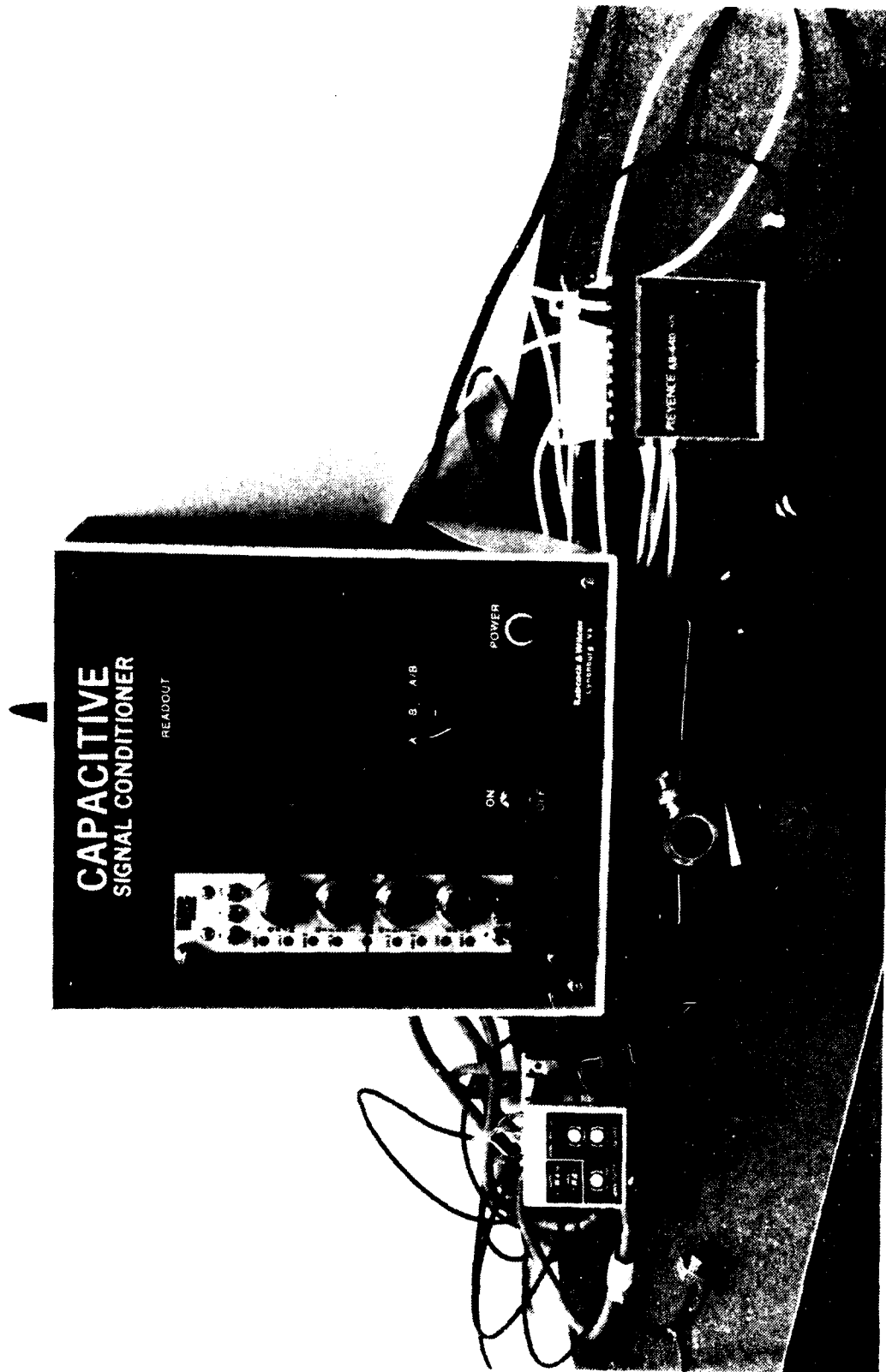


Figure 3-1, Bench Testing Sensors

0.01% repeatability of full scale output voltage. The sensor was placed above a calibrated metal fixture with a previously recorded depth from an edge of 50 mils. The sensor was coated with a waterproof sealant to prevent the entrance of cutting fluid into the sensor head.

The capacitance sensor was first checked for linearity, repeatability, and accuracy in a laboratory environment. The capacitance sensor was mounted in a test fixture with the sensor facing a steel target as shown in Figure 3-2. A calibrated gage block with an adjustable micrometer head was utilized to check the sensor's ability to measure dimensional attributes.

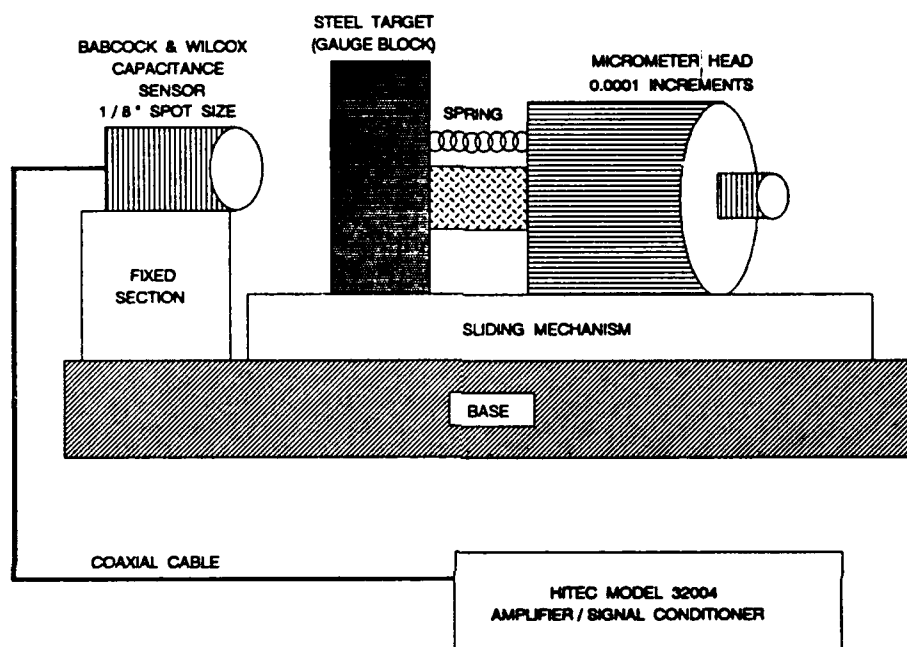


Figure 3-2, Capacitance Sensor Gage Setup

After the sensor and associated signal conditioner were calibrated, the sensors were placed in a second test fixture as depicted in Figure 3-3. The sensor was placed above a steel target with a calibrated depth from the edge of 0.050 inches. The cutout in the gage block was used to hold the oil. After the sensor was positioned to read 0.050 inches, a series of oil tests were run with the capacitance sensor. Five types of oil were tested as shown in Figure 3-4:

- Rock Island Sunnen MB-30-55 honing fluid
- Rock Island Hangsterfer 67-5
- Clean General Hone fluid
- Dirty General Hone fluid
- Monroe Fluid Technology Cool Tool II cutting fluid

The General Hone Corporation provided samples of clean and dirty honing fluid used in their honing machines. The dirty honing fluid contained cutting fines that would be found in the normal honing process. This oil was taken from the bottom of the oil collection tray of a honing machine. The oil was not tested to determine the actual composition of the fluid to determine the amount of cutting fines in the fluid.

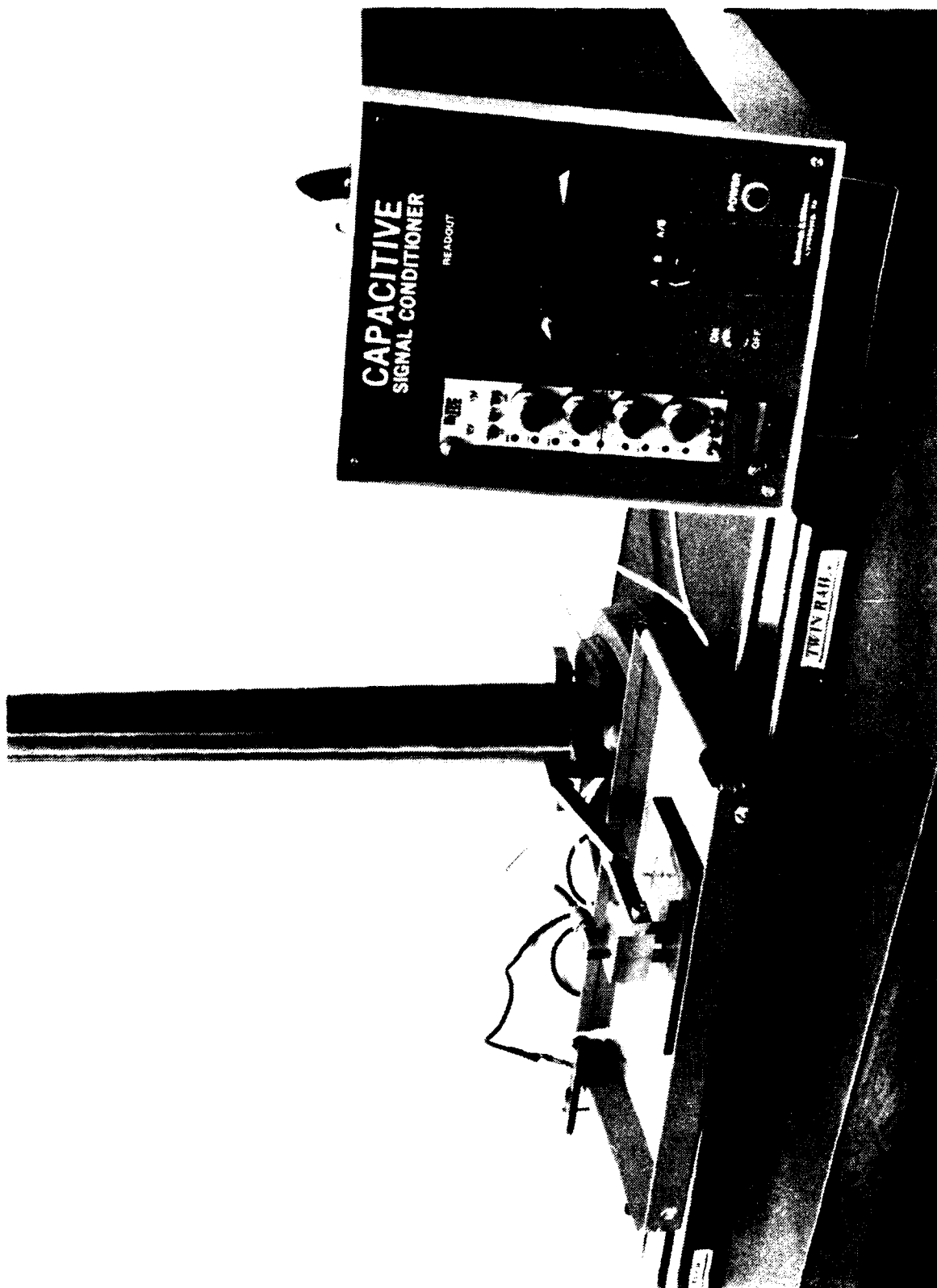


Figure 3-3, Capacitance Sensor Oil Setup

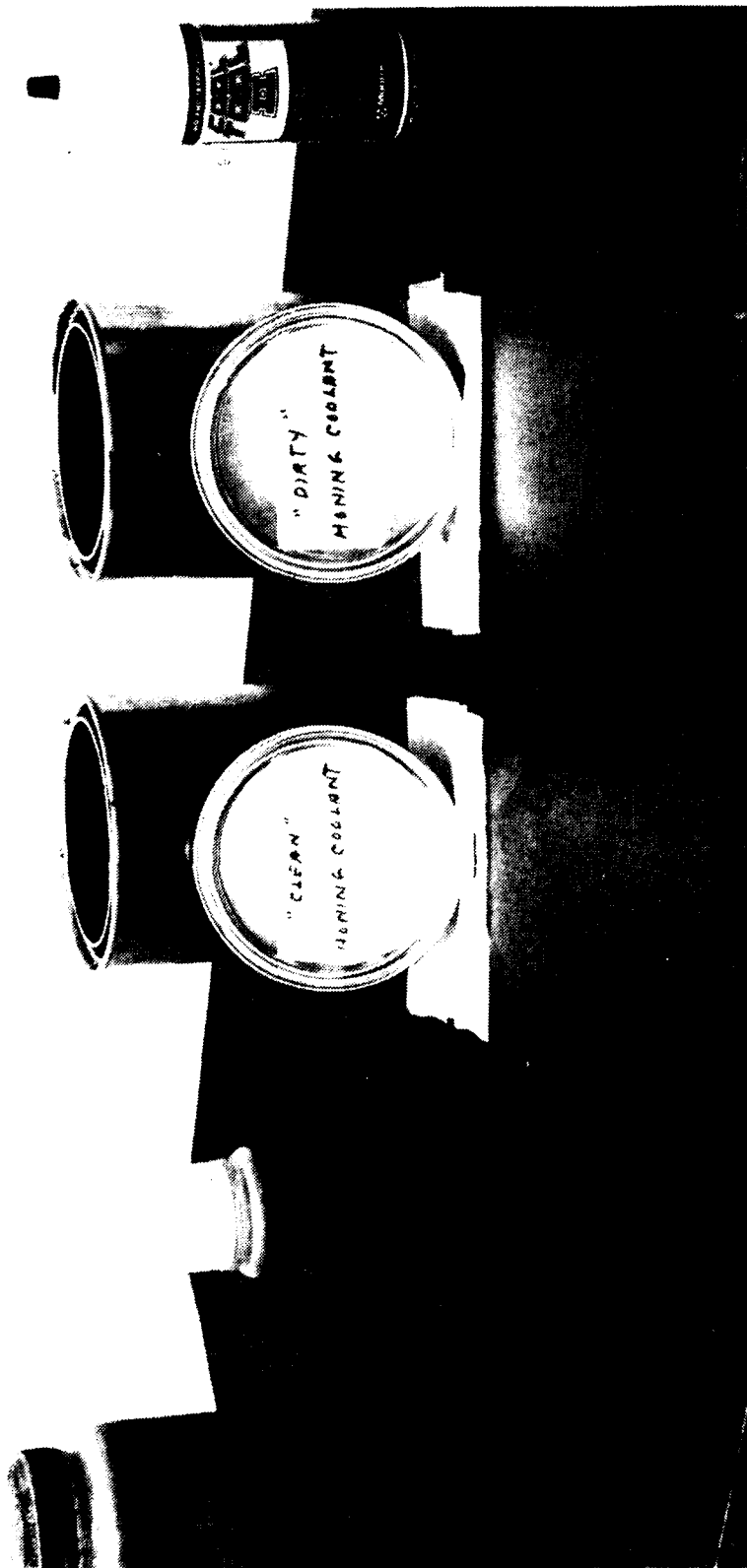


Figure 3-4, Fluids Testing

3.1.2 Test Description

The capacitance sensor was placed against the gage block to obtain a zero offset and set the micrometer head to zero. The gage block was moved away from the sensor in 0.001 inch increments to determine the linearity of the sensor over a range of 0.000 to 0.125 inches. A high tension spring (refer to Figure 3-2) was attached to the gage block and micrometer head to prevent any leadscrew backlash from affecting the readings when the gage block was moved either toward or away from the sensor. Readings were taken at 0.000 up to 0.125 inches and 0.125 to 0.000 inches in the opposite direction to check the repeatability of the sensor readings.

At this point, the capacitance sensor was mounted in the oil bath test fixture to check for the effects of various fluids on the displacement readings. The sensor was placed above the metal fixture with a calibrated depth from an edge of 0.050 inches. The sensor was positioned so that the readout on the signal conditioner was 0.061 inches. The sensor face was placed at this position so that the gage block could be moved out of the way for cleaning. If the sensor was set to read 0.050 inches the gage block could not have been easily removed for cleaning purposes without dragging the sensor face across the gage block face. Various oils were injected into the test fixture to see the effects of liquids on the displacement readings. After each fluid was tested the fixture was cleaned and the sensor recalibrated for the next fluid test.

For the first test the sensor was calibrated to read a depth of 60.1 mils over the indented area of the sample. Dirty cutting fluid was added on the cutout area and the reading changed to 38.7 mils. The cutting fluid acts as a dielectric between the two plates of the capacitor effectively changing the dielectric constant and the sensor readings. The cutting fluid was found to be non-conductive. Figure 3-5 represents the test setup used for the oil bath tests.

Additional tests were run using a cutting fluid developed by Monroe Fluid Technology at a different depth for comparison purposes with the following results:

Dry:	80.0 mils
Wet:	40.5 mils

A similar test was run using a degreaser as the medium with the following results:

Dry:	80.0 mils
Wet:	74.0 mils

3.1.3 Test Results

The raw data for the bench testing of capacitance sensors are provided in Appendix III.

The plot of displacement versus error for the gage block setup is depicted in Figure 3-6. The X-axis is the error in mils (0.001 inches) and the Y-axis is the range of displacement for the sensor. The error is less than 0.001 inches over the complete range of the sensor. The capacitance sensor is very linear and exhibits a fast response time for each reading.

B&W did find that various fluids affect the displacement readings of the sensor (see table 3-1, Oil Comparisons, at the end of this chapter. The fluid changes the dielectric of the capacitance field therefore changing the displacement readings. All five of the fluids tested had an effect on the sensor readings. The sensor was waterproofed to protect the sensitive electronics inside the sensor. The unit was tested before and after waterproofing but when immersed in oil

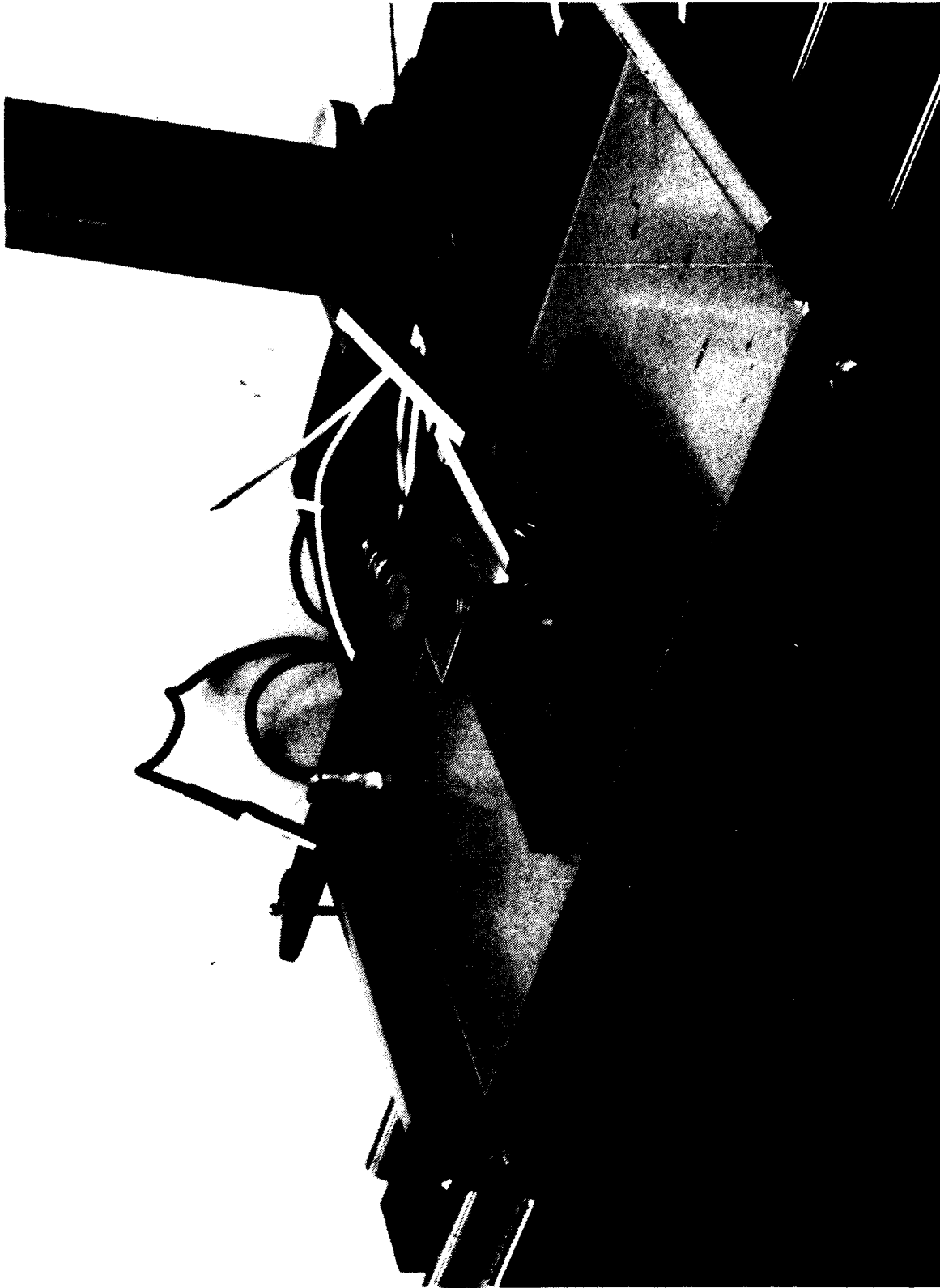


Figure 3-5, Capacitance Sensor Oil Bath

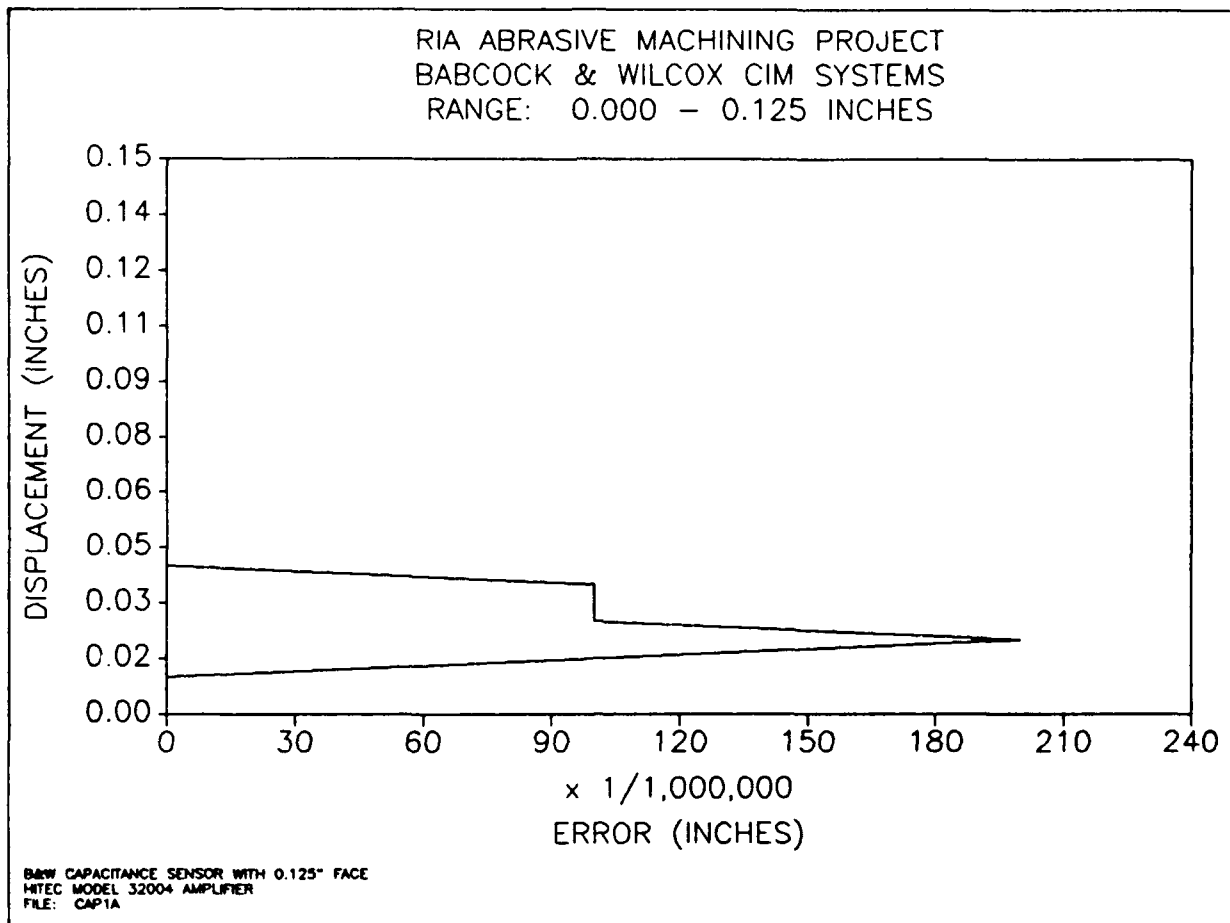


Figure 3-6, Plot of Capacitance Sensor Data

shorted out. This occurred even though the honing fluid was tested to be non-conductive. When the honing fluid entered the inside of the sensor face the sensitive electronics sensed a minimum distance due to the dielectric of the fluid.

3.1.4 Test Conclusions

Capacitance sensors cannot be used in an environment where the gap between the sensor and the target will be contaminated with fluids. As the thickness of the fluid varies the sensor readings change accordingly. An alternative is to either keep the area between the sensor face and the target completely dry or totally submerged within the fluid. In a constantly changing environment such as a honing operation there is always the possibility of contamination of the sensor readings by honing fluid. If it were possible to ensure that the sensors were always submerged, a lookup table could be setup for various fluid depths. However, as the diameter of the tube increases, the thickness of the fluid between the sensor and tubes inner wall increases thereby changing the dielectric of the capacitance sensor. This in effect increases the range of the sensor by making the sensor think it is closer to the object than it really is. The sensor range can be effectively increased by adding the proper dielectric between the sensor

face and the target material as documented in the previous tests. For a displacement of 60 mils the sensor readout was approximately 40 mils. There is a difference of 20 mils that is accounted for in the change in the dielectric constants. For a given displacement the sensor range could be increased by 20 mils depending on the thickness of the fluid. Therefore, as the fluid thickness varies capacitance sensors would not be well suited for measuring the inside diameter of a tube that is being honed.

If the cutting area is flooded with fluid the effective range of the sensor is increased by a minimum of 20 mils due to the difference in dielectric constants. One possible alternative to the capacitance sensor is the inductive proximity (eddy current) sensor. The inductive proximity sensor is suited for operation in fluid environments (cutting fluid) as long as there is not an extreme number of cutting fines within the fluid.

3.2 Inductive (Eddy Current) Sensor Testing

The selection of a sensor to replace the capacitance sensor entailed locating a sensor that would fit inside a tube that was being honed. An inductive proximity sensor with an analog output proportional to the distance between the sensor face and the target was chosen as a test subject.

The principle operation of the eddy current device is an AC current flowing in a coil causes the field of one winding to add to the field of the next winding in the sensor head. These fields will pulsate causing an AC electromagnetic field to be generated in the area surrounding the coil. As the sensor is placed in the proximity of a metallic target, a current flow is induced just under the surface of the target. This creates a circular pattern known as an eddy current. This induced current produces a second magnetic field that opposes the applied first magnetic field. This in turn changes the impedance of the coil generating the original electromagnetic field. Through the use of signal conditioning electronics, these changes are analyzed and converted into displacement readings.

The measuring system consists of a sensing coil in a section or leg of a balanced bridge network. As the sensor moves closer to the target, the current flow increases in the target and the losses increase in the coil bridge network. Figure 3-7 is a representation of the eddy current measuring system. As the sensor head moves away from the target the current in the target decreases and the losses in the bridge network decrease. The bridge is calibrated such that minute changes in the impedance of the network are detected and converted into usable signals. The output of the bridge is amplified, demodulated, and converted to an analog output signal directly proportional to the distance between the target and the sensor face.

B&W evaluated two different types of inductive proximity sensors. An inductive sensor with a range of 0.000 to 0.200 inches was chosen from Keyence with an analog output from the signal conditioner of 0.0 to 5.0 volts. A second inductive sensor with a range of 0.020 to 0.080 inches was chosen from Omron with an analog output of 4-20 milliamperes for testing purposes. A third pair of sensors was purchased from Omron with a range of 0.040 to 0.200 inches for the actual testing on the honing machine itself. The sensors were manufactured with the following specifications:

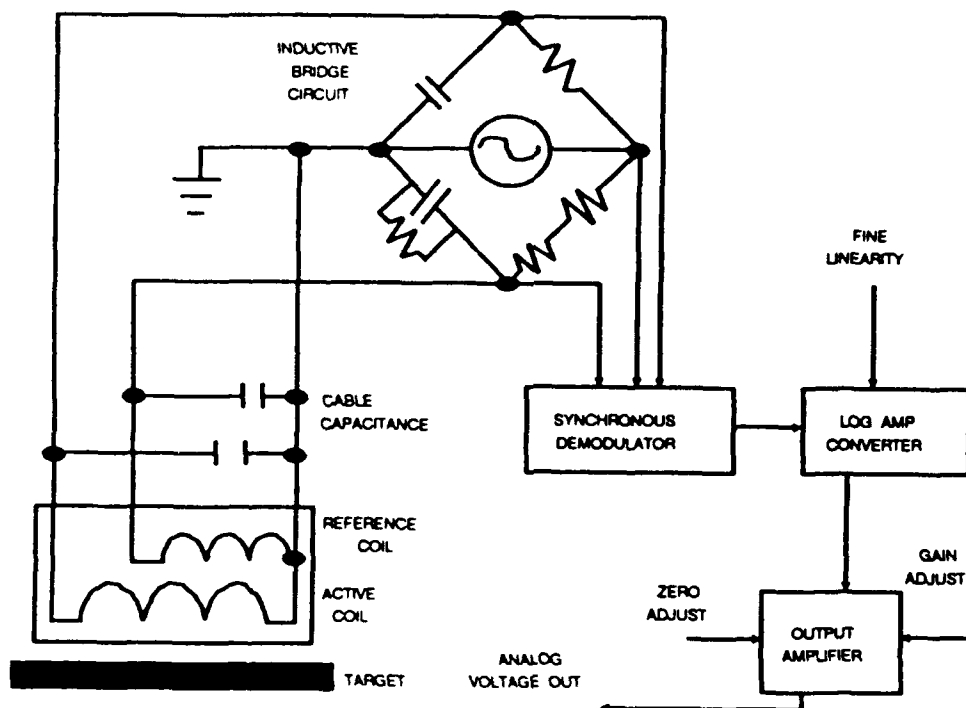


Figure 3-7, Eddy Current Sensor Schematic

Omron special purpose proximity sensor
 Threaded cylindrical inductive sensor with separate amplifier
 Shielded sensor type
 M18 size
 Nominal detecting distance: 1 to 5 mm
 0.040 - 0.200 inches
 E2CA-X5A-5M
 5 meter cable
 Detectable object type: Metallic objects
 Effective maximum detecting distance: 5 mm (0.200 in)
 Usable detecting range: 1 to 5 mm
 0.040 to 0.200 inches
 Standard target size (mild steel, L x W x H)
 18 x 18 x 1 mm
 0.71 x 0.71 x 0.04 in
 Frequency Response: 5 KHz
 Housing material: Nickel-plated brass
 Sensing face material: Plastic, acrylonitoyl butadiene styrene
 Cable sheath material: Plastic, polyethylene
 Operating range: -25 to 70 degrees Celsius
 Vibration: 10 to 55 Hz, 1.5 mm (0.06 in) double amplitude
 Shock: 50 G's

Omron E2CA-X2A

Size: M12

Nominal detecting distance: 0.4 to 2.0 mm (0.02 to 0.08 in)

Maximum detecting distance: 2 mm (0.08 in)

Standard target size: 12 x 12 x 1 mm

0.47 x 0.47 x 0.04 in

Frequency response: 10 KHz

Omron E2CA-AN-4D and E2CA-AN-4E amplifier

Supply voltage: 120 volts AC

Output range: 4 to 20 mA

Resolution: 0.05% to full scale

Linearity: +/- 1.5% of full scale

Frequency response: AN-4D 10 KHz

AN-4E 5 KHz

Keyence analog displacement sensor

Sensor: AH-416

Controller: AS-440-05

Measuring range: 0 to 5 mm (0 to 0.200 inches)

Signal conditioner output: 0 to 5 volts

Output impedance: 100 Ohms

Resolution: 0.1% of full scale

Linearity: 1% of full scale

Frequency Response: 3.3 KHz

Hewlett Packard (HP) 3468 A

Autoranging Digital Multimeter (DMM)

Resolution 5 1/2 digits

DC Volts	Resolution	Accuracy
----------	------------	----------

0.3	1 microvolt	+/- 0.002%
-----	-------------	------------

3.0	10 microvolts	+/- 0.0018%
-----	---------------	-------------

30.0	100 microvolts	+/- 0.02%
------	----------------	-----------

DC Current Resolution Accuracy

3.0	10 microampere	+/- 1.17%
-----	----------------	-----------

3.2.1 Test Apparatus

The eddy current sensors were first checked for linearity, repeatability, and accuracy in a laboratory environment. The eddy current sensors were mounted in a test fixture with the sensor facing a steel target as shown in Figures 3-8 and 3-9. A calibrated gage block with an adjustable micrometer head was utilized to check the sensor in its ability to measure dimensional attributes. The Hewlett Packard (HP) Digital Multimeter (DMM) was connected to the output of the signal conditioner for the Omron and Keyence sensors. For the testing of the Omron sensor the meter was set to measure amperage for the 4 - 20 milliampere current flow from the signal conditioners. For the testing of the Keyence sensor the meter was set to the autoranging (30.0 volt) full scale range.



Figure 3-8, Keyence Sensor Gage Setup

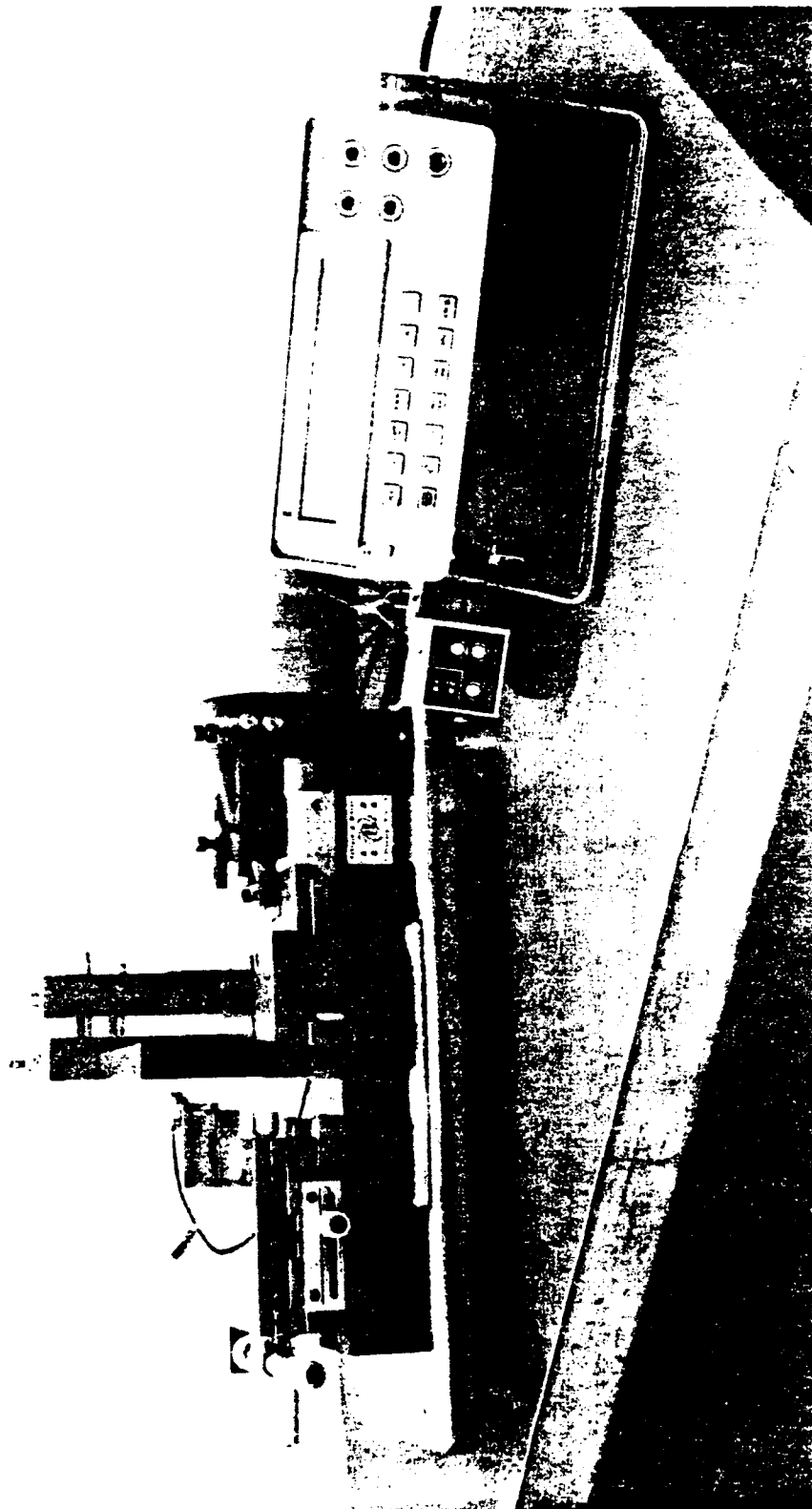


Figure 3-9, Omron Sensor Gage Setup

After the sensors and electronics were calibrated, the sensors were placed in a second test fixture as depicted in Figures 3-10 and 3-11. The sensor was placed above a metal fixture with a calibrated depth from the edge of 0.050 inches. After the sensor was positioned to read 0.050 inches a series of oil tests were run with the eddy current sensor.

3.2.2 Test Descriptions

The eddy current sensor was placed against the gage block to obtain a zero offset and set the micrometer head to zero. The gage block was moved away from the sensor in 0.001 inch increments to determine the linearity of the sensor over a range of 0.000 to 0.200 inches. A high tension spring was attached to the gage block and micrometer head to prevent any leadscrew backlash from affecting the readings when the gage block was moved both toward and away from the sensor (refer to Figure 3-2). Readings were taken at 0.000 up to 0.200 inches and 0.200 to 0.000 inches in the opposite direction to check the repeatability of the sensor readings.

Readings were taken on both sensors to determine the accuracy and repeatability of the sensor system. The sensors were checked over a full range to determine if any errors were induced at the limits of the sensor travel.

The Omron sensors with the range of 0.040 - 0.200 inches exhibited a time lag between when the gage block was set to 0.200 inches and when the sensor readout displayed 0.020 amps. As the gage block approached 0.200 inches the sensor reading would lag behind up to five seconds later. This may have been due to faulty signal conditioners that were not fast enough to accommodate changes in the gage block readings. For a real-time data acquisition system this time lag cannot be tolerated due to the need to take sensor readings on the fly. This problem occurred in the upper range (0.150 - 0.200 inch) of the sensor. The problem was not able to be corrected before the actual sensor testing was started so the sensor range for the production system was set to 0.050 - 0.150 inches. In this range the sensor readings did not lag behind the gage block readings which made this system usable for a real time inspection system.

3.2.3 Test Results

The raw data for the eddy current (inductive) sensors bench testing are provided in Appendix IV.

The Keyence sensor exhibited good accuracy (0.001 inches) and repeatability over the range of 0.000-0.200 inches. This error is not as small as the error of the capacitance sensor (0.0002 inches). The error between the sensor reading and the gage block reading was repeatable and never deviated more than 0.001 inches in any one direction. The plot of error versus distance for the sensors is shown in Figures 3-12 to 3-19. The fluids encountered by the sensor had no effect on the readings. Metal filings in the dirty honing fluid did not affect the sensor output.

The Omron sensor (Figures 3-16 & 3-17) with a range of 0.020 - 0.080 inches exhibited excellent accuracy and repeatability over the short range. The observed error was no more than 0.0005 inches over the entire range for the two sensitivities of the signal conditioner. This sensor was one third the price of the Keyence sensor and had a better overall accuracy. This price difference was one of the major factors in deciding to use an Omron sensor for actual hone retrofitting.

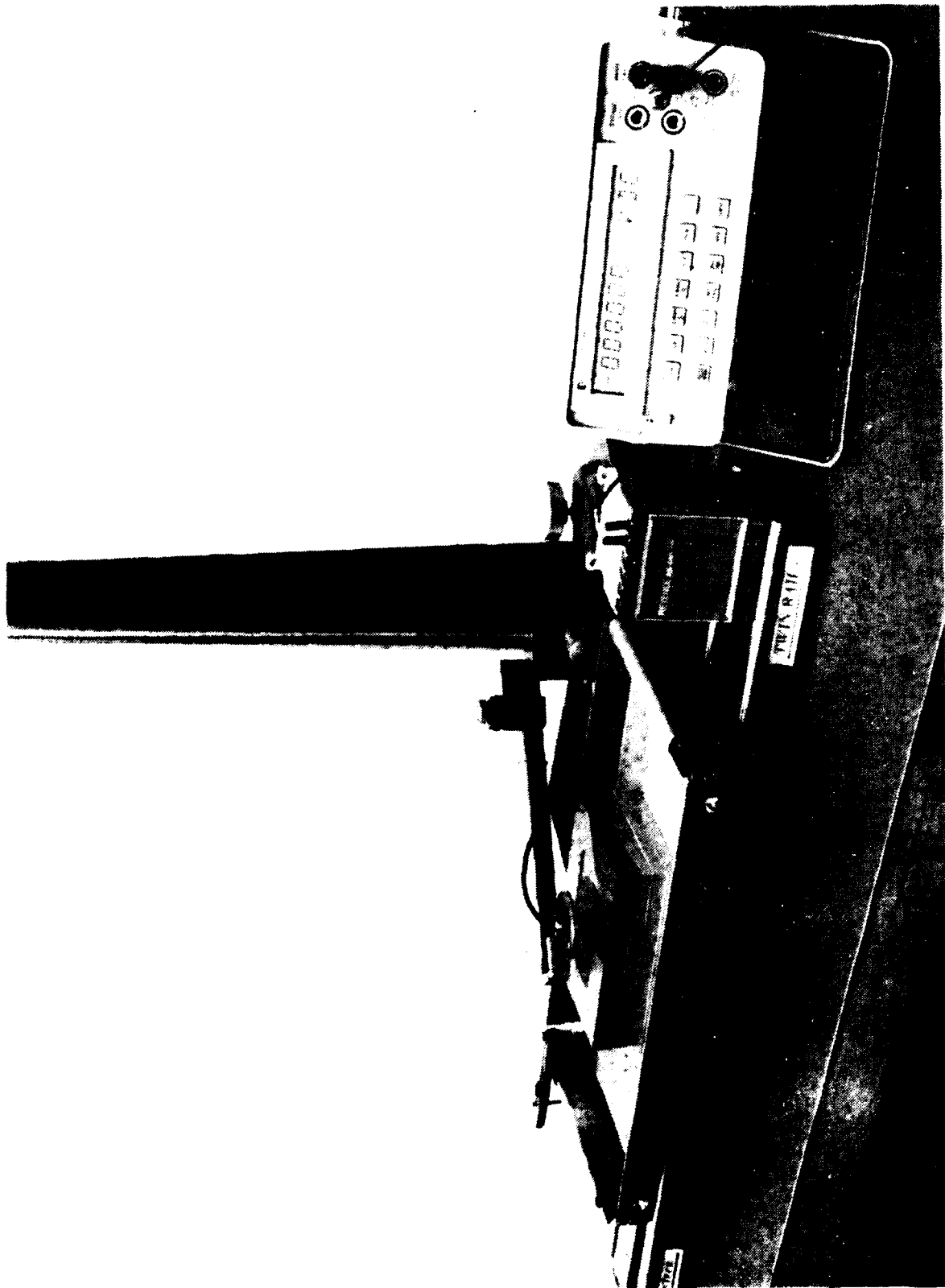


Figure 3-10, Keyence Sensor Oil Setup

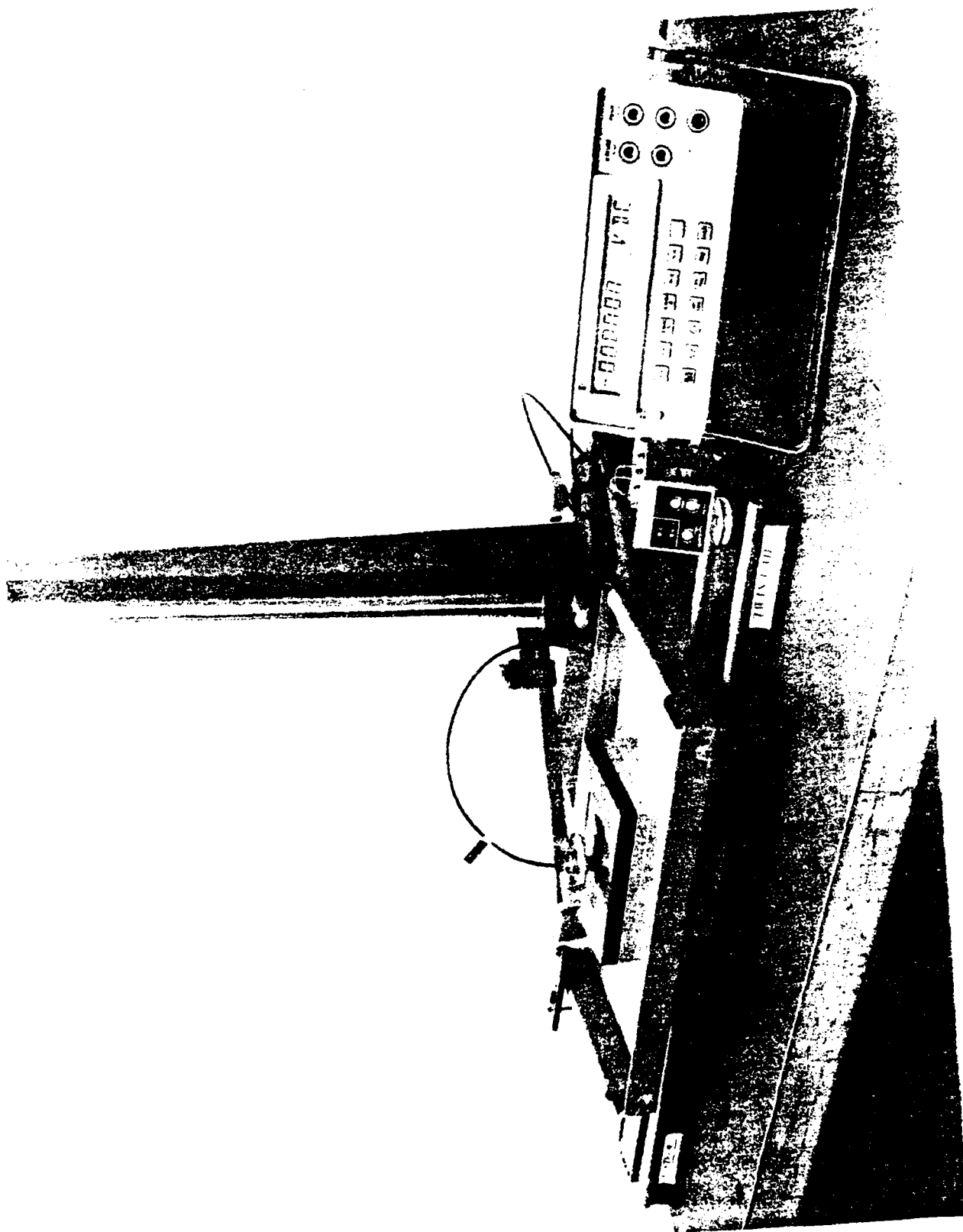


Figure 3-11, Omron Sensor Oil Setup

The Omron sensor (Figures 3-18 & 3-19) with a range of 0.04 - 0.20 inches was chosen for the actual machine testing. This decision proved to be time consuming due to the calibration problems encountered when the sensor was placed in the gage block. The sensor had a tendency to lag behind in the readings at the upper end of the range. As the sensor approached a gap of 0.200 inches the sensor readings would lag behind by five seconds before reading a displacement of 0.200 inches. This should not have happened since the frequency response of the sensors was 5 KHz. The first set of sensors was returned to Omron for replacement. The second set of sensors exhibited the same problems. The magnitude of error was as high as 0.004 inches at midrange, but repeatable (less than .0001 inches) over the entire range. Error was defined as the deviation from a theoretical straight line plot of the data. To compensate for this deviation from a linear output, a lookup table was established with actual versus theoretical data added to the table. This way the actual displacement could be detected with an accuracy of 0.0001 inches.

This error was very different from the original sensor tested in the lab which had an error on the order of 0.0005 inches. Omron was contacted about the problems but no answer has yet to be forthcoming.

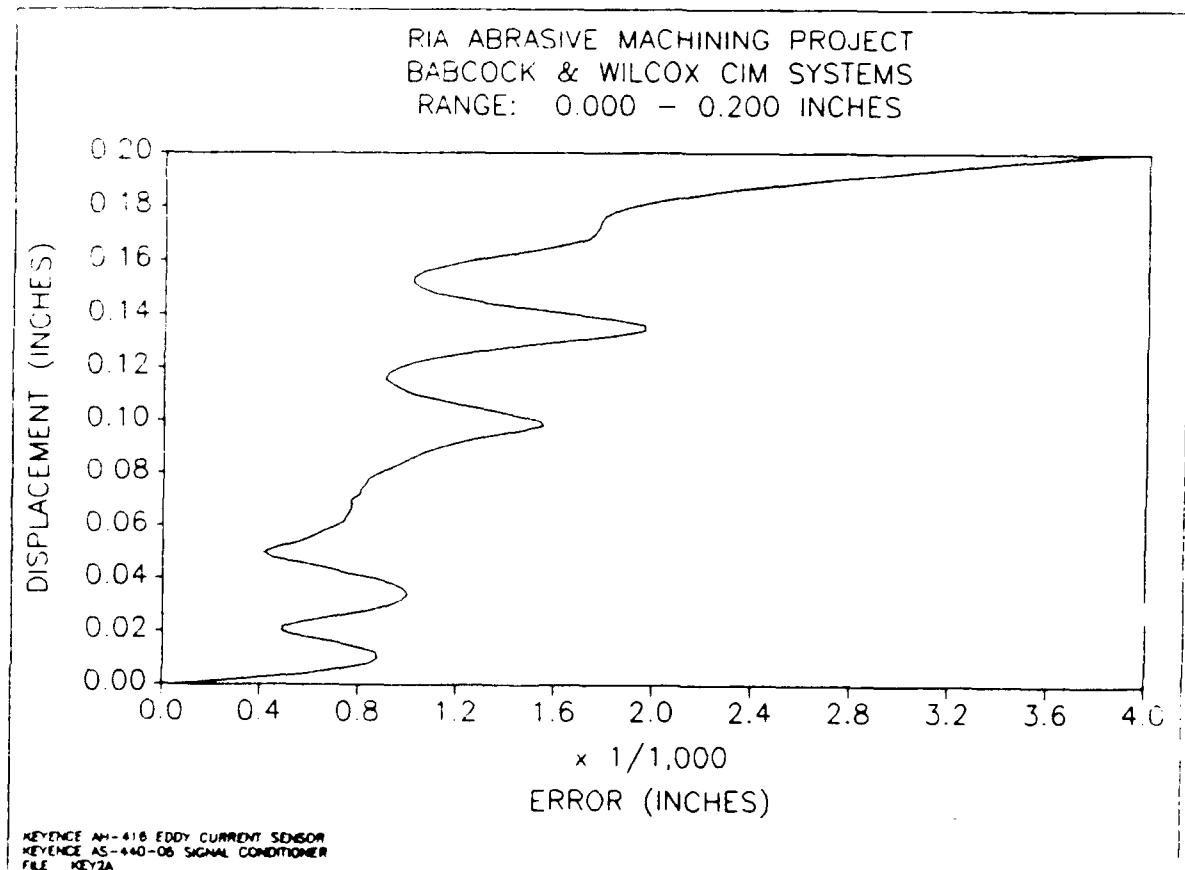


Figure 3-12, Keyence Sensor Errors

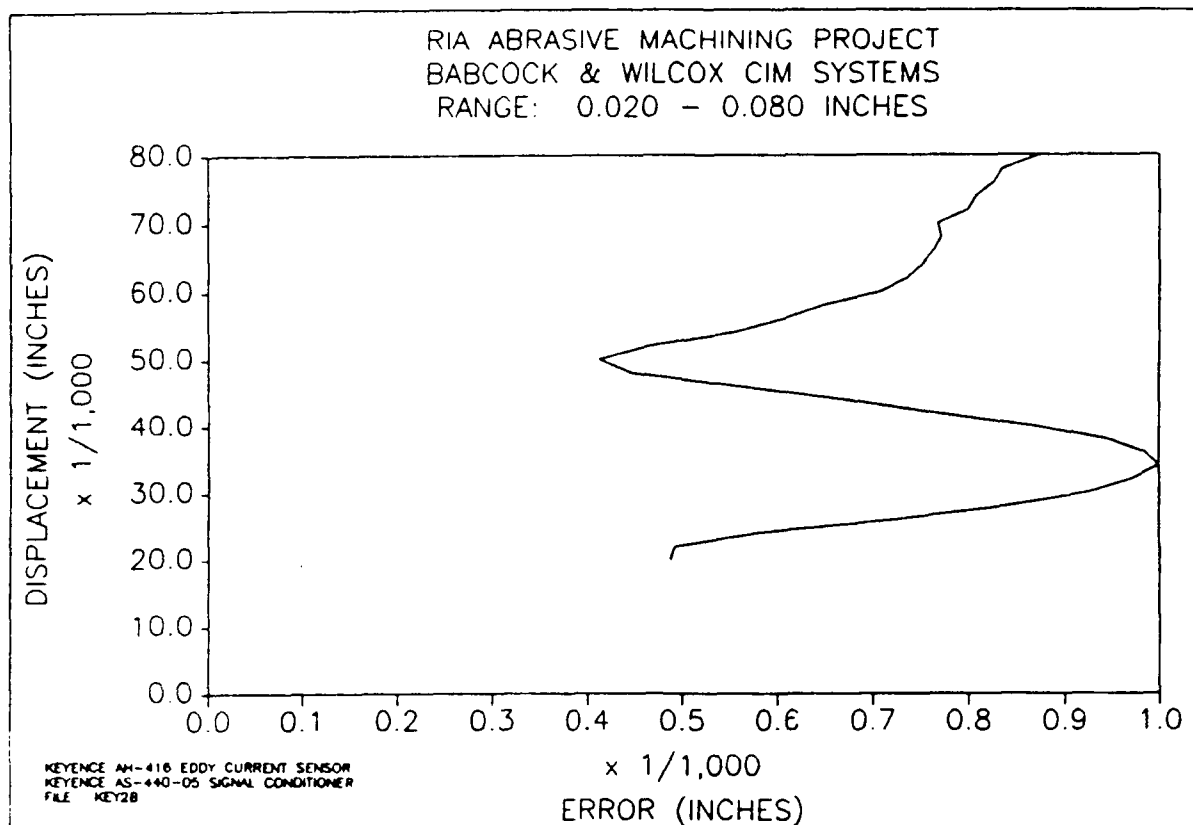


Figure 3-13, Keyence Sensor Errors

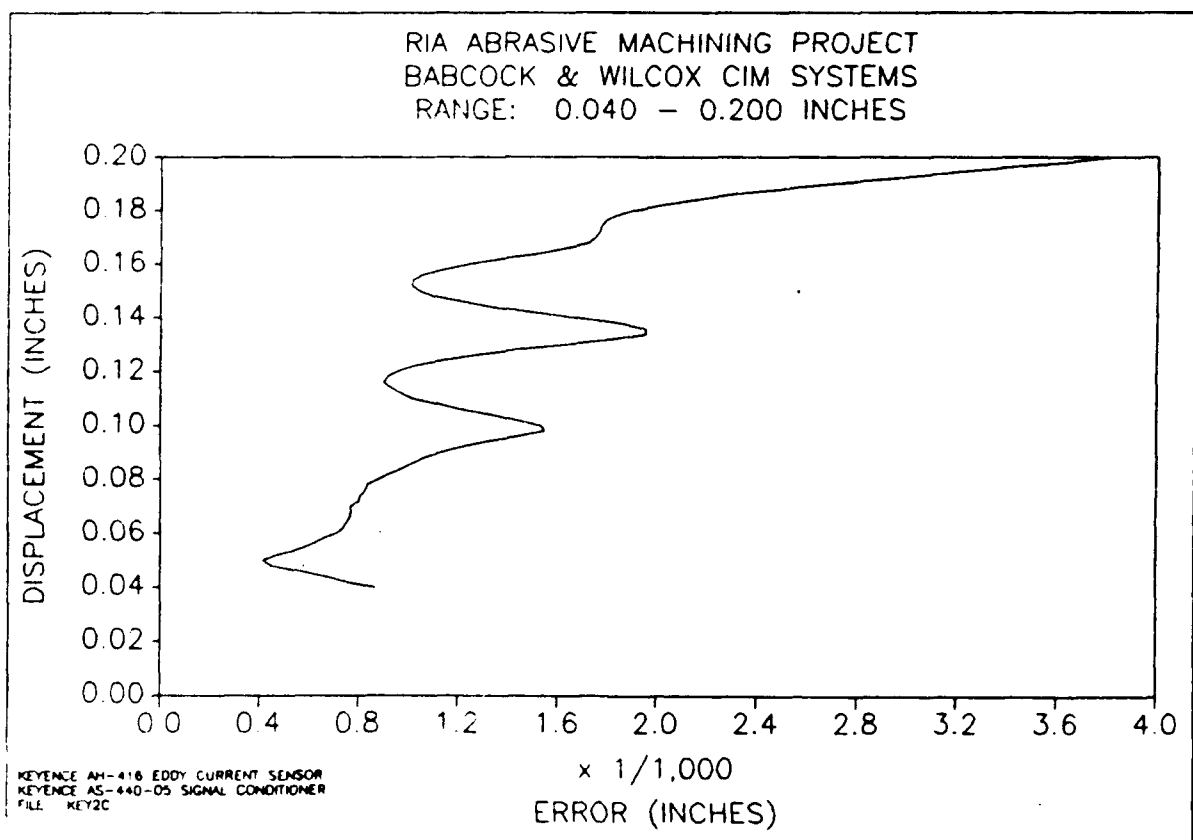


Figure 3-14, Keyence Sensor Errors

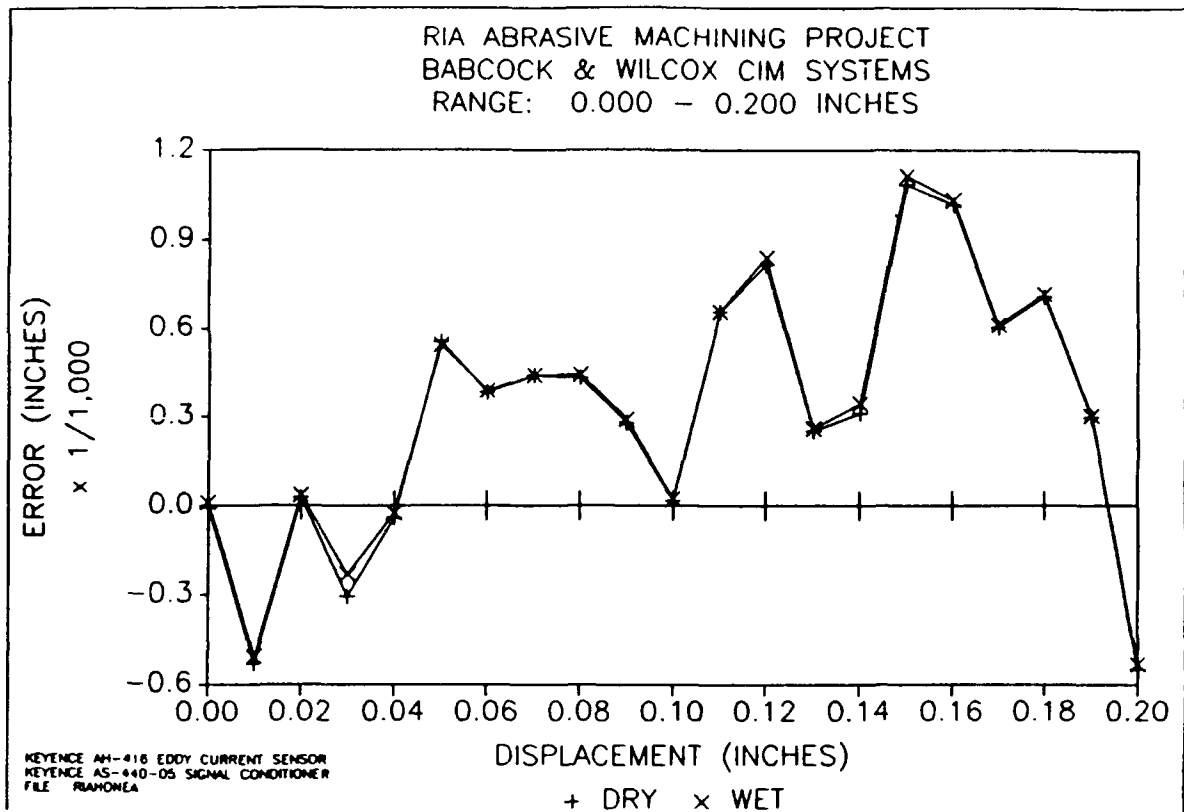


Figure 3-15, Keyence Sensor Data Wet/Dry

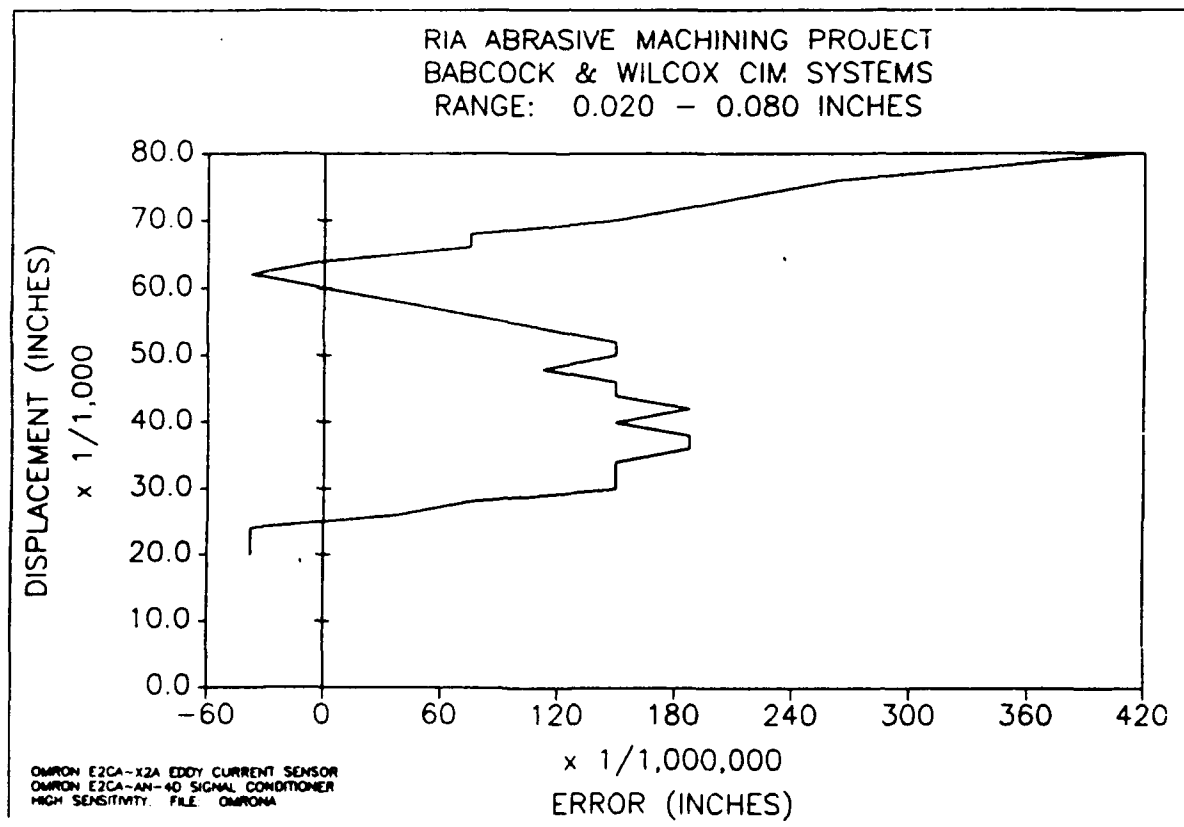
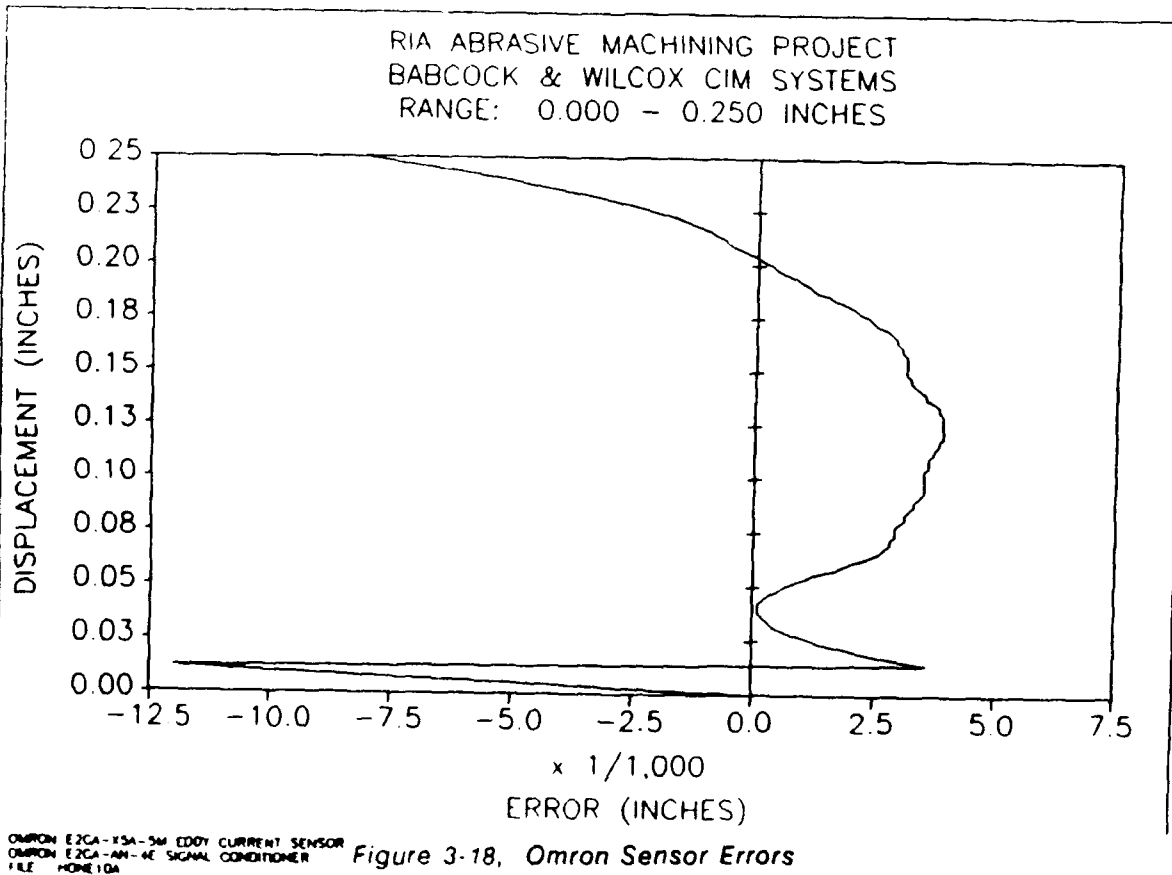
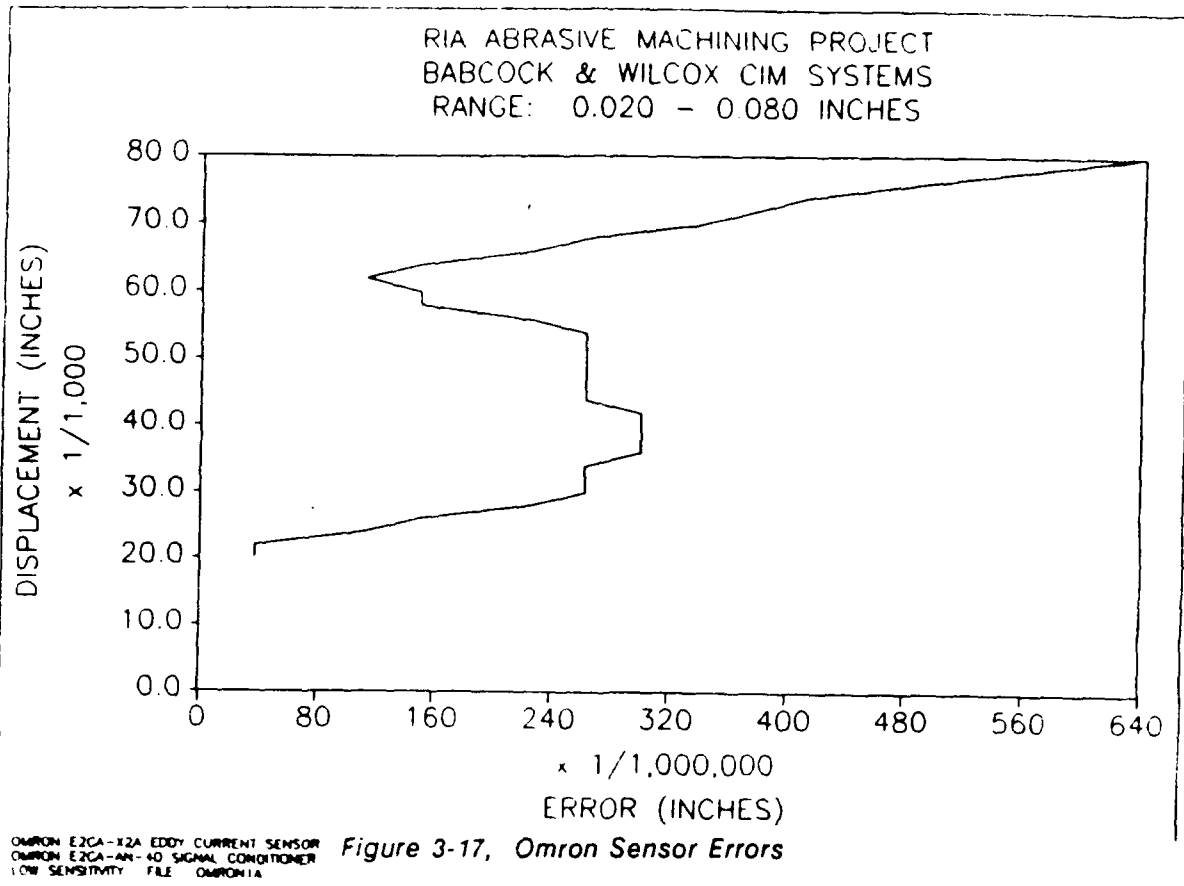


Figure 3-16, Omron Sensor Errors



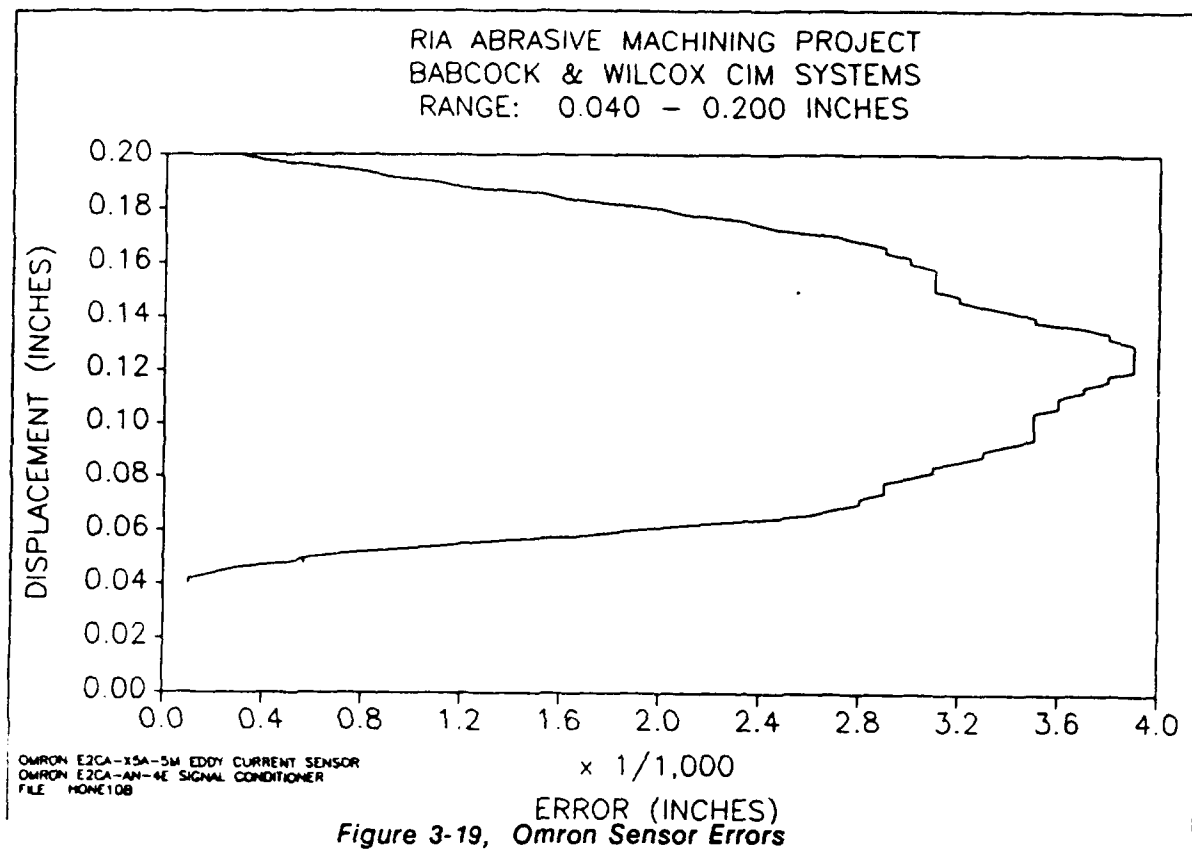


Figure 3-19, Omron Sensor Errors

3.2.4 Test Conclusions

The eddy current sensors performed well in the series of oil bath tests. The readings of the sensor were not affected by any of the fluids tested. Inductive proximity sensors were the least affected of all sensor types tested when exposed to dirt, oil, smoke and a general industrial environment. The only error that could possibly occur is when enough metal fillings get caught between the sensor face and the steel target to affect the sensor reading. The metal buildup would have to be at least on the order of 0.005 inches thick to have even a negligible effect on the sensor readings. The target thickness for steel should be at least 0.005 inches thick (three skin depths) to avoid variations due to temperature changes on the part surface.

The Keyence sensor was usable for the testing purposes but costly (\$1000 per sensor/signal conditioner). The Omron sensors cost approximately \$350 per sensor/signal conditioner combination. Therefore the logical approach would be to purchase the Omron sensors at a definite cost savings. The time lag problem with the Omron sensor was not detected on the initial test unit but appeared on the two units purchased for the hone retrofit package. Had this problem been detected in the initial testing phase, the Keyence sensor would have been purchased for the hone retrofit package. The Keyence sensor had one definite advantage over the Omron sensor in that the signal conditioner output was 0.0 to 5.0 volts. The Keyence sensor could have been ordered with a voltage output range from the signal conditioner of 0.0 to 10.0 volts. This voltage range would be directly compatible with the 0.0 to 10.0 volt range of the data acquisition board allowing a 2.4 millivolt per bit conversion rate resulting in a better accuracy of the system. The Omron sensor was limited to 4 - 20 milliamperes and was converted to 1 - 5 volts through the use of a 250 Ohm resistor placed across the signal leads. This setup only allowed half of the data acquisition boards range to be utilized. A 2.4 millivolt

per bit accuracy converts to 0.0001 inches. To fully utilize the range a 0 to 5 volt scale with 12 bits of resolution would yield 0.00005 inches of resolution for the system.

Cutting Fluid	Conditions	Sensor Readout (inches)		
		#1	#2	#3
=====				
Rock Island	Dry	0.03916	0.03525	0.05000
Sunnen	Damp	0.03916	0.03525	0.03270
	Immersed	0.03916	0.03525	0.01290

Rock Island	Dry	0.03915	0.03518	0.05000
Hangsterfer	Damp	0.03916	0.03518	0.03900
	Immersed	0.03916	0.03518	0.01540

General Hone	Dry	0.03917	0.03525	0.05000
Clean Fluid	Damp	0.03921	0.03525	0.03400
	Immersed	0.03921	0.03525	0.01120

General Hone	Dry	0.03916	0.03525	0.05000
Dirty Fluid	Damp	0.03918	0.03525	0.03300
	Immersed	0.03918	0.03525	0.01110

Cool Tool II	Dry	0.03917	0.03525	0.05000
	Damp	0.03918	0.03525	0.03000
	Immersed	0.03918	0.03525	0.00050
=====				
Sensor #1	Keyence Eddy Current			
Sensor #2	Omron Eddy Current			
Sensor #3	Babcock & Wilcox Capacitance			

Table 3-1, Oil Comparisons

4.0 MACHINE TESTING - DIMENSIONAL INSPECTION

Once the eddy current sensors were determined to be the most appropriate sensor technology for the honing environment, a study/demonstration system was developed on an actual honing machine. The study/demonstration system duplicated the critical features of the system envisioned for adaptation to a RIA production machine (within the constraints of not making permanent modifications to the hone tooling) to evaluate the capabilities of the in-process inspection concept. To accomplish this objective, the following requirements were imposed on the demonstration system:

- Utilize a representative honing machine with respect to size, construction, feed rates and turning speed, and control parameters to reveal any unforeseen problems which might occur on a RIA production retrofitted machine.
- Position the sensors as they would be on a production system, to ensure that any errors induced by the fixturing method would be exposed on the study/demonstration system.

Other requirements were considered but established as non-critical for the demonstration/study, and therefore it was decided not to simulate them on the demonstration system. These additional considerations were as follows:

- On a "production machine" the sensor leads must be wired so as not to interfere with the machine operations or the operator; however for the purpose of this demonstration this was deemed as non-critical.
- Closed-loop control is the ultimate goal; however the objective of this study is to demonstrate that sensor(s) can be used to acquire acceptable data sufficient to accurately evaluate bore attributes. Therefore, the system was designed in an open-loop manner for this phase of the project.

4.1 Mechanical System Description

The mechanical system for the demonstration/study required the rental of a honing machine and the appropriate tooling. The honing machine and tooling were rented from General Hone Corporation located in Ashland, Ohio. Testing materials and expendables were also required. The test workpieces were supplied by the RIA. The expendables included honing oil and honing stones which were purchased from Hangsterfer's Laboratories and General Hone Corporation respectively. In order to hone the RIA parts, custom fixturing blocks were designed and fabricated by B&W. To fixture the sensors and run the wire leads out of the bore, custom sensor fixturing was designed and fabricated by B&W. (Refer to Figures 4-1 for the remainder of this section.)

4.1.1 Honing Machine

The honing machine, rented from General Hone corporation, was a #3 Barnes horizontal hone shown in Figure 4-2.

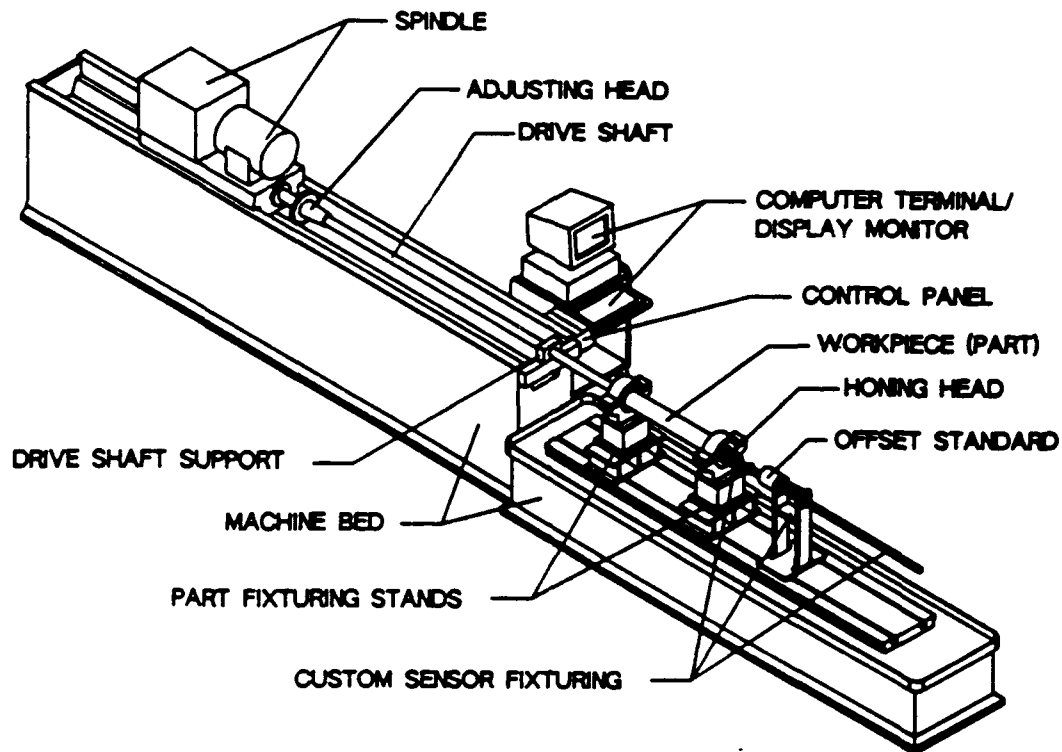


Figure 4-1, Demonstration/Study Machine

The hone machine data are as follows:

Machine Make	Barnes
Machine Model	#3
Machine Type	Horizontal
Machine Serial	8482
I.D. Capacity	1/2" - 4"
Stroke Capacity	9"
Swing	40"
H.P. Spindle Motor	7-1/2 (1740 RPM)
H.P. Hydraulic Motor	7-1/2 (1750 RPM)
H.P. Coolant Motor	3/4 (1750 RPM)
Spindle Speed - Via Pickoff Gears	136 RPM
Spindle Nose	#4 M.T.
Coolant System	In Base (125 Gal Cap)
Height	5'
Width	5'
Depth/Length	28'
Weight	13,000#
Wired	440 V, 3 Phase, 60 Hz
Year	1950



Figure 4-2, #3 Barnes Horizontal Honing Machine

Features:

1. Hydraulic Tool Feed - Linear thrust
2. Trip Dog Type Stroke Adjustment
3. Reciprocation Speed 0-70 Feet/Min
4. (2) Steady Rest Type Fixtures
5. (1) Stationary Driveshaft Support
6. Short Stroke
7. Work Base Length - 12'

4.1.2 Hone Tooling

The honing tooling, also rented from General Hone Corporation, included three major items: the honing head, the drive shaft and the adjusting head.

The honing head, used to hold and expand the stones against the bore, was a standard "push cone flanged type honing tool" (refer to Appendix I). Pertinent data are as follows:

Diameter: 3-1/2" nominal

Shell No: 6-8054-3

Stone Holder No.'s: 12,14 & 16

The drive shaft was a "push feed type drive shaft". Pertinent data are as follows:

Type: 'P'

Drive Shank: 2.5" O.D.

The adjusting head, used to adjust the stones against the part surfaces prior to expanding via hydraulic pressure, was a "manual (palm wheel) combination head". Pertinent data are as follows:

Model: 4C

4.1.3 Test Materials

Two test pieces were provided by RIA. The pertinent data are as follows:

Material	4130/4140 Stainless steel
O.D.	4.500i nches
I.D.	3.540-3.625 inches
Length	30 inches

4.1.4 Expendables

The expendable equipment included honing stones and honing oil. Two types of honing stones were purchased for roughing and finishing. Two sets (10 each) of each stone type were obtained. The pertinent data for the honing stones are as follows:

Manufacturer	General Hone Corp., Ashland Ohio
Size	3/8x3/8 x 8 inches
Part Numbers - Roughing	A150 J6 V3S 6-8054-S
- Finishing	A400 J VG2#10 6-8054-S ARC
Grit Size - Roughing	150
- Finishing	450

B&W purchased 75 gallons of #67S cutting oil from Hangsterfer's Laboratories, Mantua NJ, to fill the machine base to adequately submerge the pump intake orifice. This honing oil is currently one of two oils used at RIA. The content is 90% Mineral Oils, 9% Fats and 1% Sulphur.

4.1.5 Part Fixturing

Four nylon bushing blocks with leather inserts were designed and fabricated to accommodate honing the RIA supplied parts in the two steady rest part fixturing stands. They are shown as items 3 and 7 on B&W drawing LT-2880 provided in Appendix I.

4.1.6 Sensor Fixturing

As previously discussed in section 2.4, it was determined that the sensors should be fixtured to the honing head body in lieu of the machine spindle via a mandrel. For the demonstration/study machine B&W chose to fixture the sensors to the end of the honing head (refer to Figures 4-3 and 4-4), to simulate the anticipated production machine concept without modifying the rented honing head as would be done on production system machine. Additionally, in lieu of incorporating the sensor wire leads within the rented tooling by modification, they were brought out from the aft end of the bore via the custom fixturing. The custom fixturing design drawings LT-2880 are provided in Appendix I. The pertinent sensor fixturing features were as follows:

- The sensors were positioned opposed to each other in a custom built holder which was fixtured to the honing head by five set screws.
- A slip ring was used to translate the signals from the rotating sensors to the computer.
- The slip ring was attached to the sensor holder via a flexible coupling to accommodate any misalignment due to the typical method of part fixturing for honing.
- The slip ring was attached to a square tube which allowed for translation without rotation by sliding in the square nylon bushings of the fixture stand.
- The square tube provided a method for bringing the wires out of the bore without resting in the bore and getting caught in the hone tooling. The wires were fed through the sensor holder and flexible coupling to the rotating portion of the slip ring, and from the non-rotating portion of the slip ring out through the square tube.

After extensive preliminary testing and readjustment of the equipment, problems developed with the slip ring. The rotating shaft of the slip ring separated from the non-rotating portion. The slip ring used was small in size for the purpose of fitting within the bore of the test pieces when fixtured to the honing head. The small design did not include any inherent mechanical stress relief features for misalignment of the fixturing. The misalignment caused bending stresses beyond the limits of the slip ring (once the equipment was in it's new position) and therefore failed. B&W corrected the problem by modifying the fixturing to relieve the bending stresses from acting on the slip ring. This was done by extending the square tube frame around the slip ring to the flexible coupling such that the frame, not the slip ring, would absorb the bending stresses (refer to Figure 4-5). The modified design drawing CIM-A31-1 is also provided in Appendix I.

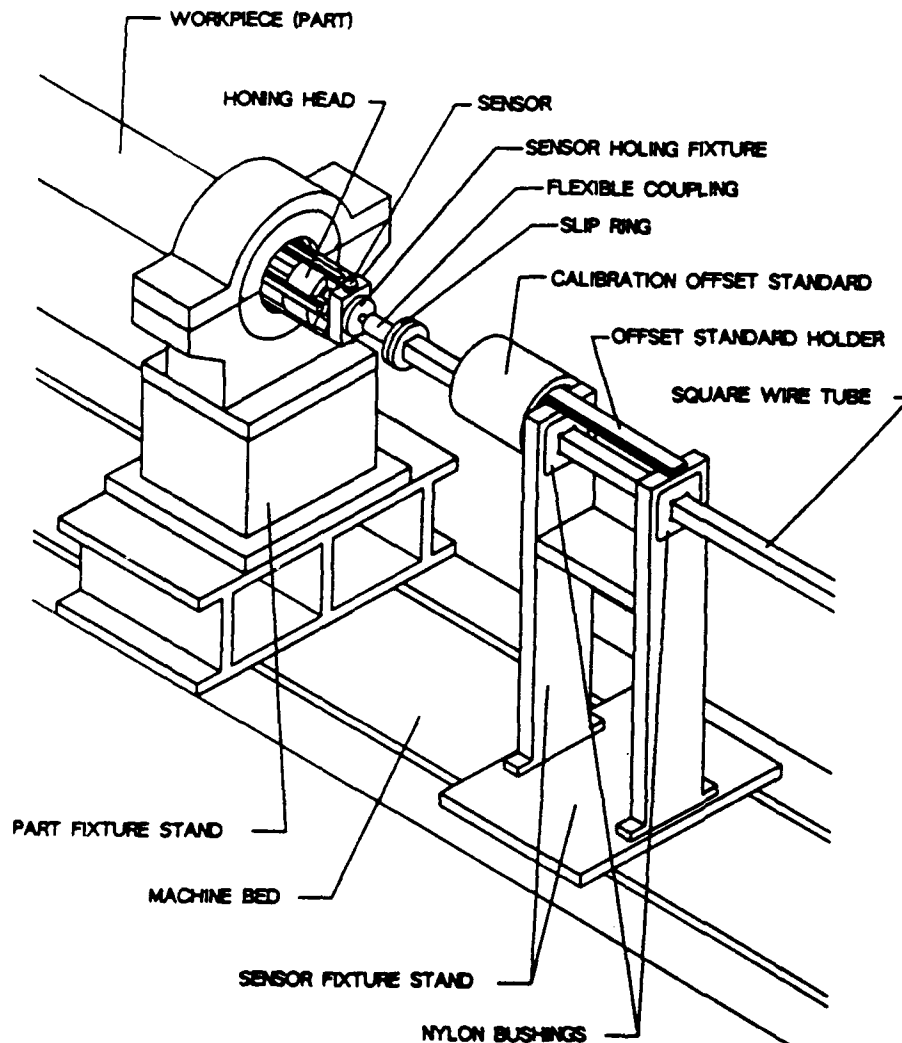


Figure 4-3, Custom Sensor Fixturing

4.2 Data Acquisition System Description

B&W assembled a data acquisition system in order to record data in real time from the eddy current sensors. An IBM-AT compatible computer was utilized along with a 12 bit data acquisition board to transfer the sensor signals from the signal conditioner to the computer software. Thermistors were attached to both the tube being honed and the calibration standard to record any temperature deviations in order to calculate dimensional changes in the part due to temperature. A slip ring was incorporated into the sensor head fixture to allow the electrical signals to be brought out from the rotating head to the data acquisition system.

4.2.1 Equipment

The main board for the data acquisition system consisted of an ADAC 5500-MF 12 bit 8 channel board mounted in an IBM-AT compatible computer. The computer was manufactured by the American Research Corporation (ARC) and was equipped with an INTEL 80286 processor running at 12 MHz. An interface box was attached to the computer to receive the 4-20 milliampere signals from the signal conditioners and convert these signals to 1-5 Volt signals that the data acquisition board could accommodate. A 250 Ohm resistor was chosen to



Figure 4-4, Custom Sensor Fixturing



Figure 4-5, Sensor Fixturing Modifications

convert the current to voltage because the maximum voltage the signal conditioner could supply was 6 volts. This resulted in a conversion rate of 0.0001 inches per bit count.

Inductive Sensor Electronics:

The sensors were mounted in the fixture attached to the honing head by five allen head screws. This fixture placed the sensors 180 degrees apart to measure the inside diameter of the tube. The sensors were set with the signal conditioners set to three and five meter cable lengths even though the sensors both had five meter cable lengths. This could not be explained but the sensors remained stable in this configuration whereas the sensor output was unstable when both signal conditioners were set to the 5 meter cable length. This phenomenon was later determined to be crosstalk between the two sensors. The separate oscillators in each of the signal conditioners produced a beat frequency between the two sensors. This problem could not be corrected because the oscillators could not be tied to a reference oscillator in this signal conditioner configuration. A terminal block was mounted directly on the fixture block as an interface between the sensor cabling and the slip ring wires.

The inductive proximity sensor signals were routed to the Omron signal conditioners to convert the eddy current signal to a 4-20 milliampere signal. The signal conditioner is a stand alone unit with 120 Volts AC input for system power and lead connection for a raw signal input and a conditioned signal output. There are upper and lower limit settings to adjust the 4 milliampere and 20 milliampere setpoints. This control adjusts the linearity curve of the system but does not adjust the offset of the system.

The sensor cabling was routed through a Litton Poly-Scientific instrumentation slip ring with a total of 12 conductors. This is a plastic slip ring with metal bearings. The brushes are made from precious metals to ensure that noise is not added to the system through the rotation of the slip ring. This slip ring is not intended to be loaded with any forces from the shaft or the mounting brackets. The mounting fixture used in this setup did place a stress on the slip ring and two slip rings were destroyed due to this design.

Temperature Sensor Electronics:

B&W selected to do external temperature measurements with a handheld Omega temperature probe. The probe was attached to the exterior of the tube as it was being honed to determine if the tube was heated due to the honing operation itself. The probe was also placed in the path of fluid exiting the hone to determine if the honing operation heated the interior of the tube during operations. A temperature rise was detected but an accurate correlation could not be determined due to the slow response time of the probe. The probe tip could not be effectively placed against tube surface to get an accurate measurement. The temperature probe has a response time on the order of one minute or longer and a resolution of one degree Fahrenheit. For fast readings a Thermistor or similar fast sensor would have to be embedded in the material itself to check for heat transfer between the hone and the target material.

B&W ran an additional test with two Thermistor probes manufactured by Yellow Springs International (YSI) connected to a Hewlett Packard 3467A data logging multimeter with separate temperature inputs. The display switched back and forth between the two sensor readings so that both temperatures could be monitored. This concept of temperature measurements entailed mounting one sensor on the outside of the tube and mounting the other sensor on the calibration standard. The temperature difference between the tube being honed

and room temperature was used to determine the amount of expansion for the tube due to a temperature increase. This data was correlated to the sensor data and a correction factor applied to normalize the data to a standard temperature. This technique could be very useful for outgoing dimensional inspection of the tubes.

The Hewlett Packard 3467A data logging multimeter with 4 1/2 digits of resolution proved to be more than adequate for the display and recording of the temperature measurements. The meter sampled each of the channels two times a second and displayed the appropriate readings to 0.1 degrees of resolution. The Thermistors purchased from YSI were excellent for this application requiring a fast time constant sensor with ease of mounting the sensor to the tube. The precision thermistors were the YSI 44000 series of Thermistors with a negative temperature coefficient and a time constant of one second for an oil filled bath. The time constant increases to 10 seconds if the probe is located in the open air. Since the probes are very small they were extremely easy to mount on the tubes with a piece of tape as depicted in Figure 4-6. A temperature rise on the order of 10 degrees Fahrenheit was considered normal during the testing phase of the honing operations.

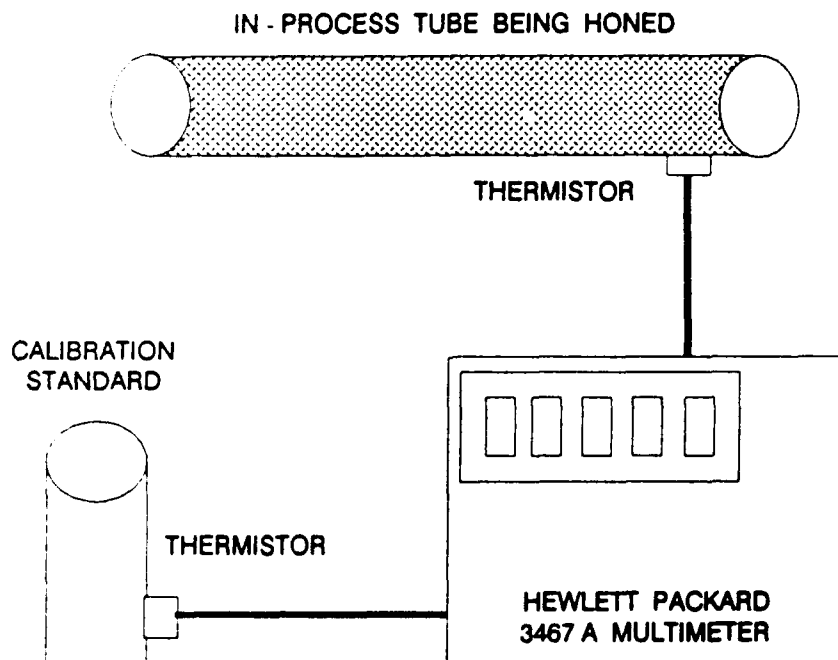


Figure 4-6, Thermistor Setup

Computer:

B&W utilized an American Research Corporation (ARC) IBM-AT compatible turbo computer with a 40 Mb hard drive for all data acquisition and analysis of data. The computer has a processor speed of 12 MHz with an AT backplane for fast data acquisition throughput. An XT type computer was tested for system throughput with a less than adequate result. System throughput for the XT was on the order of 10 samples per second. The ARC computer had the following hardware and software configuration:

- 1024 Kilobytes of RAM for program execution
- 40 Megabyte hard disk for data storage
- 1.2 Megabyte 5.25 inch floppy disk drive
- 360 Kilobyte 5.25 inch floppy disk drive
- Microsoft QuickBasic high level language version 4.5
- Mini-Micro EGA 14 inch monitor
- 800 X 600 color EGA resolution
- 256 kilobytes of video RAM
- INTEL 80286 microprocessor running at 12 MHz
- MS-DOS 3.3 operating system
- 101 key AT type keyboard

The computer was connected to the machine tool sensors by an analog to digital conversion card manufactured by the ADAC corporation. The ADAC model 5500-MF data acquisition board was equipped with the following setup:

- 8 high speed, high level multiplexed inputs
- Pseudo-differential inputs
- +/- 10 V, 0 to 10 V, +/- 5 V selectable ranges
- Input impedance 10 Megaohms
- Resolution of 12 bits (0.0024 v/count on 0 to 10 V scale)
 - $10 \text{ Volts} / 4096 = 0.0024 \text{ V/count}$
 - $5 \text{ Volts} / 2048 = 0.0024 \text{ V/count}$
- Linearity error of +/- 1 LSB
- Temperature coefficient of 30 ppm FSR/degrees Celsius
- Settling plus conversion time of 20 - 40 microseconds
- Maximum throughput of 25 KHz
- Base address of 300 Hex

The ADAC board provides only pseudo-differential inputs as opposed to truly differential inputs which implies that there is a common shield. This permitted ground noise to enter the data acquisition system with both ground shields tied together resulting in an error greater than +/- 1 LSB (+/- 0.0001 inches) for the sum of the two sensors. This lack of noise immunity could be simulated by rubbing the slip ring wires together and visually observing the display sensor readings change. The single A/D converter accommodates the two sensors by multiplexing between the two signals, thereby restricting the system from obtaining "true" simultaneous sensor readings, resulting in a small delay between the individual sensor readings that comprise a diameter reading.

4.2.2 System Schematic

The electrical schematic of the data acquisition system is presented in Figure 4-7. The sensor cabling consisted of a triaxial cable with two center conductors and a braided shield. Shielded cable was used to prevent any crosstalk between adjacent signal cables. The slip ring cabling

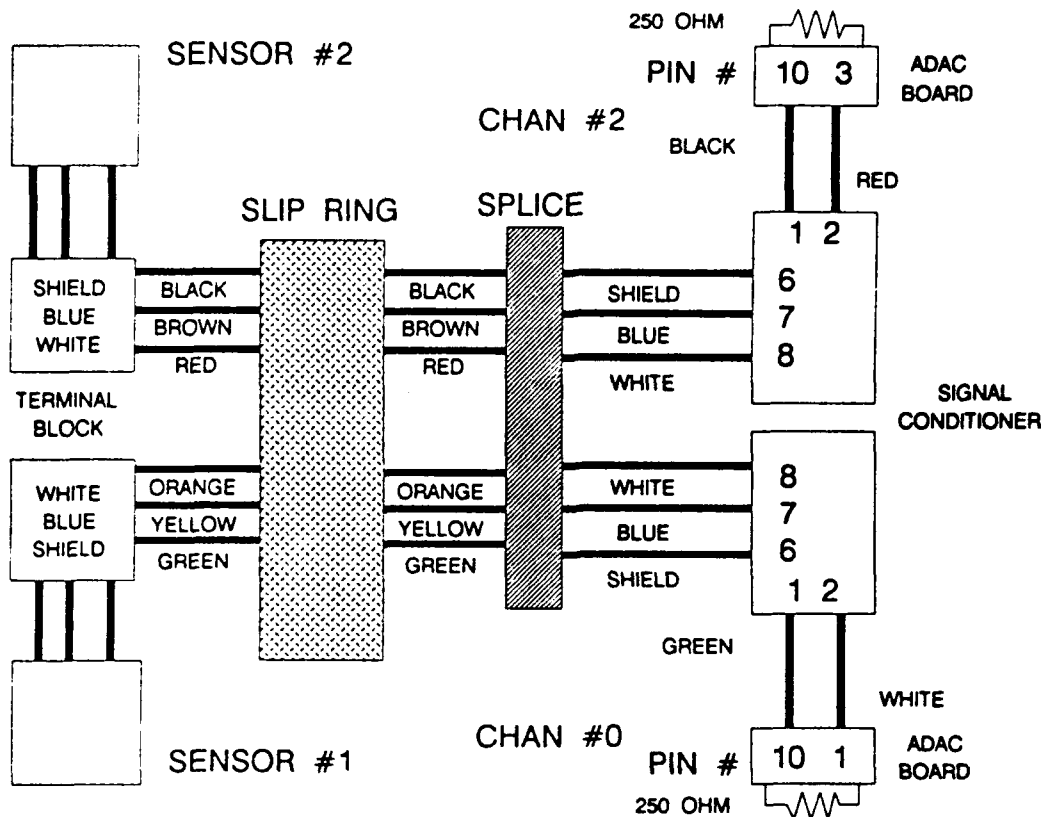


Figure 4-7, Electrical System Schematic

consisted of small diameter unshielded cable on both sides of the slip ring. Shielded twisted pair cabling was run between the signal conditioner and the data acquisition board to reduce the amount of noise picked up from the system.

4.2.3 Software Design

The software program for the honing operation was written in QuickBasic using the Microsoft QuickBasic compiler version 4.5. The code is provided in Appendix II. All of the programs were compiled and linked into executable files to enhance the data acquisition throughput rate of the total system. The program was written in modules with a main module used for executing the menu options. Currently 6 options are available in the system software:

1. Build lookup tables
2. Show raw data
3. Display data
4. Display quick data collection routine
5. Copy collected data to users file
6. Quit, return to DOS

When a menu item is chosen, the subprogram is called into memory and executed. This type of design promotes modularity and ease of documentation. Photographs of some of the computer screens are presented in Appendix X.

The ADAC data acquisition board has QuickBasic commands associated with it to start the data acquisition process. The main command needed for this system is the BASEADD command which represents the base address of the data acquisition board. From this address all of the input and output functions are addressed at different memory locations. The ADAC board was set with a base address of Hex 300. The command "BASEADD = &H300" defines the address of the board. A channel is selected and the data conversion is initiated. An associated memory location is polled to check for the end of conversion flag when finished. After the conversion is complete the next channel is selected and read. All of the subprograms utilize this same routine to acquire the data and differ only in the display and file handling routines.

The program 'honeraw.bas' executes a continuous collection of the data at channels 0 and 2 and displays a bit count of the data. This is the fastest collection routine but is only used for sensor checkout and limit setting of the signal conditioner. This routine collected data at a rate of 50 samples per second but for a one second data collection time there were 25 samples of channel one data and 25 samples of channel 2 data. To effectively collect the most amount of data, the program 'Honeread.bas' was utilized. The readout of the screen read between 154 and 2048 counts for the lower and upper limits of travel of the sensor calibration points which corresponded to 0.050 to 0.150 inches respectively.

The program 'lookup.bas' creates a lookup table for the sensor over the full range of the sensor. The purpose of the lookup table was to accurately log the data for the sensor over the usable range of the sensor. The error for each sensor was repeatable but not negligible. The deviation from linear was 0.004 inches at 0.100 inches which defined the need for lookup tables to obtain an extremely accurate system. A file name, start setting, end c' range, and distance between readings is input by the operator and the system then prompts the user to set the micrometer head to the correct position for the calibration process. The computer prompts the user at each position of the micrometer head over the entire range of the sensor. After the range of data collection is complete a file with 2048 points is created to linearize the readings between the sensor readings taken on the micrometer head. For a set sensor range the program interpolates between points to get a complete range of 2048 points for better accuracy in the data acquisition program. A sensor accuracy of 0.0001 inches per sensor is easily achievable with the concept of lookup tables to determine the corrected sensor reading.

The program 'honeread.bas' is the major portion of the data acquisition system software. Display functions are created for the operator to interpret what is going on during the honing operation. The lookup tables created earlier are loaded into system memory for both sensors. The honing sensor head is placed inside a calibrated section of pipe to determine the offset between the two sensors. The offset is defined as the distance between the two oppositely opposed sensor faces. This distance, when added to the reading of the two sensors, determines the actual inside diameter of the tube. This value is saved in a file named 'offset.dat' so that each time the program is executed the offset value does not have to be recalculated. Each time this program is invoked the operator has the option of either recalibrating the offset or using the previous offset value. The sensor values are then read into the system and compared to the values in the lookup tables previously created with the program 'Lookup.bas'. The software uses an algorithm routine to locate the closest value in the table and locate the correct reading as physically calibrated with the micrometer when the lookup tables were created. In this manner the actual sensor reading is compared to the calibrated sensor reading to determine the

calibrated value of the sensor. These calibrated values are added to the sensor offset value to determine the actual inside diameter of the tube.

The graphics routine creates a display of the inside diameter of the tube versus time. The time scale is variable so that one full pass through the tube can be displayed on the screen. The diameter scale is also variable to display the diameter as more material is removed from the tube. The sample rate is variable such that up to 20 samples can be taken and averaged before data is written to the screen to smooth out the display.

Options available for the operator are:

(Q)uit	Return to main menu
(R)escale	Change display limits
(C)ollect data	Collect data for later use
(E)nd	Stop data collection
(Z)oom	Zoom in on sensor reading display
(B)ackup	Return to previous display values
(U)p	Increase range of display values
(D)own	Decrease range of display values
(A)uto scale	Display 6 mil band of sensor reading
(F)ull Scale	Display full range of sensor readings
(L)imit reset	Set limits of tolerance band
(S)ample size to average	Input number of samples

Each of these options are available for use anytime during the data acquisition process. The operator enters the first letter of the word and the sequence is initiated. Some of the screen displays and menus are provided in Appendix IX.

4.3 Calibration Procedure

Prior to physically assembling the sensors on the machine, the sensors were calibrated. Calibration is a two step operation, sensor characterization and sensor offset determination. Sensor characterization is done once for each sensor preferably in a lab environment while the offset determination is done on the machine and is performed whenever necessary. (I.e. when the sensor's radial position's are adjusted for various size part diameters.) Both steps are required since three values are used in the systems's diameter readings. Two sensor gaps (distance between the sensor face and the part surface, and the offset (distance between the two sensor faces) are summed as a single diameter reading (refer to Figure 2-2).

4.3.1 Sensor Characterization

There are two popular methods of sensor characterization. The first is to calibrate the endpoint signal readings of the sensor electronics to match a known distances (gap). It is then assumed that the signal output changes (change in voltage versus change in distance) are linear between the two end points. However, as seen in the bench testing the non-linearity errors were as large as 0.004 inches, but very repeatable. This is not accurate enough for purposes of this project where the six standard deviation limit for accuracy and repeatability are desired to be less than 0.001 inches. However, the exceptional repeatability of the sensors leads to the second method of calibration, which is to characterize the sensors for incremental readings throughout the entire range of the sensors, and generate lookup tables in the software where

every sensor reading is compared to closely calibrated data. When characterizing, for example every 0.001 inches, the non linearity effects were almost entirely eliminated, since the smaller the increments used the smaller the non-linearity errors between the data points. B&W found that 0.001 inch increments were more than adequate.

When characterizing the sensors, B&W utilized the exact electronics to be used on the machine, inclusive of final wire lengths, and the tagging of all components for re-assembly on the machine. This was to ensure that the inherent resistance in the system would not change. Refer to Figure 4-8 for the calibration setup. Each sensor was characterized individually using the B&W developed lookup table software, discussed in Section 4.2.3, and provided in Appendix II. The sensors were set up in a B&W calibration fixture. The sensor being characterized was set at a known distance, .0500 inches from a curved calibration block (refer to Figure 4-9). The calibration block represented a diameter of 3.800 inches, and had a surface finish of 40 micro-inches. This was representative of the anticipated average machine test. A curved surface is used to minimize any error associated with characterization. The sensor was then moved away from the gauge block .0010 inches at a time to .1600 inches. The converted signal in A/D counts was read for each distance and saved in a data file. The second sensor was kept active and fixed during the calibration to simulate any electrical noise or bias that may exist in the system when both sensors are active (refer to Figure 4-8).

4.3.2 Offset Determination

Once the characterized sensors are fixtured to the machine in the holding fixture, the offset (distance between the sensor faces - refer to Figure 2-2) is measured. This value is read into the data acquisition program at system start up. B&W used a section of the RIA supplied part (No. 2) to use as an offset standard. The part was surveyed using a Zeiss CMM, to find the diameter 1 inch inward from each end (refer to Appendix V for the Zeiss data). For the offset determination the hone was expanded in the standard (refer to Figure 4-10) such that the sensors were reading the diameter at the point where the diameter variance appeared to be at a minimum according to the Zeiss data (approximately 30 degrees clockwise from point A). The value used for the offset was calculated as the remainder after subtracting the two sensor readings from 3.54679 (the average diameter of the standard calculated by the Zeiss). Note, this form of determining the offset corrects for any bias in the sensor characterization generated from initiating the characterization readings with a gap. For example, if the .0500 reading was read when actually .0490 from the gauge block, each successive diameter reading would also be reading .0010 to high. But since the offset is calculated from a known diameter, any bias in the individual sensors will be included in the offset value.



Figure 4-8, Calibration Setup

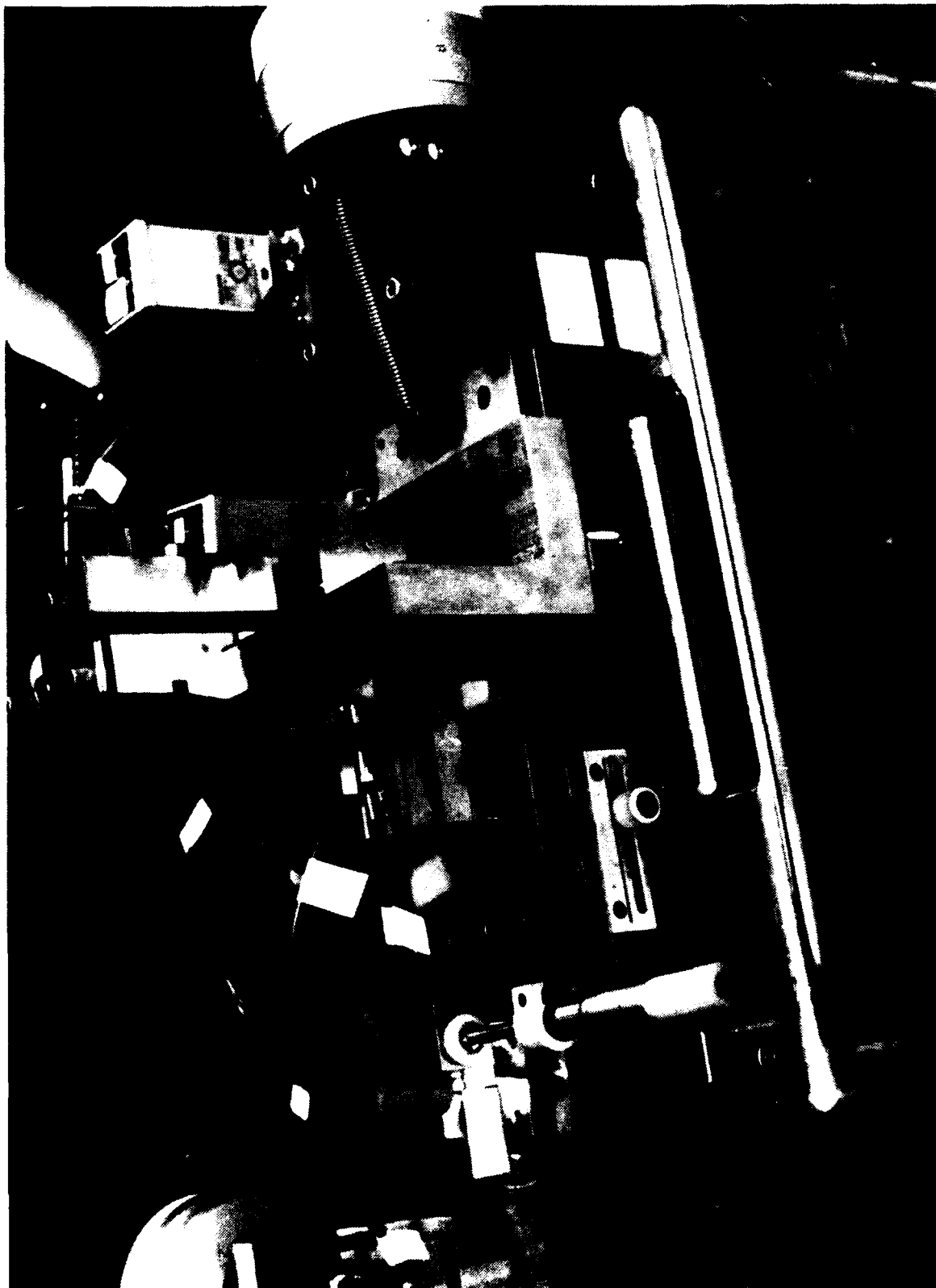


Figure 4-9, Calibration Fixture



Figure 4-10, Offset Calibration

4.4 Test Procedure

After the aforementioned calibrations and preliminary tests were performed, a final test plan (procedure) was developed. The purpose of the procedure was to perform all of the tests deemed necessary to obtain the data required to complete the project study. These tests were created with specific goals in mind from knowledge gained and judgments made during the preliminary trials of the system. (Note: the information learned during the preliminary tests will be incorporated into the discussions that follow).

The goals of the final tests were as follows:

- Obtain data to calculate the data acquisition rate (readings per second and readings per revolution).
- Determine the magnitude of temperature change during honing to evaluate for in-process dimensional measurement bias due to thermal effects and to determine the ability to compensate for the errors.
- Obtain data to graphically represent the bore profile in real time, demonstrating what an operator can observe on the display terminal.
- Obtain the data necessary to calculate the bias, variance and standard deviation for the errors in accuracy while rotating in tube cross sections. Determine the effects of filtering (local averaging of data) on the variance and standard deviations.
- Obtain the data necessary to calculate the variance and standard deviation for the errors in repeatability while rotating in a tube cross section.
- Evaluate the effects on the readings, if any, of using roughing stones versus finishing stones (i.e. vibration and surface finish effects.)

The step by step procedure to obtain the data sets were as follows: (See Note at the end of this section for the data file nomenclature.)

- 1) Setup to hone Part 1 with the roughing stones. Hone the part full length to smooth out the bore. Obtain a set of data for the complete bore length to generate graphs of the bore profile. Save to a data file. Calculate the data acquisition rate per revolution and the corresponding angle between diameter readings.
- 2) Layout part O.D. with a blue marker at five linear positions. (Refer to Figure 4-11). Mark the positions on the drive shaft with masking tape, such that the tape will align with the drive shaft support post when the sensors are at the appropriate station. Also mark the five positions on the shaft of a contact bore gauge with masking tape such that when the tape is aligned with the end of the part, the probe is at the proper station. (This is required such that data can be taken with the bore gauge at the same locations where the system read the part diameter, such that comparisons can be made for determining system accuracy and repeatability.)
- 3) Setup the hone such that the sensors are at position 1 (3 inches from the exit end). Tape the Thermistor leads to the part exterior surface and turn on the data logging meter. Run the hone at normal operating parameters but without reciprocation. Take data for at least ten (10) revolutions (approximately 5 seconds). Stop the machine. Save the

bore attribute and temperature data. The data will be used for the error analysis. (Note: do not use any software filtering. This will be done in the statistical analysis.)

- 4) Repeat step 3 at the other four locations, backing out as to not to rehone the previously inspected stations prior to overinspection with the bore gauge.
- 5) Once complete remove hone from bore at the entrance end. (NOTE: Be sure to support the honing head when as it exits the bore, until the sensor fixturing head is disconnected.)
- 6) Survey the bore at the five locations with the bore gauge. Measure and record the diameter readings at increments corresponding to the angle calculated in step 1, for 180 degrees. Also use the same offset standard used to calibrate the system to calibrate the bore gauge.
- 7) Repeat steps 1 through 6 with the finishing stones. Do not rehone the bore in case further inspection of the parts are required.

NOTE: The nomenclature used for the data were as follows:

EXAMPLE DATA FILE NAME: P1S1.DAT

Where the 4 characters are as follows:

P1 = Part number. Either 'P1' or 'P2'.

S1 = Station location. 'S1','S2','S3','S4', or 'S5' and
'PRO' for the entire bore profile.

4.5 Test Results, Analysis & Discussions

The majority of the raw data taken by the IPIS for the final tests outlined in section 4.4 are provided in Appendix VI. Any remaining data is presented throughout this section.

During preliminary testing the original slip ring failed. This occurred after repositioning the part holding and sensor fixturing to correct for a non-related electrical malfunction of the honing machine, which resulted in a larger misalignment between the slip ring and the honing head. The slip ring used was small in size for the purpose of fitting within the bore of the test pieces. However, the small design did not incorporate any inherent mechanical stress relief features to account for misalignment in it's fixturing. The misalignment caused bending stresses beyond the limits of the slip ring and therefore caused it to fail. B&W corrected the problem by modifying the fixturing to relieve the bending stresses from acting on the slip ring. The correction was described in Section 4.1.6.

However, during the final testing a newly replaced slip ring failed, resulting in abnormal (unrepeatable biased) data displays observed on the screen. The abnormal displays were significant after the station 2 readings were obtained. B&W could not repeat the tests on Part 1, since the part diameter had reached it's limit for re-inspection within the range of the bore gauge (.040 inches over the diameter of the offset standard). In lieu of this, the testing with the finishing stones was completed on Part 2 (originally slated for demonstrations). Hence, only the data obtained from stations 1 and 2 on Part 1 were considered valid and used for the statistical error analysis supplied in addition to the data from Part 2. (Note: The modified fixture used to correct for the failing slip rings and discussed in Section 4.1.6, was incorporated after testing on Part 1 and prior to testing with Part 2.)



Figure 4-11, Test Piece Station Layout

4.5.1 System Resolution & Electrical Noise

The resolution of the system is dependent on the Analog to Digital data acquisition board and the range of the sensors. The calibrated usable range of the sensors (.000-.200 inches) was used over a range of 2048 usable bits counts. This converts to a resolution of:

0.0001 inches/count

Hence the accuracy of the board is ± 0.00005 inches per sensor. Since two sensors are used the system accuracy becomes $\pm .0001$ inches. Additional A/D noise (without running the hone and rotating the part) resulted in an additional $\pm .0001$ inches, or a total system error of $\pm .0002$ inches. This is the worst case error expected, and is depicted in Figure 4-12.

B&W tested the slip ring to ensure that no additional noise was added to the system when the signals were being brought through a rotating coupling. This was done by taping a penny to the sensor faces to provide a constant reading. The rotating coupling and slip ring did not induce any additional noise to the system. A bias shift was noticed in the data due to the rotational resistance of the slip ring.

4.5.2 Data Acquisition Rate / Phase Shift Error

During the inspections B&W used the computer clock to measure the data acquisition rate. The average rate from all stations in Parts 1 and 2, was:

33 diameter readings/second

This is greater than the 10 readings per second required by the specification.

The hone spindle speed was set at:

125 RPM

This equates to approximately:

16 diameter readings/rotation

Or a diameter reading every 22.5 degrees of rotation.

This seemingly insignificant value actually proved to be quite significant as explained in the "phase shift" error discussion that follows.

Phase Shift Error:

During the 22.5 degrees of rotation, two independent sensor readings were taken to comprise a single diameter reading (when summed to the calibrated offset constant between the sensor faces). Since the two readings were not taken simultaneously, but one after the other, as much as 11 degrees ($22.5/2$) of rotation can exist between the two readings. Although small, this 11 degree "phase shift" between a pair of readings was found to set up a larger source of error than expected. If the honing head rotational travel is less than perfect, the gaps between the sensors and the inspection surface may change during the 11 degree rotation between individual sensor readings, causing an error in the readings. The imperfect rotation can be caused by mechanical "slop" in the honing head, such as clearances between the push cone and the stone

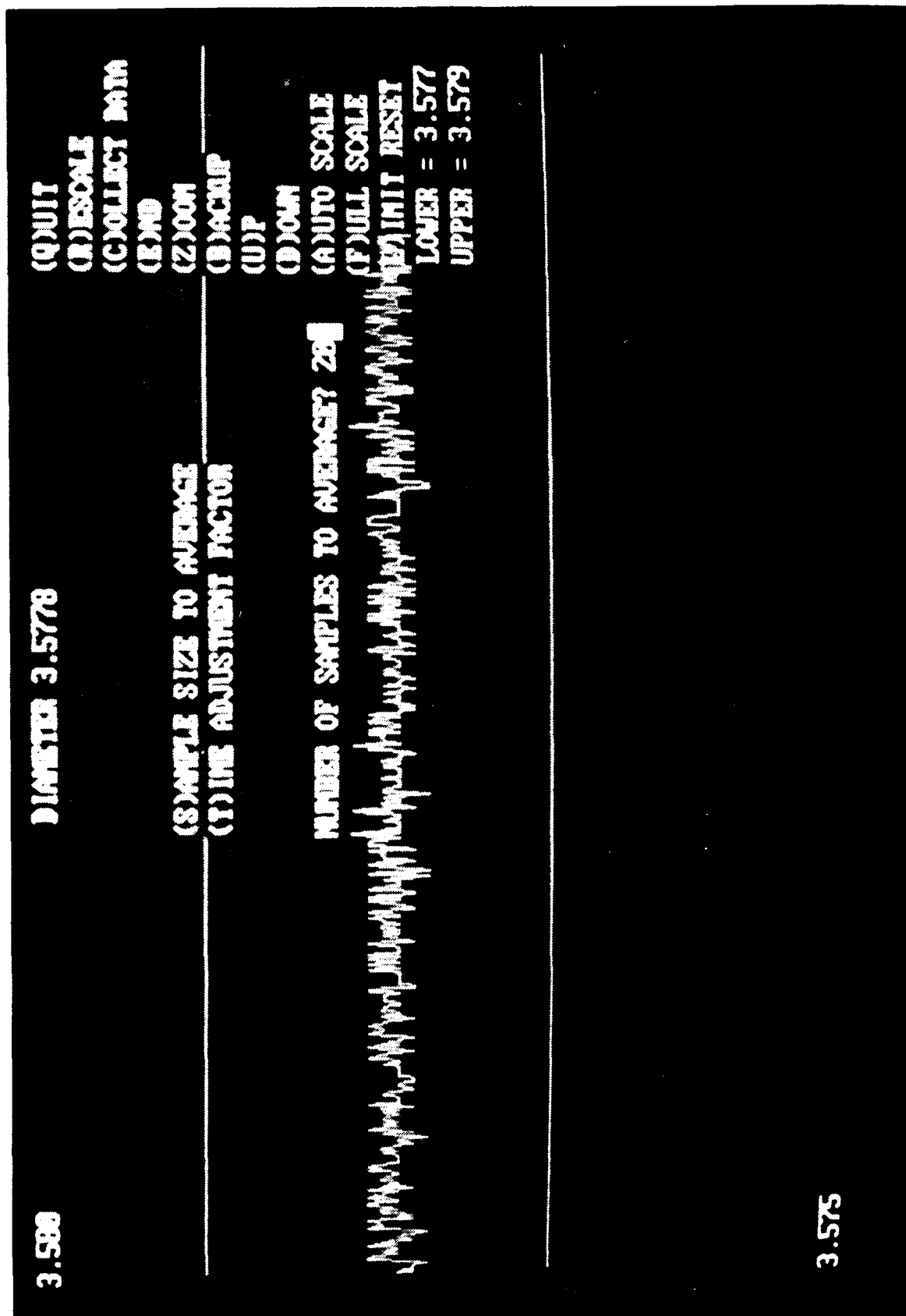


Figure 4-12, System A/D Noise Resolution

holder body and variations in the radial distance to the stone faces, results in a "wobble" of the honing head and associated sensor fixturing.

B&W found that this "wobble" phenomena does occur, and was a significant contributing factor to the total error seen in the data (the total errors will be presented in Section 4.5.5.) In a round part (as was the case for the parts in question), the gap between the sensors and the part surfaces are expected to remain fairly constant. However, by running the system with only one sensor active, B&W discovered that the gap would vary, for example, .008 inches within 180 degrees of rotation (refer to Figure 4-13). This evidence proves that the "wobble" phenomena does occur. Therefore, .008 inches of variation in 180 degrees implies that 11 degrees of rotation between the sensor readings could yield an incorrect measurement, the second reading could be an incorrect gap reading by as much as $\pm .0005$ inches ($11 \text{ degrees} / 180 \text{ degrees} \times .008 \text{ inches}$). The difference in the correct and the actual gap measured results in a "phase shift error" which is equal to the wobble of the honing head during the 11 degrees of rotation. This error can be applied to the total diameter worst case reading error.

The resulting output (screen display) due to the phase shift error would be an oscillation in the data revolving around the mean (actual) diameter of the part. This oscillation will also be presented in Section 4.5.5.

B&W notes that the oscillations shown in Figure 4-15 vary in magnitude. This was due to the relative position of the honing head during the stroke. As the honing head moves down the bore, it would tighten and loosen, depending on the local conditions of the bore and the related force against the stones. This variance in oscillation magnitude was observed during all testing where reciprocation was involved, providing additional evidence that the wobble effect phenomena does exist and is significant. The magnitude of the overall fluctuations were observed to vary in a range of .0005 to .002 inches. B&W also noticed a relationship where the oscillations were greater when the hone was rotating without reciprocation, as was the case when the error analysis data was taken, or when the honing head was reversing directions in the bore. The wobble seemed to be minimized when the hone was being forced down the bore, and maximized by the absence of the additional force when the honing head was reversing direction.

This problem can be resolved by taking simultaneous sensor readings where the phase shift error is eliminated and the readings are therefore unaffected by mechanical slop. This was not possible with the data acquisition equipment used in the study. The methods for obtaining simultaneous sensor readings are discussed in the conclusions and recommendation sections of this report.

4.5.3 Thermal Effects

The thermal expansion coefficient for steel is:
 $.00000633/\text{per unit length/degree Fahrenheit}$

Therefore, for the 3.55 inch diameter test parts, this equates to:
 $.0000255 \text{ inches/degree F}$

B&W observed the temperature of the parts during the honing various honing operations to vary from 5 to a maximum of 30 degrees above room temperature. For honing at normal

1.468

DIAMETER 3.4539

SENSOR 2 READS LOW

(S)AMPLE SIZE TO AVERAGE
(T)IME ADJUSTMENT FACTOR

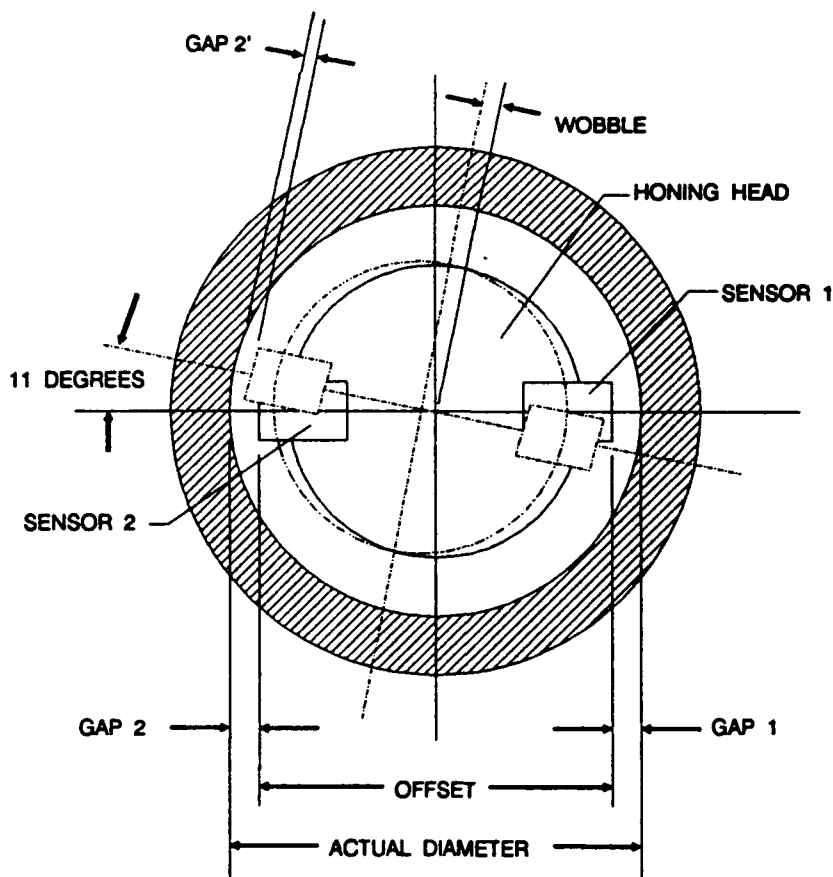
NUMBER OF SAMPLES TO AVERAGE? ☐

(Q)UIT
(R)ESCALE
(C)OLLECT DATA
(E)ND
(Z)OOM
(B)ACKUP
(U)P
(D)OWN
(A)UTO SCALE
(F)ULL SCALE
(L)IMIT RESET
LOWER = 3.504
UPPER = 3.514

CHANNEL 0 = 869
CHANNEL 2 = 0

149

Figure 4-13, Honing Head Wobble Effects



$$\begin{aligned}
 \text{ACTUAL DIAMETER} &= \text{SENSOR 1 GAP} + \text{OFFSET} + \text{SENSOR 2 GAP} \\
 &= \text{GAP 1} + \text{OFFSET} + \text{GAP 2} \\
 \text{MEASURED DIAMETER} &= \text{GAP 1} + \text{OFFSET} + \text{GAP 2}' \\
 \text{GAP 2}' &= \text{GAP 2} - \text{WOBBLE} \\
 \text{PHASE SHIFT ERROR} &= \text{WOBBLE}
 \end{aligned}$$

Figure 4-14, Phase Shift Reading Error

pressures, as was done during the testing, a delta temperature of approximately 10 degrees was typically observed. This equates to an expected temperature bias of:
.000247 inches

And since the offset calibration and post inspections with the bore gauge was done at room temperature, a .00025 bias can be expected in the error analysis. This proved to be the case for Part 1.

4.5.4 Bore Profiles

Typical Bore profiles are presented in Figures 4-16 and 4-17. From the graphs, the following observations are made:

- The readings oscillate with an approximate amplitude of .001 inches (+/- .0005). This fluctuation is comprised of three sources:

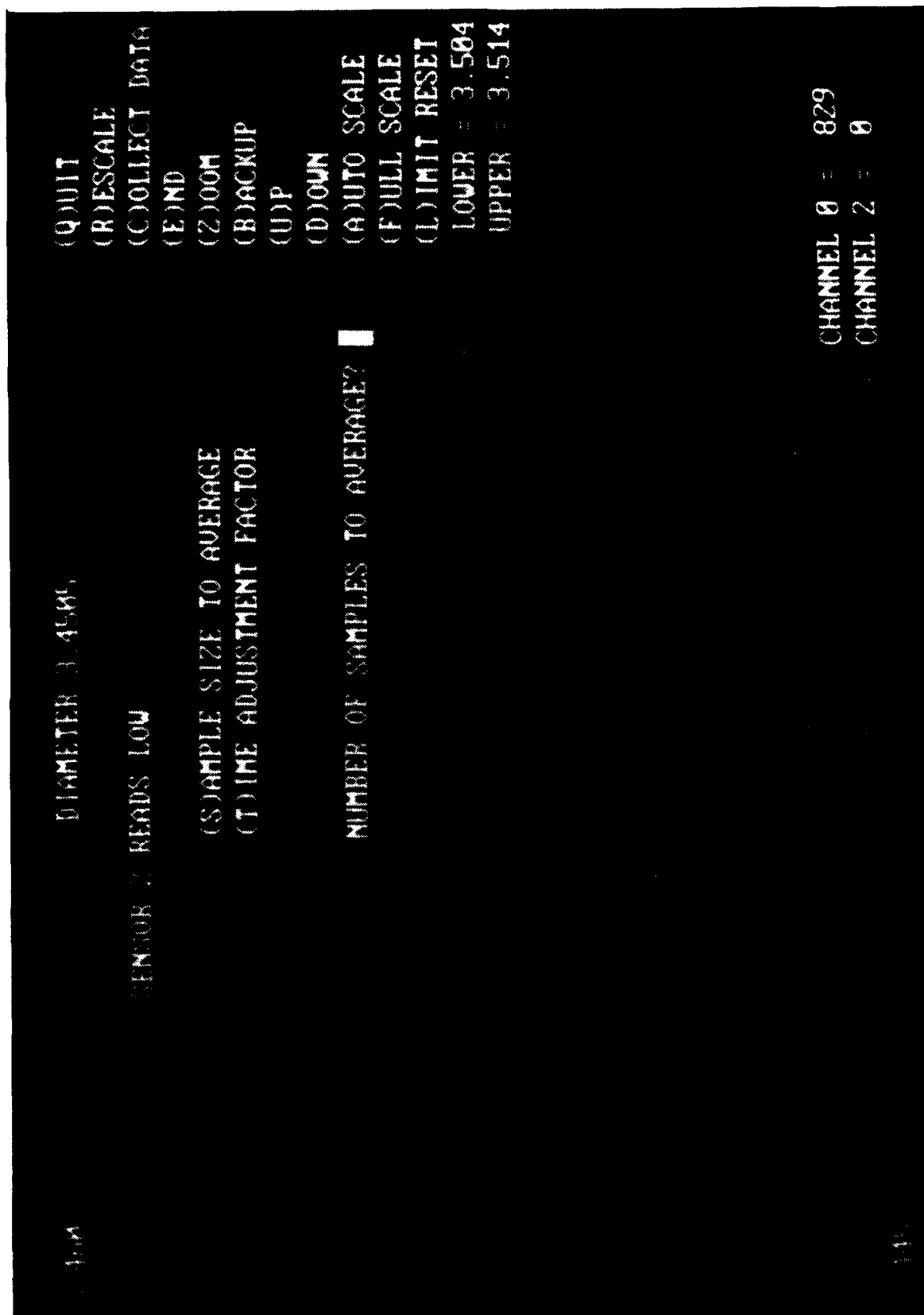


Figure 4-15, Variation in Hone Head Wobble

- 1) Electrical noise in the system and the Analog to Digital (A/D) signal conversion resolution as discussed in section 4.5.1. (Contributes .0000 to .0004 inch total fluctuation.)
- 2) The phase shift error. As discussed in section 4.5.2. (Contributes .000 - .001 fluctuation)
- 3) Out-of-roundness. Once rotating, any out of roundness will cause a sine wave pattern with two peaks and two valleys per revolution and the amplitude representing the magnitude of the out-of-roundness. Unfortunately, the A/D conversion and phase shift errors discussed above wash out the roundness and eliminate any chance of deciphering the true roundness of the part at a particular cross section. However, it would be possible if the A/D resolution was increased and the phase shift error was eliminated. Methods to do this are discussed in the conclusions and recommendation sections of this report. Based on the bore gauge surveys of the parts they were typically out of round by as little as .0001 inches and as large as .001 at the ends.

Based on the three sources of fluctuations above an average fluctuation of .0008 (+/- .0004) inches with .0016 (+/- .0008) inch fluctuations at the ends are expected. These values were typical as seen by the data in Appendix VI (presented in Figure 4-15).

- From the graphic screen displays the general bore profile can easily be depicted. The Y-axis is the diameter reading, while the X-axis corresponds to the positions in the bore. The graph of Part 1's profile is of one stroke (approximately 30 inches). The data points at the extreme left indicate where the sensors protruded from the bore at one end. Ignoring the oscillations, it can be seen that the general profile indicates a .001 bell mouthing at each end of the part. This was an accurate assessment of the actual part profile, and could easily be corrected by short-stroking the ends. The photograph of Part 1 is of two strokes (down and back) compressed to fit on the screen. The extreme left and extreme right is where the sensors protruded from the bore. The two blue horizontal lines indicate a .002 inch band. Again, the data oscillates about the mean by about +/- .0005 inches. The photograph was taken after the part was short stroked to correct for the bell mouthing at one end. It can be seen that the bell mouthing was removed at the one end. (This correction was made without removing the hone from the bore for surveying with a bore gauge.) The high spot in the center is the turn around point at one end of the part. A .0015 inch bell mouthing is still evident. The oscillations are greater at this point since the hone is changing directions where the "wobble" effects seem to be the greatest. If the target diameter of the finished part was for example 3.578 inches, the part could still be corrected (remove bell mouthing) by short stroking (honing the smaller diameter portion of the part only) from the opposite end without ever stopping the machine.

4.5.5 Statistical Error Analysis

The statistical error analysis are provided in tabular form in Appendix VII for accuracy and for repeatability. As previously stated the data taken by the system was taken at specific stations while rotating without reciprocation, at the rate of approximately 16 diameter readings per revolution (22.5 degrees apart). Therefore, 16 bore gauge diameter readings were also taken at each station approximately 22.5 degrees apart for the error determinations.

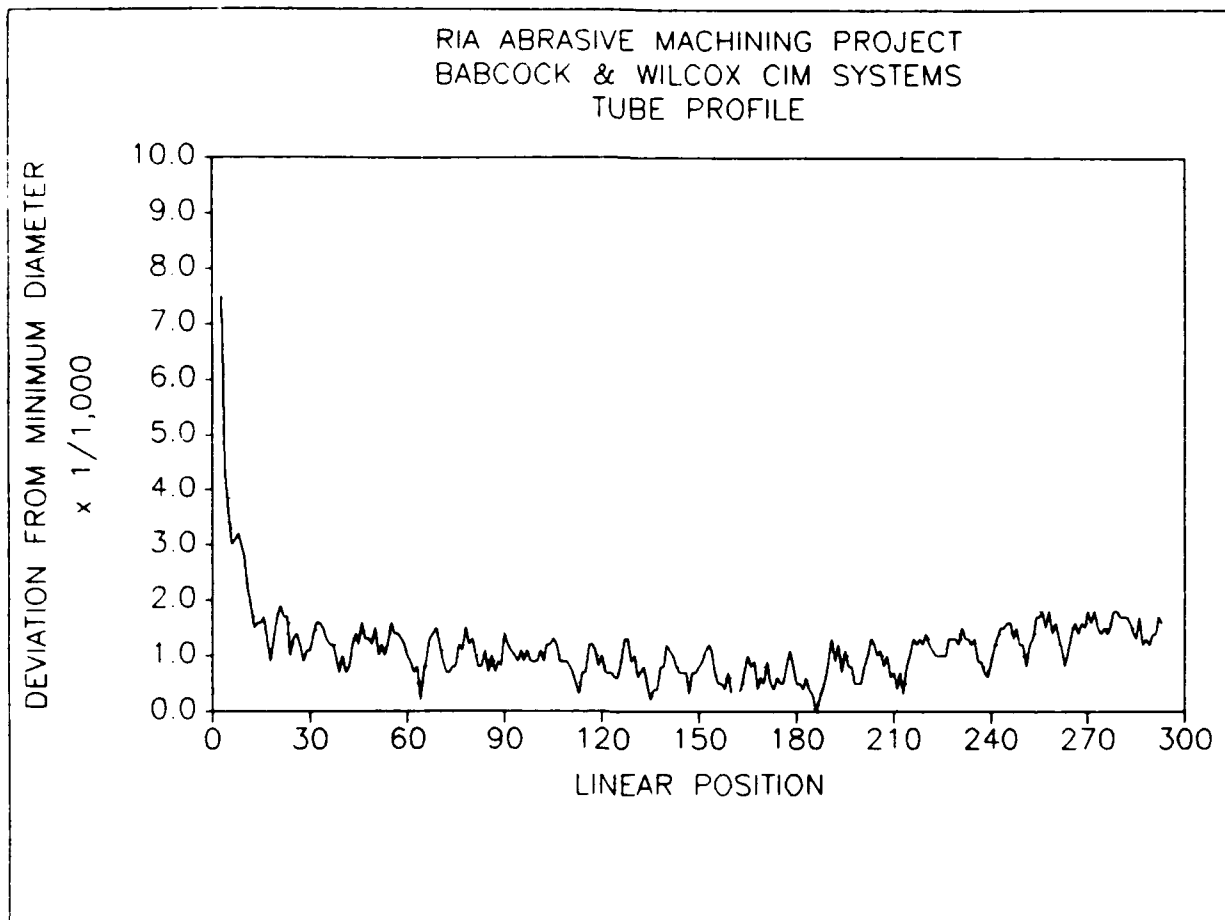


Figure 4-16, RIA Test Part 1 Bore Profile

Accuracy:

For the accuracy analysis, a randomly selected revolution of data taken and stored by the system was chosen for comparison with the bore gauge data. The resolution and accuracy of the hand held bore gauge is .0001 inches. When graphed, a revolution of data appears as a repeatable wave-form (with a complete period being one revolution). In order to properly compare the readings point-for-point, the two data sets were shifted visually to overlay with each other, based on the assumption that the trends in the data (slopes of the curves) represented the part roundness and therefore could be used to match the corresponding measured values. The reading error was the difference between the system reading and the corresponding bore gauge reading. The accuracy analysis was further broken down on a point-for-point comparison basis, an average of two adjacent point comparison basis, and an average of sixteen consecutive data points comparison. The last representing a single data point read for the cross section of the part based on an average of 16 readings. Averaging represents software filtering where data can be averaged prior to displaying on the operator's screen in order to minimize the reading errors.

The statistical accuracy analysis for the data taken from stations 1 and 2 in RIA Part 1 (prior to slip ring failure) is provided in Appendix VII. The roughing stones were used in this test.

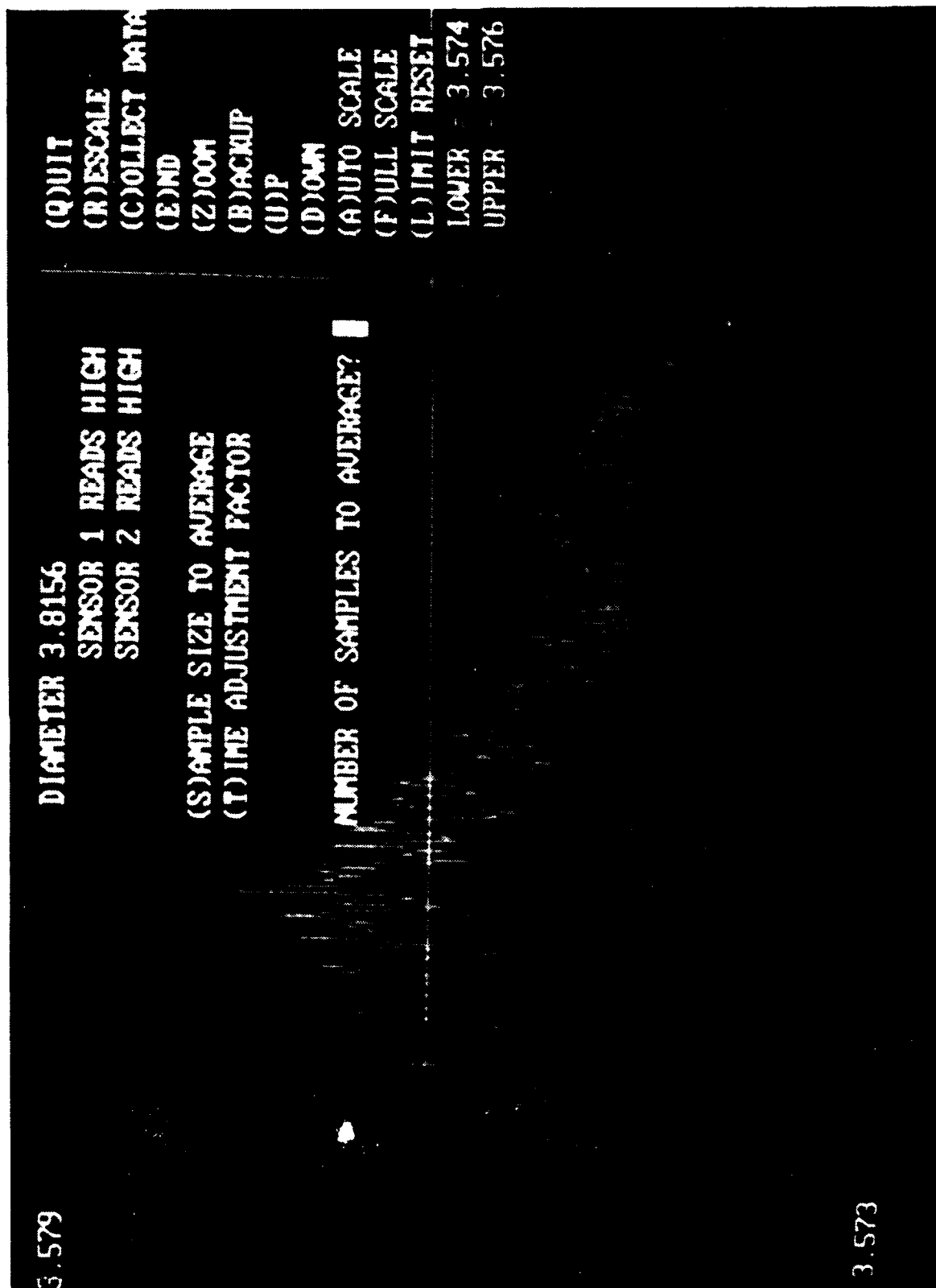


Figure 4-17, RIA Test Part 1 Bore Profile

The calculated bias was .0002 inches which was as expected based on the thermal expansion of the part calculated from the measured part temperature. The standard deviation (one Sigma) and corresponding six standard deviation (6 Sigma) values calculated for Part 1 were as follows:

	One Sigma	Six Sigma
No averaging:	.00024 inches	.00144 inches
Averaging 2 points:	.00022	.00132
Averaging 16 points:	.00011	.00066

The target six standard deviation limit was .001 inches. Hence, the results indicate that if only a single diameter reading (averaged from 16 data points (one revolution)) the six standard deviation limit of .001 inches is achievable and that with a few equipment improvements (see Section 7.0, Recommendations), the .001 inch six standard deviation limit should be achievable on a point for point basis.

The statistical accuracy analysis for the data taken from stations 1 through 5 in RIA Part 2, with the finishing stones, is also provided in Appendix VII. The bias calculated was -.002 inches which was much larger and opposite in sign from the bias expected from the thermal expansion of the part. An incorrect bias can be due to an inaccurate offset calibration. However, for this test, the maximum incorrect bias expected is $\pm .0003$ inches (.0002 due to the IPIS resolution, and .0001 due to the bore gauge resolution). B&W did, however, observe that with the new slip ring, the readings seemed to drop in value when the honing head was rotating. One explanation can be that there is an internal resistance change associated with the slip ring once it is rotating. An internal resistance will reduce the measured voltages, subsequently reducing the calculated diameter values, resulting in a negative bias. B&W notes that the bias (average error) was consistent for all 5 stations, where the average error was from -.0018 to -.0022 inches. This relatively constant error indicates that the error exists in a form of a bias, not a variance. It is assumed that all biases can be corrected for once they are calculated. The standard deviation (one Sigma) and corresponding six standard deviation (6 Sigma) values calculated for Part 2 were as follows:

	One Sigma	Six Sigma
No averaging:	.00033 inches	.00198 inches
Averaging 2 points:	.00031	.00186
Averaging 16 points:	.00020	.00120

Again, the target six standard deviation limit was .001 inches. The results are not as promising as they were for Part 1, but do indicate that with a few equipment improvements, the six standard deviation .001 inch limit should be achievable on a point for point basis, and even more likely on a single diameter reading per linear position basis.

Individual (un-averaged) readings are required to resolve roundness. The calculated accuracies for the un-averaged data indicated that they were too large (.0014 inches) to resolve the insignificantly small roundness deviations (only .0001 to .001 inches) in the actual test parts. But the primary source of error found in this study (phase shift reading errors), which resulted in larger calculated errors, can be greatly reduced making resolution of more significant roundness problems achievable.

In order to survey for attributes such as overall part diameter, tapering, barreling, and bell mouthing, only the average diameter at various linear positions are required. This was achieved by the IPIS.

Repeatability:

In the repeatability analysis, one randomly chosen period (revolution) of data taken at station 1 in RIA Part 1, was compared to 4 other randomly chosen revolutions of data taken at the same location. The complete statistical analysis is provided in Appendix VII. Eighteen data points were used to match the periods (revolutions). The difference between any set of readings at any point was the reading error and it was assumed that the mean error was zero. The standard deviation (Sigma) for all 72 (4 comparisons x 18 points) reading errors calculated in Appendix VII were as follows:

One Sigma	Six Sigma
.00014 inches	.00084 inches

This meets and exceeds RIA's target six standard deviation limit of .001 inches for repeatability.

4.5.6 Stone Pressure & Roughness Effects

Throughout the testing no significant effects from the stones (roughing versus finishing) or the corresponding surface finish were observed on the data. However, B&W recommends sensor calibration to be performed on the equivalent material with a representative surface finish, since inductive proximity sensors have been known to be impacted slightly by the surface finish. Unfortunately, oscillations from the phase shift reading errors inhibited B&W from observing changes of this small magnitude.

During the testing B&W found the stone pressure affected the magnitude of the oscillations. The higher the pressure, the smaller the oscillations. This was a result of minimizing the mechanical "wobble" in the hone when tightened against the bore. The variation in the magnitude of the oscillations was also seen to vary during reciprocation where the tightness would vary depending on the local diameter and roundness of the part.

5.0 BENCH TESTING - SURFACE FINISH INSPECTION

In addition to the dimensional inspection, bench and machine testing performed during this study, further sensing techniques were evaluated and bench tested for use with in-process surface finish inspection of abrasive machining (honing). These tests were performed as an additional workscope to the original workscope and are thereby presented separately by this chapter.

5.1 Technical Approach

Various sensing techniques were studied prior to choosing two best suited for bench testing. (It was decided that only bench testing, in lieu of machine testing, was necessary to prove or disprove the capabilities of in-process surface finish inspection.) Standard contact surface finish inspection techniques were eliminated for testing due to the excessive dynamics (rapid rotation and translation) of the honing operation which are too large for standard profile meters, in addition to the concern of causing damage (scratching) of the final honed surface. Capacitance and inductive sensing were eliminated for testing since traditional applications for surface finish inspection involve placing the sensor face against the part surface to create a consistent offset datum. A known offset is essential to the validity of the inspection such that changes in sensor output indicating a change in surface finish will not be confused with a change in offset distance. This in effect becomes a contact gauging situation since the part must not move and the sensors are held in place on the part surface, contradicting true in-process inspection.

The two non-contact gauging techniques ultimately chosen for the bench testing were "optical" and "through-the-stream ultrasonic" inspections. The optical bench testing was performed by B&W's metrology laboratory while the through-the-beam ultrasonic inspection techniques were evaluated on honed bore samples by the National Institute of Standards and Technology (NIST).

5.2 Optical Sensor Testing

The optical testing for surface finish detection was done with the use of a Photonic sensor. This sensor delivers a known light intensity through a fiber optics bundle of which half of the fibers are used to transmit the light to the surface and half to transmit the reflected light back to the photo detector inside the sensor head. The reflected light will have an intensity, depending on the reflectivity of the surface being tested, which is detected by the photo detector. As the surface finish quality increases, the reflectivity increases and thus the intensity of the reflected light increases. By comparing the voltage output from the sensor for various surface finish standards, surface finish can be determined on unknown surfaces.

5.2.1 Test Apparatus

The initial step in setting up a Photonic sensor is to determine the characteristics of the fiber bundle in its ability to transmit and receive the reflected light. This is done by creating a "calibration curve". The calibration curve is produced by mounting the probe perpendicular to a known surface finish standard and varying the distance between the probe and the standard. The standard in this setup is to be used to reference all others against. Figures 5-1 and 5-2 show the calibration setup with a micrometer stand against a two microinch surface finish standard. The output from the Photonic sensor is fed into an analog to digital converter and

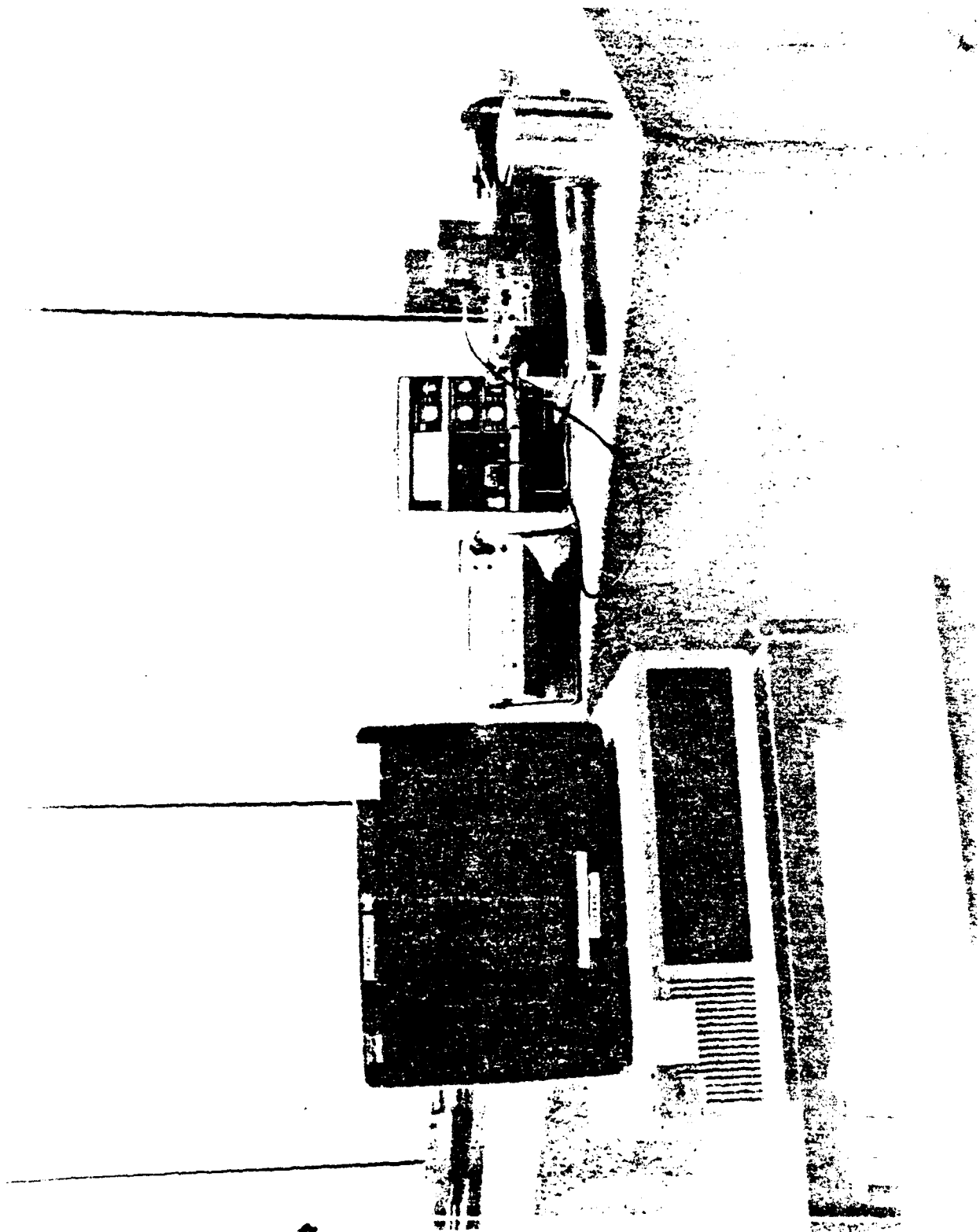


Figure 5-1, Photonic Sensor Calibration Setup

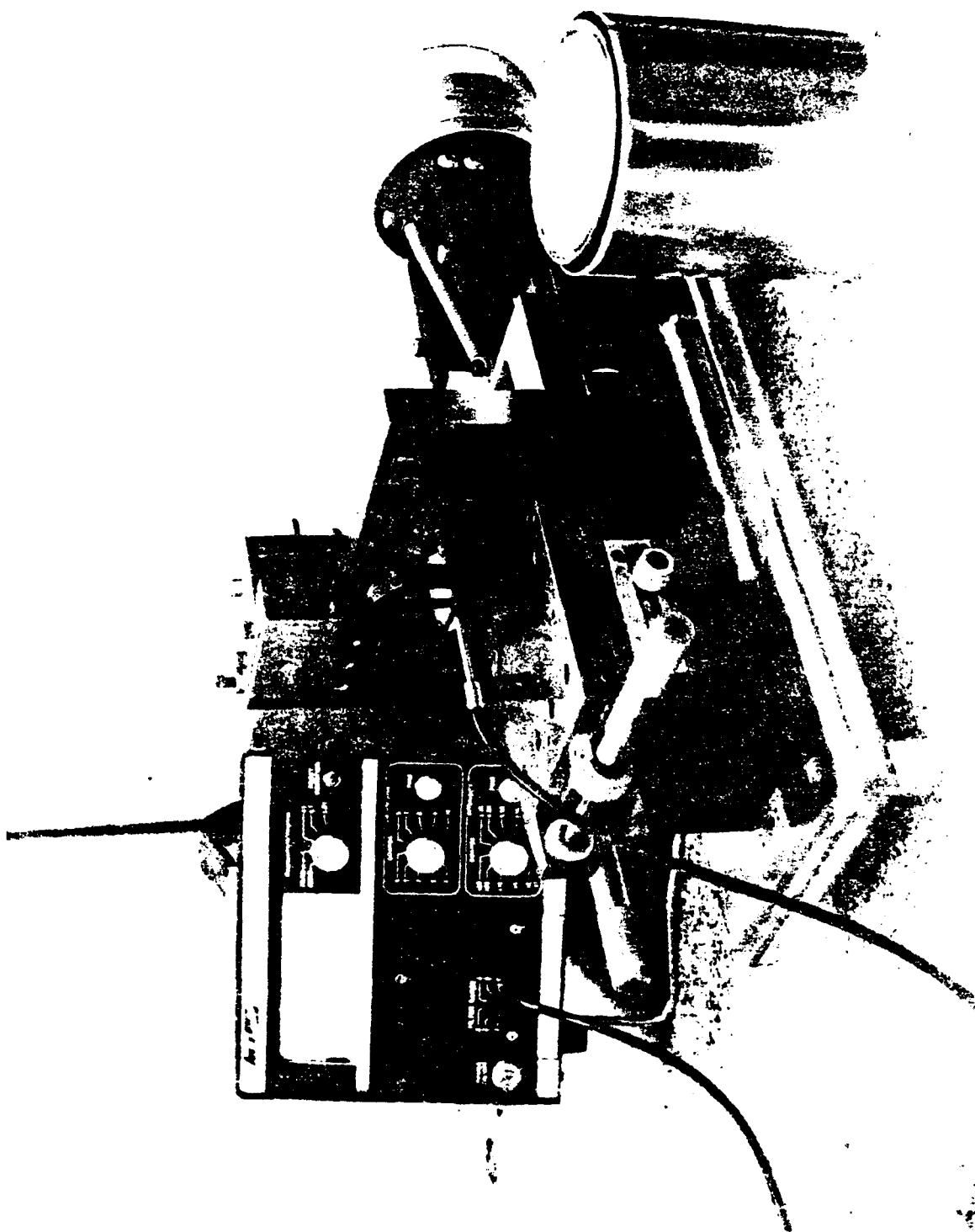


Figure 5-2, Photonic Sensor Calibration Fixture

VOLTAGE vs DISPLACEMENT
FOTONIC SENSOR USING A 2 MICROINCH
SURFACE FINISH

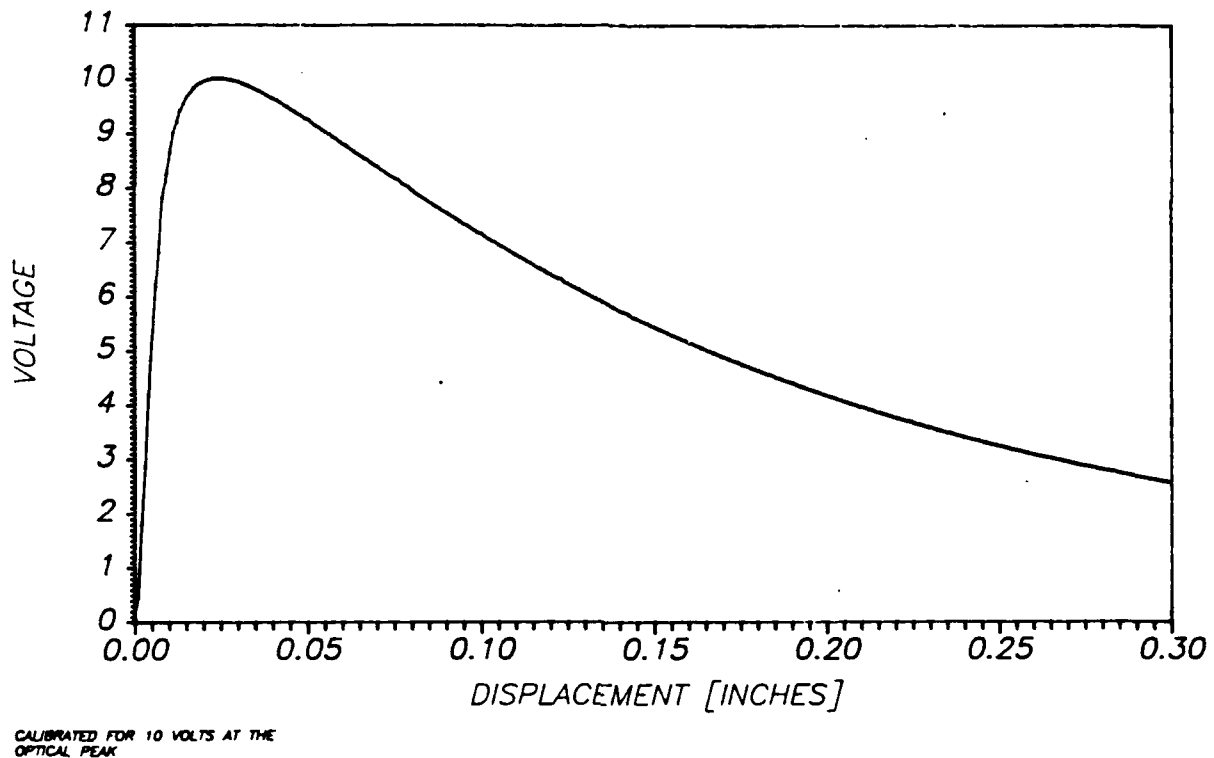


Figure 5-3, Photonic Sensor Calibration Curve

then into a PC computer where the data can be tabulated and set into graphical form. The voltage verses displacement data is provided in Appendix VIII, and depicted graphically in Figure 5-3.

The actual testing for surface finish is done with a different setup. Since the honing requires a coolant or lubricant, the test apparatus must be able to house this lubricant. This setup requires the probe to be in the vertical position facing downward towards the surface standard. This setup allows for a comparison between a clean surface, one with an oil film, and one where the probe is totally submerged in the oil. Figures 5-4 and 5-5 depict the testing setup with the test standard lying in a metal tray supported by twin rails so that the standard can be passed under the sensor. Here too, the sensor signal is fed into a PC computer through an A/D converter to tabulate the data.

5.2.2 Test Procedure

The initial testing was to determine the voltage output of the sensor over a range of surface finishes at a constant probe offset. This offset was determined from the two microinch surface finish standard where the distance was set at the optical peak. The optical peak is at a distance from the standard where the voltage output reaches a maximum and as the distance

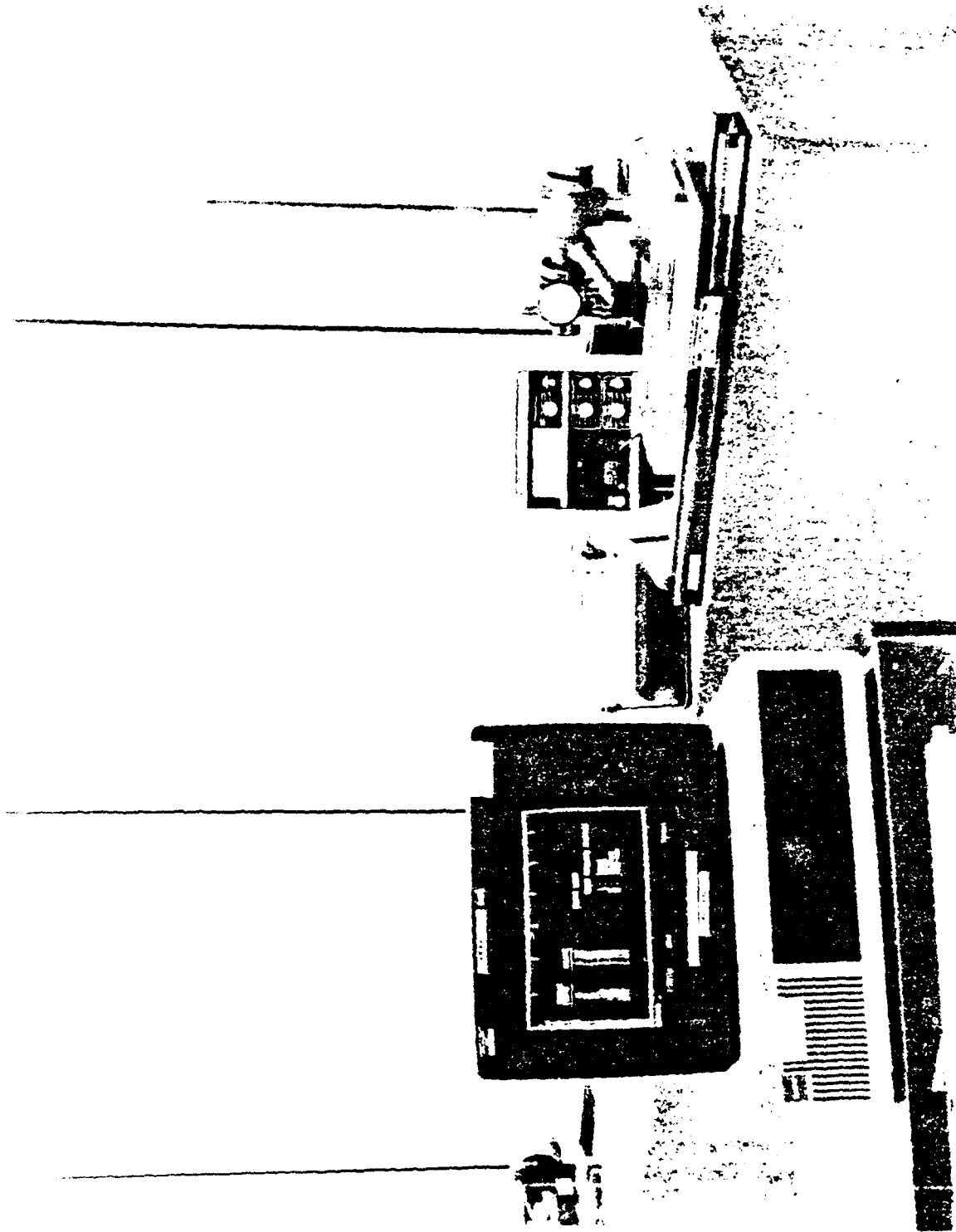


Figure 5-4, Photonic Sensor Test Setup

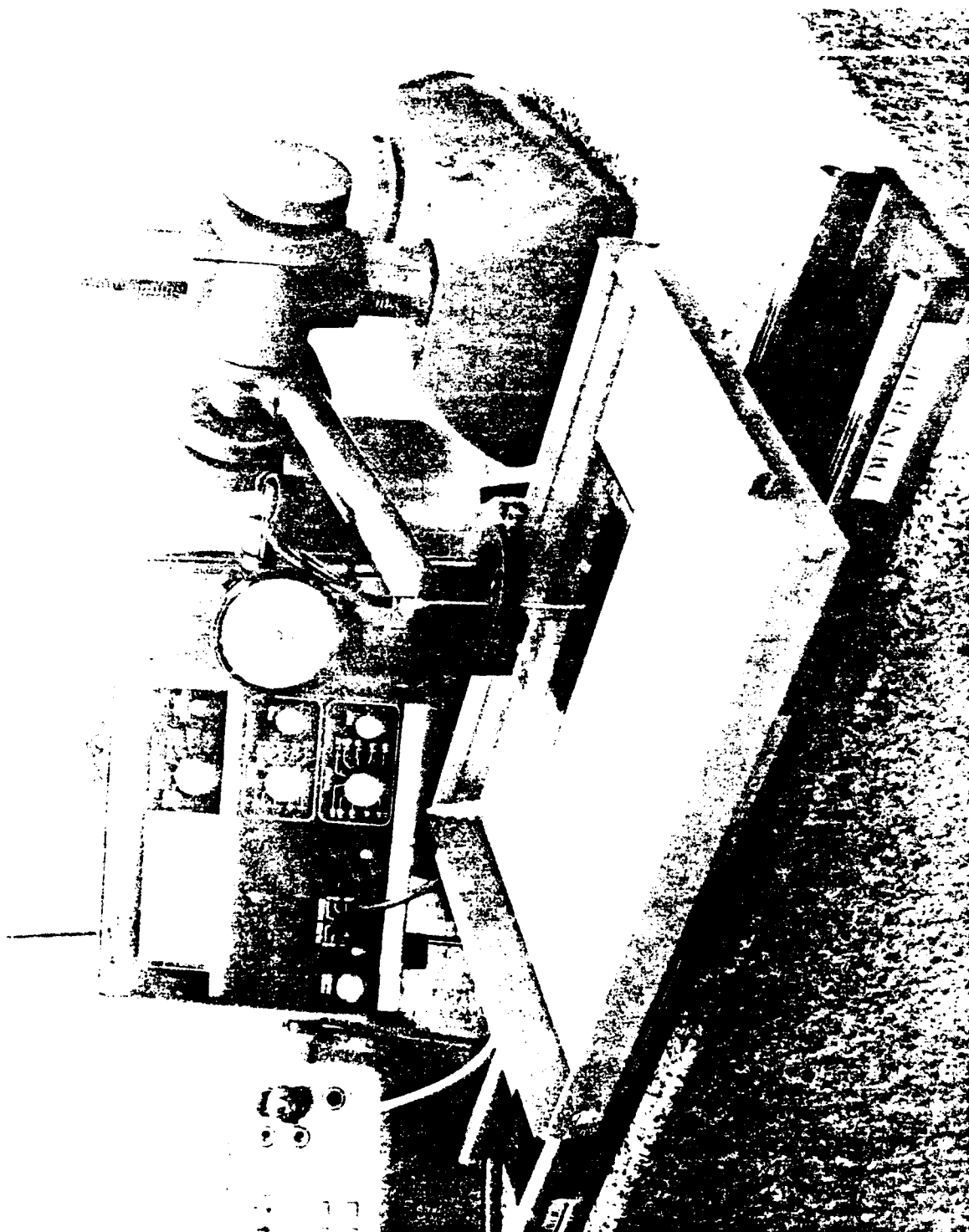


Figure 5-5, Photonic Sensor Testing

increases from this point, the voltage begins to decrease (refer to Figure 5-3). By setting the offset to this two microinch surface finish, any other surface finish that is rougher than two microinch will have a smaller voltage output.

The three tests were conducted, as mentioned previously, with no oil, an oil film, and totally submerged in oil. The surface finish standard used has nine different surface finishes. The test began by setting the optical peak on the two microinch finish and then passing the other finishes under the probe at this same offset. As the probe is moved over the surface finishes, the voltage signal is recorded by the computer and associated to the appropriate surface finish. The data is automatically transformed into a spreadsheet using SMART software and a graph is created showing the variations in voltage output as compared to the associated surface finishes. (Refer to Figure 5-5)

5.2.3 Test Results

The raw data for each of the three tests are provided in Appendix VIII and presented graphically in Figures 5-6 through 5-8.

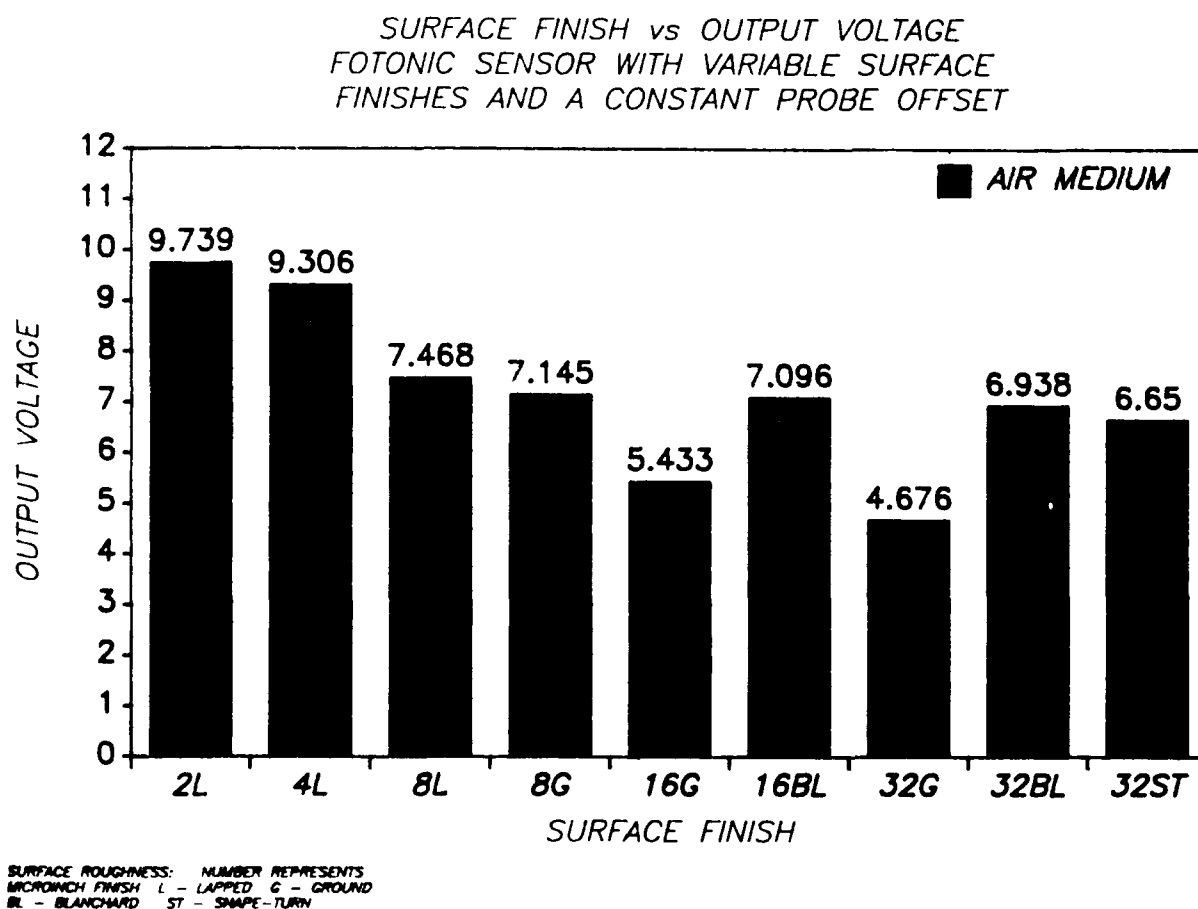


Figure 5-6, Photonic Sensor Results For Dry Surface Finish Testing

**SURFACE FINISH vs OUTPUT VOLTAGE
FOTONIC SENSOR WITH VARIABLE SURFACE
FINISHES AND A CONSTANT PROBE OFFSET**

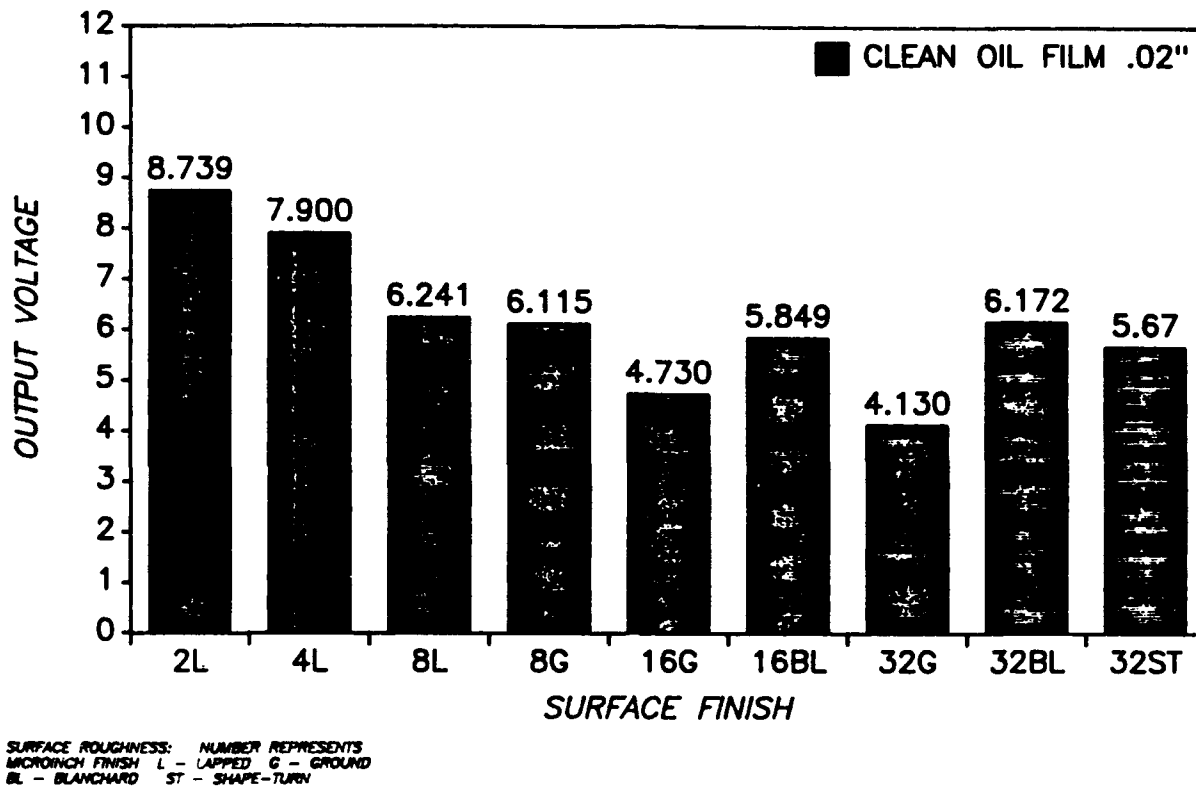


Figure 5-7, Photonic Sensor Results For Oil Film Surface Finish Testing

The predicted voltage decrease with increasing surface finish was found as long as the same type of surface finish is used. As an example, in Figure 5-6, when comparing lapped surfaces, it is found that the four microinch finish has approximately 400 millivolts less output from the sensor as compared to the two microinch surface finish standard. Similarly, the eight microinch finish has less voltage output than the four microinch finish. However, by changing the type of finish, the reflectivity changes and thus the voltage output signal changes.

It was found that lapped finishes reflect a greater percentage of the light than a ground surface of the same microinch finish. Similarly, a blanchard finish is more reflective than a shape-turned finish of the same microinch finish. The difference in the output voltage of two surface finishes of the same microinch finish with different surface types is approximately the same as two surface finishes of the same surface type with different microinch finishes. This is true for microinch finishes which are very similar (comparing an eight microinch finish to a four microinch finish).

**SURFACE FINISH vs OUTPUT VOLTAGE
FOTONIC SENSOR WITH VARIABLE SURFACE
FINISHES AND A CONSTANT PROBE OFFSET**

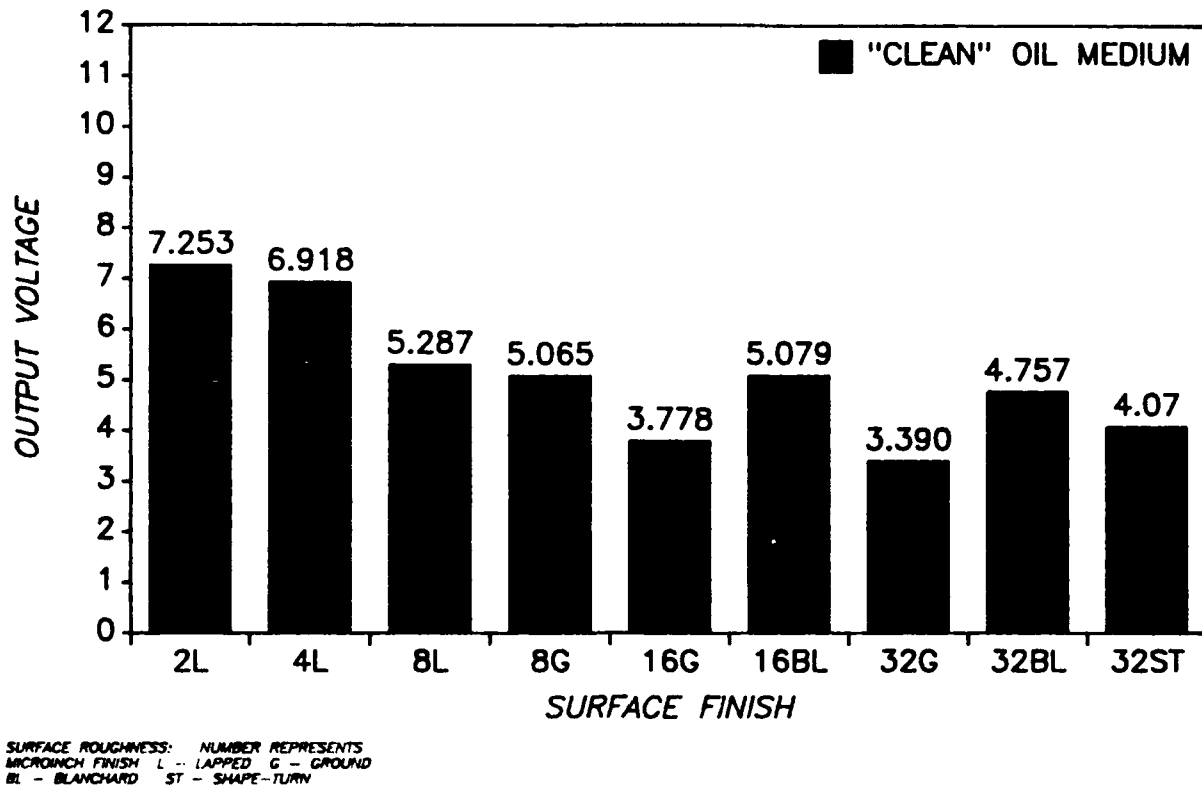
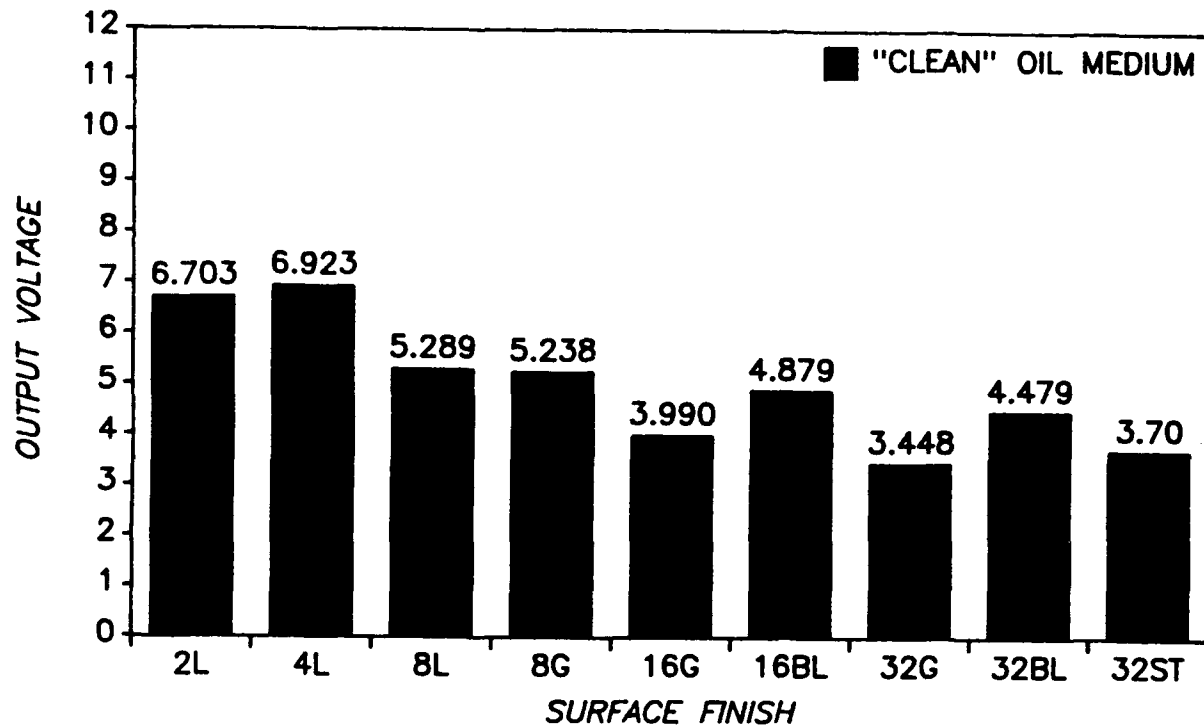


Figure 5-8, Photonic Sensor Results For Oil Medium Surface Finish Testing

When comparing Figures 5-6 through 5-8, by changing the amount of fluid present between the sensor face and the surfaces only, it can be seen that the sensor output is reduced with an increasing amount of fluid. The reduction in sensor outputs due to the presence of oil is similar in magnitude(s) to the changes in sensor output due to changing surface finishes.

Another problem occurred when the offset was changed but the oil medium remained constant (refer to Figure 5-9). By changing the offset of the probe by .001 inch in the positive direction the voltage output decreased as expected. However, in a manufacturing procedure such as honing, it would be difficult to maintain the offset to less than .001 inch. A change in offset may look like a change in surface finish. In this case, the data for a test with an oil film with a .001 inch offset would look very similar to the data taken with the entire probe submerged in the oil without an offset.

**SURFACE FINISH vs OUTPUT VOLTAGE
FOTONIC SENSOR WITH VARIABLE SURFACE
FINISHES AND A CONSTANT PROBE OFFSET**



TESTING DONE WITH A .005" POSITIVE
OFFSET OVER THE PREVIOUS TESTING AT
THE OPTICAL PEAK

Figure 5-9, Photonic Sensor Results For Oil Medium Surface Finish Testing with a New Offset

5.2.4 Test Conclusions

The data obtained through the testing shows that it would be very difficult to determine the actual surface finish of the bore tube with the constraints involved. Even if the sensor offset distance could be controlled, the variation in the fluid flow present in the tube would cause difficulty in determining if the surface finish was changing or the amount of fluid present was changing. For these reasons, it is recommended that the Photonic sensor not be used for the determination of surface finish. However, it may be possible to use it as a controlling device to identify a severe problems such as if the honing stones were to chip or break and large identifiable surface flaws occurred during the honing. The sensor would be able to determine large changes in surface finish prior to creating further flaws.

5.3 Ultrasonic Sensor With Stream Coupling Testing

Two specimens (1B1 and 2B1) from actual RIA parts were honed by B&W and submitted to the National Institute of Standards and Technology (NIST) to determine whether, with a minimum amount of effort, the feasibility of distinguishing between the surface roughness of the two specimens using ultrasonic and a liquid coupling technique could be established. The liquid supplied was Hangsterfer's #67 SU Honing Oil. This feasibility, along with other

considerations regarding implementation, is relevant to the possibility of using ultrasound to monitor the surface of cylinders as they are being honed.

The application of ultrasound as a sensing system for monitoring surface roughness during machining has been implemented recently for several machining/finishing processes. These include implementation on a milling center and on a turning center [1,2]. In both systems the ultrasound was coupled to the moving surface using a low velocity stream of the extant coolant (water based). The parts were fixtured and moving past the stream in some cases as fast as 1,000 surface feet/minute. Part surfaces were flat or cylindrical and measurements were made while additional coolant was being abundantly applied to the nearby cutting tool. Average surface finishes typically sensed were around 50 microinch and higher. Frequencies used for the monitoring were 6 to 15 MHz. (In some applications, 1 MHz ultrasound in air has been used.)

Generally, the ultrasonic transducer in the surface monitoring system is positioned so that the wave packet produced by the transducer arrives perpendicular to the surface being monitored. In certain applications non-normal incidence may have some advantages. Unlike the immersion technique, the ultrasound is transported to the surface by a couplant/coolant stream where it interacts with the surface of interest. Part of the energy is reflected directly back up the coolant stream to the sending transducer which also acts as a receiver. Part of the incident ultrasonic energy is also scattered. If the wavelength of the ultrasound is chosen to be appropriate for the surface roughness range of interest, the rougher the average surface roughness, the more energy will be scattered and the lower the amplitude of the reflected and received ultrasonic wave. This relation between the amplitude of the received ultrasound and average surface roughness has provided the basis for several of NIST's surface roughness monitoring applications. Also, for appropriately designed ultrasonic transducers as the surface roughness increases, the point-to-point variation in amplitude becomes larger, providing a second correlation for monitoring surface roughness [3].

In addition to roughness, the received ultrasonic wave amplitude depends to some extent on the incidence angle of the ultrasound with respect to the surface and on the distance from the sensor to the surface and on the characteristics of the coupling fluid. The sensitivity of a system to geometric factors (incidence angle and separation between sensor and surface) depend on the design of the transducer (e.g., focal length and depth of focus) but for some common designs there is no measurable difference in amplitude for changes of $\pm .5^\circ$ from normal incidence and no measurable change in amplitude for changes from $\pm .010$ in. to $\pm .1$ in. from the focus (depending on design). The dependence of the amplitude on the type of couplant (coolant) can within limits be calibrated out for any specific fluid.

Some of the critical problems in implementing an ultrasonic in-process surface roughness monitor for honing are associated with the honing oil. It was suspected that the attenuation of this fluid would be substantially higher than water or water based coolants and that this problem would tend to be more acute at the higher frequencies required for smoother surfaces. Because of this, ultrasonic (and limited mechanical) measurements were made using the immersion technique with the submitted honing oil, and some limited measurements using the immersion technique in water.

Surface Finish:

Estimates were made of the average surface finish of the specimens 1B1 and 2B1.

Measurements were made using a Taylor-Hobson Surtronic 3*. Note that these are not to be interpreted as a NIST calibration of surface finish measurements; they are useful working estimates of the relative average surface finish. Each specimen was measured at ten arbitrary locations along the inner center surface. For specimen 1B1 and a cut off of 0.01 in., the surface finish readings ranged from 29 to 37 microinch (R_a). For specimen 2B1 and a cut off of 0.01 in., the surface finish readings ranged from 15 to 20 microinch (R_a). These estimates are consistent with the estimate provided by the requestor based on knowledge of the process but not based on measurements.

*Certain commercial equipment is identified in this report in order to adequately specify the experimental procedure. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the equipment identified is necessarily the best available for the purpose.

Ultrasonic Measurements - Water:

Measurements were made of the reflected amplitude of ultrasonic pulses from various positions along the central interior of specimens 1B1 and 2B1. The purpose was to establish that, with water as the couplant, the surface roughness of the two specimens could be distinguished. The purpose was not to optimize the frequency (wavelength) or transducer design.

Data was taken with a 50 MHz (nominal) transducer which was tightly focused at 0.5 in., but the measured nominal operating frequency taken from the echo from a flat glass plate was approximately 40 MHz. The pulser was a shock excitation type and both pulser and receiver have a claimed bandwidth of 100 MHz to which they would be sensitive.

Specimen 2B1 was immersed in water and the transducer was normalized and refocused. The amplitude of the reflected signal was measured at eight arbitrary positions along the central interior of the specimen. The CRT voltage setting was 0.1 V/division. The readings were:

Location	1	2	3	4	5	6	7	8
Amplitude (divisions)	5.9	5.8	5.8	5.85	5.85	5.8	5.8	5.85

This yields an average of 5.83 divisions for specimen 2B1 with all readings between 5.8 and 5.9 divisions.

This procedure was repeated with specimen 1B1. The CRT settings were the same as with specimen 2B1. The readings for this specimen were:

Location	1	2	3	4	5	6	7	8
Amplitude (divisions)	5.6	5.6	5.4	5.2	5.5	5.25	5.6	5.6

This yields an average 5.47 divisions for specimen 1B1 with readings ranging from 5.2 to 5.6

The lower value for amplitude readings on specimen 1B1 are consistent with, and in fact felt to be a measure of, the rougher surface of 1B1 as compared to specimen 2B1. The larger amplitude variation from point to point on specimen 1B1 is consistent with and a measure of a rougher surface as probed by a tightly focused ultrasonic beam. With a larger beam (less

focused), the values for average amplitude would be expected to be approximately the same as tested, but variations from point-to-point would be expected to be smaller than tested.

Ultrasonic Measurements - Honing Fluid:

Information supplied with the honing fluid indicate that its density is approximately 93% of that of water. An estimate of the sound speed of the honing fluid based on approximate measurement and published data indicates that it is 95% of that of water plus or minus 3%. Thus the acoustic impedance of the honing fluid is very similar to that of water and so the overall acoustic beam produced by a transducer will be similar in both fluids; e.g., the focal point and depth of focus will be very similar. This does not account for attenuation which can strongly affect the signal amplitude as well as the waveform, i.e., the frequency content of the ultrasound that actually arrives at the specimen surface and that is returned to the transducer.

With the specimens immersed in honing oil, measurements analogous to those in water were attempted. The nominal frequency of the waveform was noticeably lower than in water, around 20 MHz as opposed to an estimate frequency of 40 MHz with water. The transducer emitted a wave packet of superimposed frequencies, which was nominally rated by the manufacturer as 50 MHz, but the couplant selectively attenuated the individual frequencies. The signal amplitudes were also much lower. The reflected signal from the specimen in honing oil at the focus position (separation between transducer and specimen of about 0.5 in) was approximately 50 dB (converted from voltage) lower than the signal level at focus in water. This leads to some noise problems at this large a separation. Further, the echo amplitude from the two specimens were not significantly different so that the surface roughnesses could not be distinguished.

It is believed that at this 0.5 in. separation, the honing oil scatters and severely attenuates the higher frequencies necessary to interact and distinguish between the two surfaces (with such low surface roughness), the signal attenuation of the fluid rising rapidly with frequency.

Some thought was given to working in the near field of the transducer (closer than its focal length), but its large case diameter and the specimen curvature prevented this.

Some measurements were attempted using transducers with nominal frequencies of 15, 20, and 30 MHz but these also did not result in distinguishing between the surface roughness of the two specimens.

The last measurements were made using a 20 MHz transducer with a 0.05 in. case diameter and a focus at about 0.1 in. Measurements were made very close (less than 0.1 in.) to the specimen surface. The waveform in honing fluid was, at this distance, indistinguishable from the waveform in water, the amplitude and waveform shape being extremely similar. Although this frequency was not high enough to distinguish between the two specimen roughnesses, the results indicate that a similar set up of a small transducer with a very short focus and a very small separation from the surface, but with a higher frequency, might well distinguish the roughness of the two specimens.

A subsequent inquiry to the transducer manufacturer indicated that such a transducer could likely be provided in the near term and at a reasonable cost.

Conclusions:

- 1) The roughness of specimens 1B1 and 2B1 were estimated to be 29-36 microinch and 15-20 microinch, respectively.
- 2) The density and sound speed of the honing fluid are similar to water but the attenuation is much higher. The frequency in the honing fluid also was lower than in water, as the honing fluid selectively filtered the higher frequencies. At a 0.5 in separation the reflected signals from a surface in honing oil have much lower amplitude than in water.
- 3) In water (and likely in most water-based coolants), it is possible to distinguish between the roughness of the two specimens based on signal amplitude or on point-to-point signal amplitude variation.
- 4) In honing oil, and with 0.5 inches separation, it was not possible to distinguish between the two roughnesses. Results using a very small transducer in honing fluid very close to the specimen gave waveforms that indicate that a small transducer of higher frequency may distinguish between the surface roughness although the 20 MHz transducer does not. Such high frequency transducers can be ordered without an onerous penalty in time or cost.

References

1. G. V. Blessing and D. G. Eitzen, "Surface Roughness Sensed by Ultrasound," Surface Topography 1 (1988) 253-267.
2. G. V. Blessing and D. G. Eitzen, "Ultrasonic sensor for measuring surface roughness," Surface Measurement and Characterization, 19-21 Sep 1988, Hamburg, Germany, Proc. SPIE 1009. 281-289.
3. D. G. Eitzen and G. V. Blessing, "Ultrasonic NDE for Surface Roughness," MRS Bulletin, April 1988. 49-52.

6.0 CONCLUSIONS

This section summarizes the conclusions drawn from the bench and machine testing for dimensional and surface finish inspection and any additional discoveries/conclusions not otherwise documented in the previous sections of the report.

6.1 Dimensional Inspection

The overall results of the dimensional inspection bench and machine testing performed by this study conclude that in-process inspection data can be accurately obtained during an abrasive machining (honing) process. Furthermore, the data can be used to generate real-time output displays that can be used by an operator to make in-process corrections, without interrupting the honing operation, and achieve a 100% acceptable part yield.

6.1.1 Sensors

The Omron eddy current sensors performed reasonably well but there are a few shortcomings that must be addressed in the production system design:

- Smaller sensor head
- Signal conditioner with a 0-10 Volt output
- Faster response time from the sensor
- Faster response time from the signal conditioner
- Ability to adjust gain, offset, and linearity

There are no off-the-shelf sensors currently on the market that meet all of these criteria for the optimum system.

The Kaman corporation manufactures custom eddy current sensors with custom modifications that can meet or exceed these specifications. For a production machine the sensor head should be small with a range of 0.200 inches. A flat sensor as opposed to a cylindrical one would be more appropriate for this application. The signal conditioner output voltage/current should be directly compatible with the data acquisition input voltage range to provide the maximum amount of resolution over the range of the sensor (i.e. $5 \text{ Volts}/4096 = 0.00122$ versus $5 \text{ Volts}/2048 = 0.00244 \text{ Volts/Count}$). The Omron sensors did not have any adjustment capabilities for offset and gain to achieve the best curve fit possible for a given range. These adjustments are very necessary to achieve the most accurate system possible. The sampling rate of the sensor and signal conditioner should be on the order of 10 KHz or greater to respond to diameter changes with a reasonable amount of accuracy. The Omron sensors did not meet the claimed specified 10 KHz frequency response. The sensors require a completely shielded cabling system with the appropriate impedance connectors to reduce the amount of crosstalk and noise picked up by the system. A smaller sensor head would be easier to mount in an existing honing head. A flat pancake type sensor would be appropriate for this application. As the diameter decreases so does the range of the sensor resulting in a trade-off of size versus range. For the honing machine application a sensor with a range of 0.200 inches is the best that can be achieved with the space constraints of the inside of a tube.

6.1.2 System Resolution

The resolution of the complete data acquisition system was on the order of ± 0.0002 inches for a non-rotating system. To measure attributes (such as roundness) on the order of .0001 inches, a dynamic system with a resolution of ± 0.00005 inches would be required. This could be accomplished by using a higher resolution data acquisition board (16 bits) and increasing the resolution of the eddy current signal conditioners. Also the eddy current signal conditioners should have gain, offset, and linearity adjustments to achieve a higher accuracy on the sensors themselves. Additional front-end electronics could be added to the two sensor signals before they are brought to the data acquisition board to reduce the number of channels needed to be read into the computer.

6.1.3 Data Acquisition Rate

The data acquisition rate for the system is currently 33 samples per second. This equates to an effective rate of 16 samples per revolution of the honing spindle. A faster sample rate of 10 KHz would be preferable to ensure that no data points are being skipped during the data acquisition process. The bandwidth of the sensors is approximately 5 KHz for a stationary system. Therefore a sample rate of at least 10 KHz should improve the quality of the data. The current system has the inherent flaw of a slow data acquisition rate that only permits a sensor to read only every 22.5 degrees of rotation within the bore tube, or 11 degrees between the two sensor readings comprising a diameter reading.

6.1.4 Phase Shift Reading Errors

B&W established that the primary source of error was due to the 11 degree rotational phase shift between the two sensor readings comprising a diameter reading. Although small, this phase shift was found to result in a larger error in the diameter reading. If the honing head rotational travel is less than perfect, the gaps between the sensors and the inspection surface may change during the 11 degree rotation between the two individual sensor readings, causing an error in the total diameter reading.

The imperfect rotation can be caused by mechanical "slop" or "wobble" in the honing head such as clearances between the push cone and the stone holder body and variations in the radial distance to the stone faces. B&W determined that this phenomena does occur, and was a significant contributing factor to the errors seen in the inspection data as follows; In a round part (as was the case for the RIA supplied test parts), the gap between the sensors and the part surfaces are expected to remain fairly constant. However, by running the system with only one sensor active, B&W discovered that the gap would vary, for example, by 0.008 inches within 180 degrees of rotation (refer to Figure 4-13). This evidence proved that the wobble phenomena does occur.

The .008 inches of variation (wobble) over 180 degrees, converts to an incorrect diameter reading of about ± 0.0005 inches for an 11 degree rotational phase shift. The real-time graphical output display appears as a curve that oscillates around the actual mean diameter of the part (refer to Figure 4-16). The solution to this problem is to obtain simultaneous sensor readings such that there is no phase shift between the two individual sensor readings and hence no phase shift error due to any amount of mechanical wobble. This was not possible with the equipment used in this study. (The recommended equipment for obtaining the simultaneous sensor readings are discussed in the Recommendations, Section 7.0, of this report.)

6.1.5 Temperature Effects

Thermal expansion, although small, is a factor when performing real-time inspection on a honing machine when considering the accuracies required to resolve attributes such as roundness on a part with diameters as large as the RIA test parts. Thermal expansion during honing results in a biased reading error, where a 10 degree F difference can result in a .0002 inch bias. Hence, as a minimum, a representative part temperature should be monitored for a minor thermal correction factor (bias), such that the diameter reading will be correct at room temperature (ambient temperatures are usually assumed for dimensional inspections). Accuracies of ± 2 degrees F are more than adequate for the temperature sensing device.

6.1.6 Accuracies

The accuracies obtained during the testing indicated that a target six standard deviation limit of 0.001 inches for accuracy was achieved by a single diameter average per cross section basis (generated from a full revolution worth of readings). If the attributes required to disposition the part is the mean diameter, local and overall tapering, barreling and/or bell mouthing only one reading per linear position is required and therefore the attributes can be resolved to the desired accuracies. One should also remember that during a honing operation the hone translates a few inches per revolution (depending on the required surface speed, part diameter and cross hatch angle - usually about equal to the diameter in linear travel per revolution). Therefore, the average reading is not per cross section, but would be per linear sections. This data can still be used successfully inspect the aforementioned attributes.

If additional bore attributes are desired such as roundness, the six standard deviation limit of .001 inches is required on a point for point basis. Point for point readings are required to resolve and locate the deviations in roundness. Unfortunately the six standard deviation accuracies of single (point-for-point) readings were up to twice the expected maximum out-of-roundness. But the primary problems found (phase shift reading errors which caused the errors) can be greatly reduced making the target accuracies achievable (i.e. by implementing the recommendations of this report).

The system was found to be repeatable and did meet the six standard deviation limit of .001 inches. This is encouraging, since while rotating, the repeatability was not much larger than the inherent system resolution, while standing idle ($\pm .0004$ inches as compared to $\pm .0002$ inches).

6.1.7 Practical Application of Data

As seen in the study, the real-time graphic display can be used by an operator to easily evaluate variations and deviations in various bore attributes (mean diameter, tapering, barreling, and bell mouthing). In short, the operator can be provided a real time picture of the parts overall profile in which the gradual formation of the profile can be observed. The operator (or software) can make decisions and take actions to correct part attributes without interrupting the operation to gauge the part. Corrective actions for these attribute deviations are simple. They involve short stroking and/or localized rotation without reciprocation until the part is nearly perfect such that full stroking can resume. Furthermore, the system presents 100% coverage on the part in lieu of the small sampling that can be obtained only after stopping the machine and probing the part. Additionally, 100% in-process coverage will reveal the development of a severe local deviation, while the degradation may be missed by intermittent randomly positioned manual inspections. With the in-process inspection system developed during this study, 100% acceptable yields should be achievable.

Theoretically, roundness can be measured by the rotating inspection system, where any out-of-roundness in the part would result in a sinusoidal wave pattern on the operators real-time graphical output display, about the mean diameter of the part. However, due to the large diameter fluctuations from the phase shift error, smaller fluctuations from roundness could not be resolved by the demonstration system. B&W notes that roundness measurements are not as important as other attributes, for example bell mouthing, since small amounts of roundness (.0002 inches) are not easily corrected for even if known to exist. Additionally, the nature and secondary purpose of honing is to remove any deviations in roundness, such that any out-of-roundness will be too insignificant. The recommended retrofit package includes the equipment and corrections necessary to eliminate the phase shift error, such that larger amounts of out-of-roundness (.001 inches) can be found. If necessary, a deviation of this magnitude can be minimized by rotating the workpiece 90 degrees to compensate for the effects of gravity, although if used properly, the system will reveal the evolution of a severe roundness deviation prior to its formation.

6.2 Surface Finish Inspection

The photonic optical sensor was shown to be capable of detecting changes in surface finish in an ideal (dry) laboratory environment. As the surface finish becomes rougher, smaller amounts of reflective light is received reducing the output of the sensor. However, further bench testing to simulate the less stable machining conditions and hostile environment seen in typical honing applications proved that it would be very difficult to determine surface finish in an "in-process" inspection setup. There were at least three other factors that reduced the output of the sensors by magnitudes similar to that seen from the change in surface finish only. Type of finish, the amount of honing fluid between the sensor and the part surface, and the offset distance between the sensor and the part surface were among those identified. All of these parameters are found to vary in a typical honing operation such that it would be extremely difficult to resolve the response of the sensors due to surface finish only. However, the sensors could be used to detect larger changes that may indicate a problem occurring with the cutting abrasives and the metal removing operation without controlling these parameters.

Although the results of the ultrasonic with stream coupling testing were somewhat inconclusive, previous studies have indicated that it may have a higher potential for success than the optical techniques in "in-process" inspection for abrasive machining, since the technique is typically less sensitive to change in sensor offset and finish type. Therefore, it is more capable of resolving the surface finish. It did show a greater attenuation from honing oil than from water that would require smaller sensors with higher frequencies (than that typically used) in order to resolve changes in surface finish. With the appropriate sensors, this technique may be able to resolve surface finish within a reasonable range. However, calibration of the sensors for the expected ranges of surface finishes and fixturing to an existing honing machine design for "in-process" use would be complicated.

In conclusion, pursuing "in-process" surface finish inspection techniques for abrasive machining would require significant additional R&D. However, "post process" on-machine inspection utilizing an automated probe with either sensing technologies (following a cleaning operation to remove the coolant/grind slurry for optical sensors) could be implemented with little or no R&D to inspect the surface finish of a honed part. This could be done both as intermediate and final inspection steps.

7.0 RECOMMENDATIONS

Based on the results of this study and the knowledge gained of honing, B&W recommends pursuing retrofitting an existing machine at RIA with an IPIS for production use in a Phase II effort. The system would be used to aid the operator in producing a more perfect part, in less time, with 100% "dimensional" acceptance rates and provide a test bed to implement and verify the recommendations. Statistical process control (SPC) methods could be utilized to assure the quality of part's dimensions for final disposition per the IPIS data.

A Phase III effort would be to close the loop - eliminating the operator from changing the machine parameters per the IPIS data. It is recommended this not take place until the test bed in Phase II verifies the concepts recommended herein. Retrofitting a RIA hone with the Phase III controller could be costly since the existing older machines would require significant control electronics modifications. A control system that would allow a closed loop strategy should be considered for incorporation into a more modern honing machine.

The Phase II and III recommendations are presented herein which describe the proposed open loop retrofit system concept and an envisioned closed loop system respectively.

7.1 Proposed Open-Loop Retrofit System

The proposed retrofit IPIS is shown in Figure 7-1. The system includes incorporating the following minimum features to an existing machine at RIA.

- Four (4) Inductive (eddy current) Sensors/Electronics
- One (1) Customized Stone Holder Body (Honing Head)
- One (1) Customized Drive Shaft
- One (1) Instrumentation Slip Ring (High Speed)
- One (1) Rotary Encoder
- One (1) Linear Encoder
- One (1) Flexible wire tube (GoreTube)
- One (1) Infrared Red Temperature Sensor (not shown)
- One (1) High Speed Data Acquisition Board
- One (1) 80386 Based Computer System
- One (1) Computer Enclosure
- One (1) Operator Station
- Custom Mechanical Fixturing (for the integration of the items above)
- One (1) Offset Calibration Standard (not shown in figure 7-1)

7.1.1 Sensor & Equipment Fixturing

The system design concept is based on integrating the necessary equipment to an existing machine without interfering with the operator, or adding any additional production steps which would increase the setup time for a machine. This would be accomplished by packaging the sensors into the honing head, and mounting the related electronics at the machine spindle

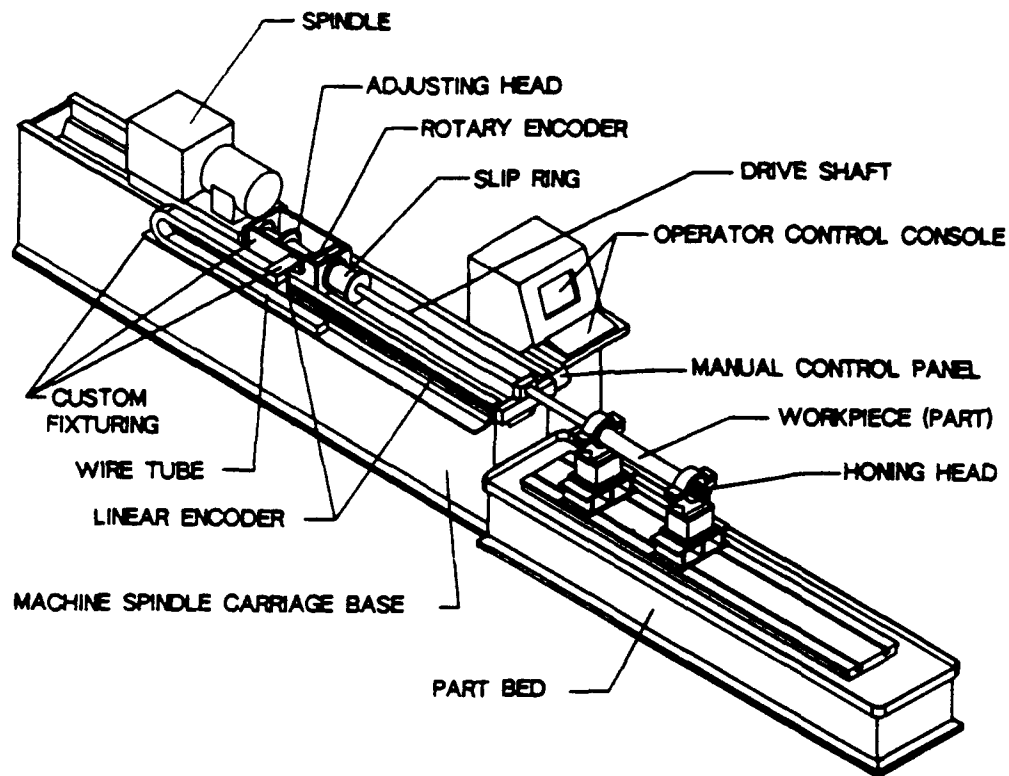


Figure 7-1, Proposed Retrofit System

interface, such that the only additional setup required by an operator would be to connect and disconnect the sensor leads, and the insertion and expansion of the honing head into an offset calibration standard. The offset standard can either be mounted in line on a stand, or be set near the machine.

The optimum sensor fixturing design from a reliability standpoint is to imbed the sensors into the honing head body (refer to Figure 7-2). To achieve a reliable, functional system, customization of the honing tooling (honing head and drive shaft) cannot be avoided. A nylon guard surrounding the sensor is mounted to the hone body. The surface of the sensor is set below the surface of the guard, to protect the sensor from being bumped, possibly knocking it out of calibration. Four sensors are required, two at each end of the honing head, such that two opposing sensors will be in the bore at all times during the stroke to provide 100% dimensional inspection of the bore. For the smaller hone bodies and for the (5) stone type honing heads, mounting two sensors opposite each other may be possible. For the larger honing heads (larger than 3" diameter and larger) which are either of the (4) stone and (6) stone design, the sensors could be incorporated into the honing head. However, the diameter of a given honing head actually changes to accommodate actual size of a the part being honed.

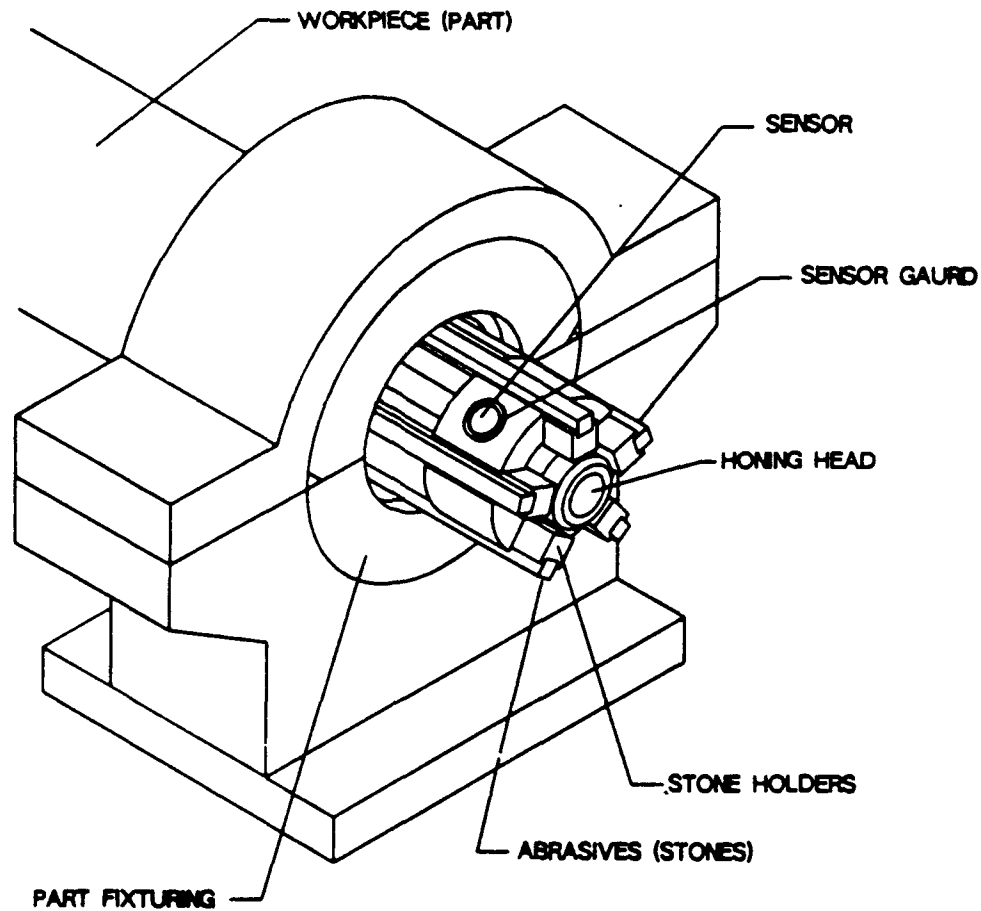


Figure 7-2, Proposed Retrofit System Honing Head

The range of a typical honing head is usually at least 0.500 inches and can be as high as 1.500 inches, depending on the nominal size of the hone. The range of even the smallest honing head (.500 inches greater than its fully closed (smallest) diameter) is larger than that of typical eddy current sensors (.150 for one and .300 for a pair). Hence, mounting the sensors in the honing head does not allow for the tooling to be used to it's full capacity, since a pair of sensors will not be able to cover the entire range of the honing head. Additionally, imbedding the sensors into the honing head will not allow the sensors to be utilized on more than one honing head, adding cost to the system if various honing heads are used on a particular machine by the end user. Therefore, B&W recommends an alternative method, where the sensors are mounted in a four (4) piece clamping ring which is clamped to an extension to the neck and end of the hone body (refer to Figure 7-3). This concept also requires minor redesign to the honing head, but allows for adjustability to the sensors for any diameter, and for the sensors (and clamping rings) to be utilized on more than one hone head. A clamping ring arrangement, for example, could be adjusted to accommodate a range of an inch or more.

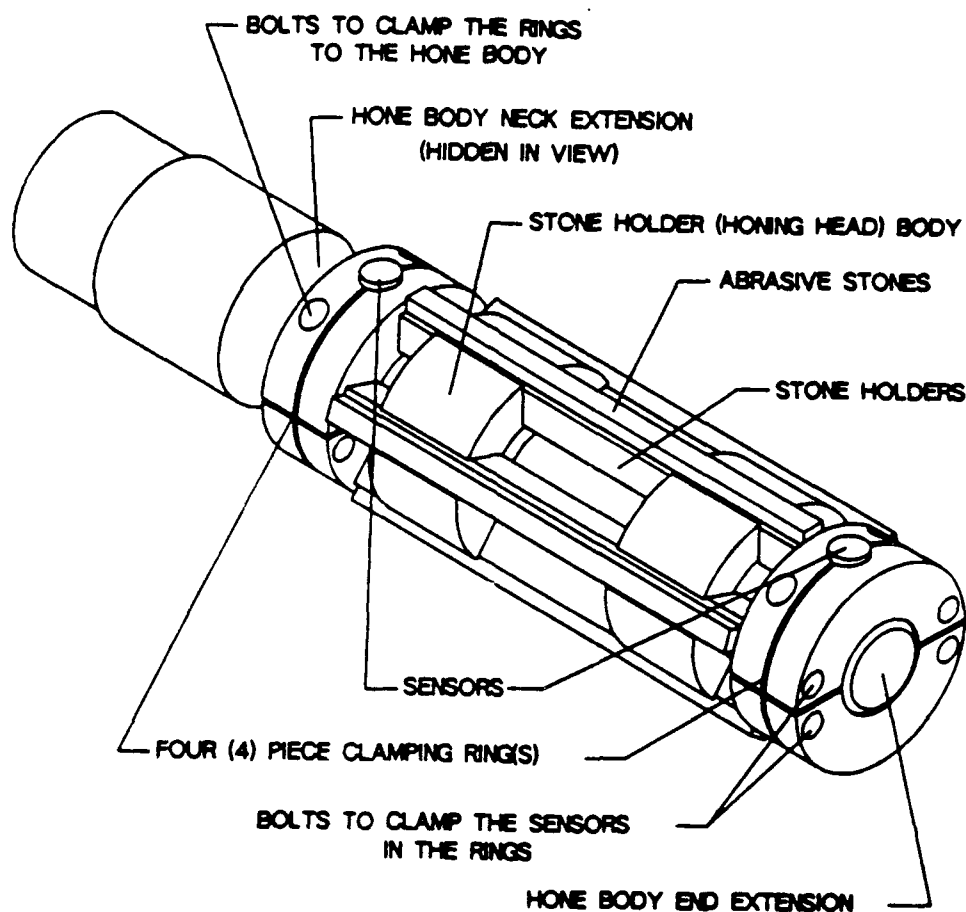


Figure 7-3, Alternate Proposed Retrofit System Honing Head

The lead wires for the sensors would be mounted in the drive shaft. A small groove would be machined into a standard drive shaft to provide for potting the lead wires. This will protect the wires from being damaged by the drive shaft supports. The plug connection for the wires could be mounted at the drive shaft-honing head interface, such that when the honing heads are interchanged, the sensors leads would be connected automatically.

At the opposite end of the drive shaft, a torus style slip ring and rotary encoder are to be fixtured to the spindle carriage. The fixturing would surround the adjusting head such that it can be accessed by the machine operator (refer to Figure 7-4). A linear encoder and flexible wire tube are fixtured, out of the operator's way, to the side of the machine via additional fixturing. The scanning part of the linear encoder and moveable end of the wire tube are fixtured to an extension in the slip ring fixture, such that they will travel with the spindle (refer to Figure 7-4). The purpose of the encoders are to provide rotational and axial positioning feedback for mapping the part profile. This exact feedback is needed in order to make corrections such as short stroking or rotation of the part.

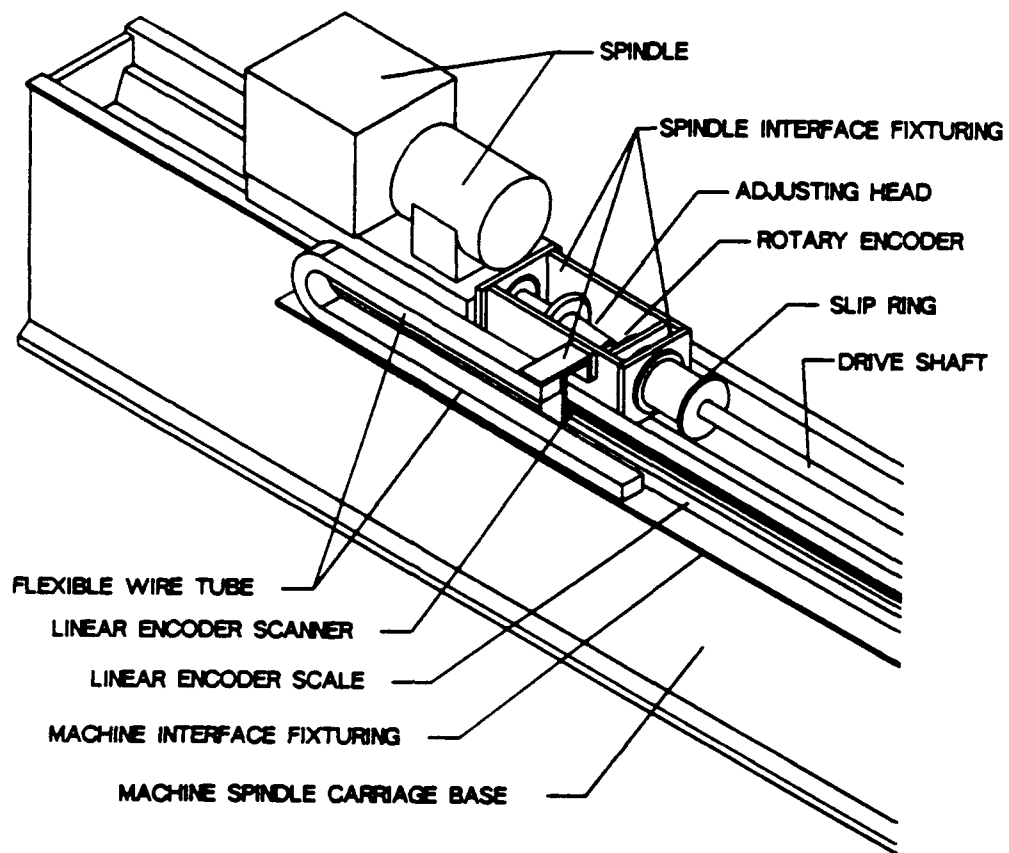


Figure 7-4, Proposed Retrofit Machine Modification

An infrared temperature sensor would be mounted on a stand on the opposite side of the machine from the operator, and aimed at the workpiece surface (not shown in Figures). The sensor would measure a representative temperature of the part, which would be used by the software to compensate for the thermal expansion in the diameter measurements. (Utilizing the outside temperature of the part to represent the average temperature of the part is based on the assumption that after a couple of minutes of honing (typical operations may involve up to a half hour of honing), the part temperature reaches an equilibrium temperature that is fairly constant throughout. (This was the case during the study.) Non contacting temperature sensing is required such that the part could rotate freely during honing without being restricted by sensor leads and such that the leads will not interfere with each other. The necessity for temperature compensation can only be determined by observing the temperature increases actually experienced at RIA. Once the maximum temperature variations are determined, the effects on the inspection errors can be calculated and the need for temperature compensation can be assessed.

A Phase II approach on sensing would be specific size and range eddy current sensors. These new sensors would have a fast frequency response (10 KHz) and be tightly packaged in order to fit in any currently available honing machine head. The sensor would preferably have a right angle electrical plug connection as opposed to a straight out wire as is currently available to reduce the amount of noise in the system and to better adapt to the fixturing.

The sensors would plug directly into the triaxial cabling that would be mounted in grooves on the spindle shaft. This cable would be watertight and oil resistant to prevent any cable deterioration due to oil and metal filings flowing over the sensors. Shielded cable will be utilized on each sensor such that all four cables can be mounted in the same groove without any cable crosstalk.

An instrumentation slip ring would be required to permit the passage of high frequency signals without any signal degradation due to rotational resistance. Triaxial cables and connectors would be required for isolation between each of the sensors so that no signal feedthru or bleedover would be encountered. Mounting the slip ring at the rear of the honing machine is preferable. This would reduce the forces applied to the slip ring that create worn spots, since the slip ring surrounds the drive shaft in lieu of being an integral structural part of the tooling. These worn spots would eventually increase in resistance and vary the sensor readings in an unpredictable manner. As the slip ring wears and the brush resistance increases the sensor readings deviate from normal. This type of wear is unpredictable because brush wear is a function of both slip ring load and rotational speed.

The signal conditioners would be manufactured by the same vendor as the sensor manufacturer to ensure 100 percent compatibility and the highest quality system available. A signal conditioner with a 0-10 Volt output is more than adequate for a data acquisition board to handle. A 4-20 milliampere current loop signal could be utilized if the environment is electrically noisy. This would prevent any unwanted voltage spikes from appearing in the system causing erroneous readings. It is preferable for the signal conditioner output to match the data acquisition board input to make full utilization of the possible volts per bit ratio (i.e. $5 \text{ Volts}/4096 = 0.00122 \text{ Volts per count}$). The sensor electronics would be mounted in the computer cabinet as depicted in Figure 7-1.

7.1.2 Data Acquisition Equipment / Operator Interface

A data acquisition subsystem would be mounted in a computer cabinet convenient to the operator for operator input and real time diameter feedback. The data acquisition board must have at least 12 bits of resolution with a preferable resolution of 16 bits. The board would be required to acquire data at a rate of 50,000 samples per second to prevent any signal degradation or aliasing. Also, the inputs to the board must be differential (separate shields) to prevent any channel crosstalk due to noisy ground cabling as opposed to a pseudo-differential data acquisition board. A data acquisition board mounted outside the computer would decrease the noise created from the computer itself. A normal computer backplane with an 8 MHz bus rate is a great source of noise for a sensitive data acquisition board to pickup due to other cards in the backplane and a common power supply. Along with a noisy bus are the power supplies, motherboard, hard drives, and floppy drives that contribute to the noisy environment. The board would then be connected to the computer through an RS-232 interface.

The data acquisition system would be comprised of a four channel analog input system which is capable of taking data from four sensors simultaneously. The data would then be conditioned in order that the software could plot the real-time diameter readings of the tube. The data acquisition system would be triggered such that all of the sensors were taking data simultaneously. The frequency response of the system should be on the order of 50 KHz or greater to prevent aliasing of the data.

The real time data acquisition software would be employed in the design the Phase II system. This software would be capable of monitoring the honing operation in addition to the data acquisition. The sensor data would be plotted to the screen after each pass of the honing head through the tube. The computer display would be further customized with a real time graphical interface package to better inform the operator about the status of the honing operation. The software will be menu driven to enhance the capabilities of the system. A commercial software program will be integrated into the overall system to enhance the data acquisition rate of the overall system.

Note: B&W does not recommend pursuing in-process "surface finish" inspection for honing, where the potential for success is low and extensive development effort is still required to prove feasibility for a production system. B&W recommends an on-machine post-process inspection gauge, where the ability to control the sensor standoff on a clean, dry surface permits various sensor techniques to be utilized successfully in an automated manner.

7.2 Closed-Loop System

The ultimate goal of an in-process inspection system for abrasive machining is to link the data acquisition system proposed in Section 7.1, and the machine parameters with a closed loop computer controlled system. The machine would automatically *control the entire honing operation*. Based on the real-time data obtained, the system would automatically adjust the machine parameters, such as start and stop, stroke lengths and possibly hydraulic pressure (to adjust to the desired metal removal rate), and alarming the operator when assistance is required (i.e. remove the finished part from the machine or change from roughing to finishing stones), to produce a near perfect part every time.

The operator's responsibilities will entail loading and unloading parts from the machine, changing tooling when required, inserting the honing head in the part and starting the process via the computer. The software program would be menu driven for pre and post operation checks and ease of operation. The operator could set limits on the machine parameters or part parameters (i.e. tolerances) such that the system will automatically make corrections when the limits are reached or stop the machine and alarm the operator when assistance is required. Since the process is constantly monitored and completely run (inclusive of prompting the operator through the setup procedure automatically), an operator can easily run more than one machine at a time.

The closed loop system requires that all of the similar equipment recommended in Section 7.1 be retrofitted to a new or existing honing machine. The additional features required to close the loop involve integration with the existing honing machine controls - replacing relays, switches, and electromechanical equipment where necessary to be compatible with the automated control system equipment. These replacement parts along with the data acquisition equipment could eventually become an option for a new honing machine or a standard retrofit

package for a used hone, offered for any type of honing machine manufactured. Hence, the control software must be developed to accommodate monitoring and controlling all of the machine parameters that an end user may possibly require for any new or retrofitted honing machine.

Appendix I

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APPENDIX I - DRAWINGS

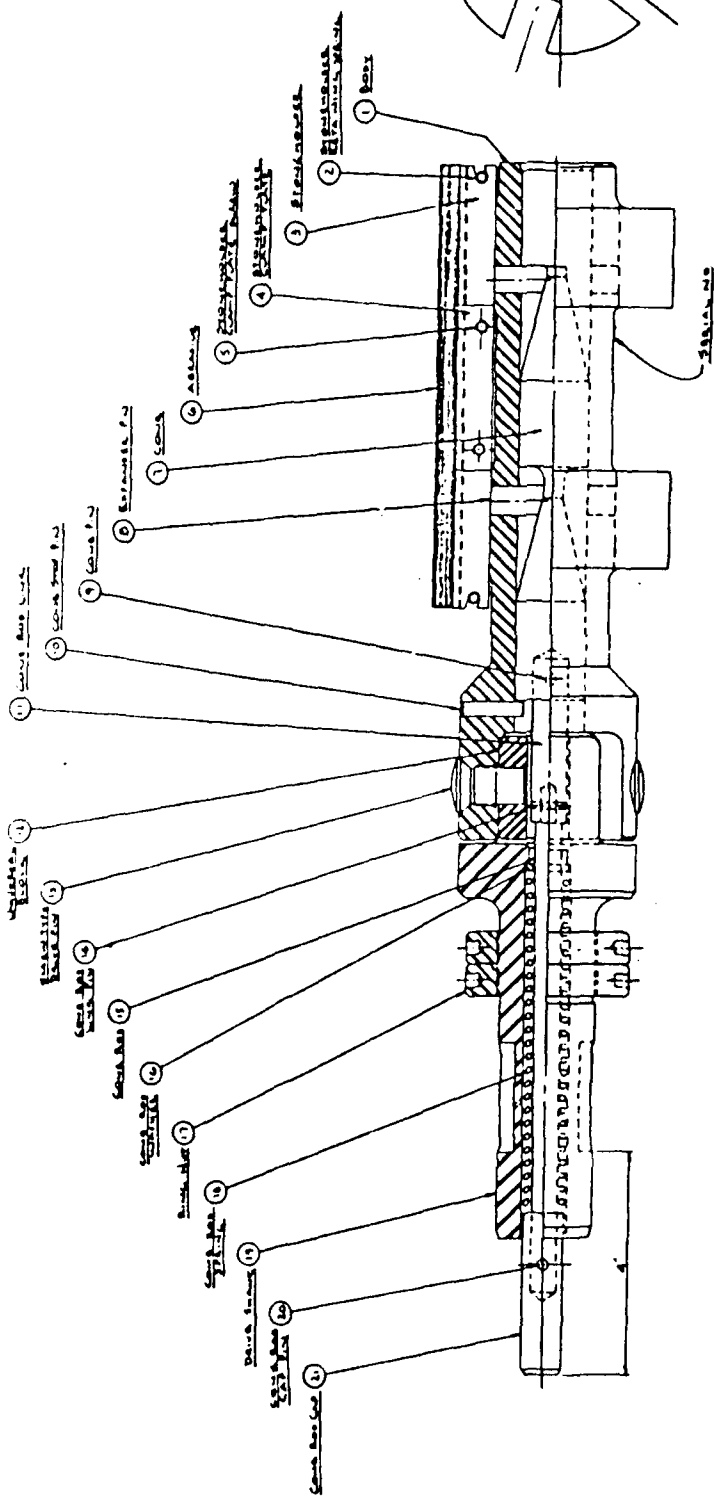
General Hone Drawings:

G10D116	Hone Body Assembly
G40D102	Standard Drive Shaft
G30C103	Adjusting Head

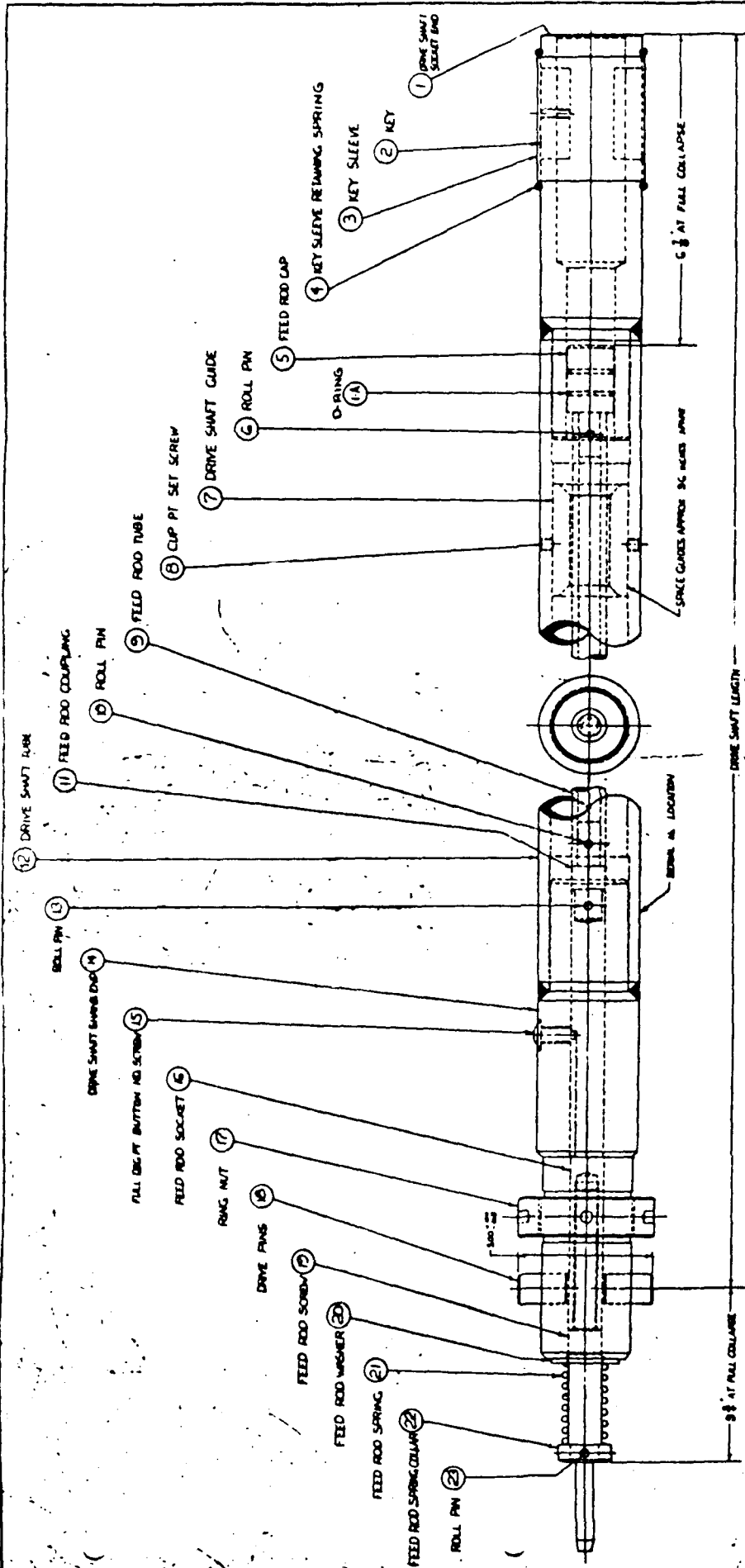
B&W Drawings:

LT-2880, Sheets 1 to 4, Sensor & Part Fixturing for RIA
Honing
CIMS-A31-1, RIA Sensor Fixturing Modifications

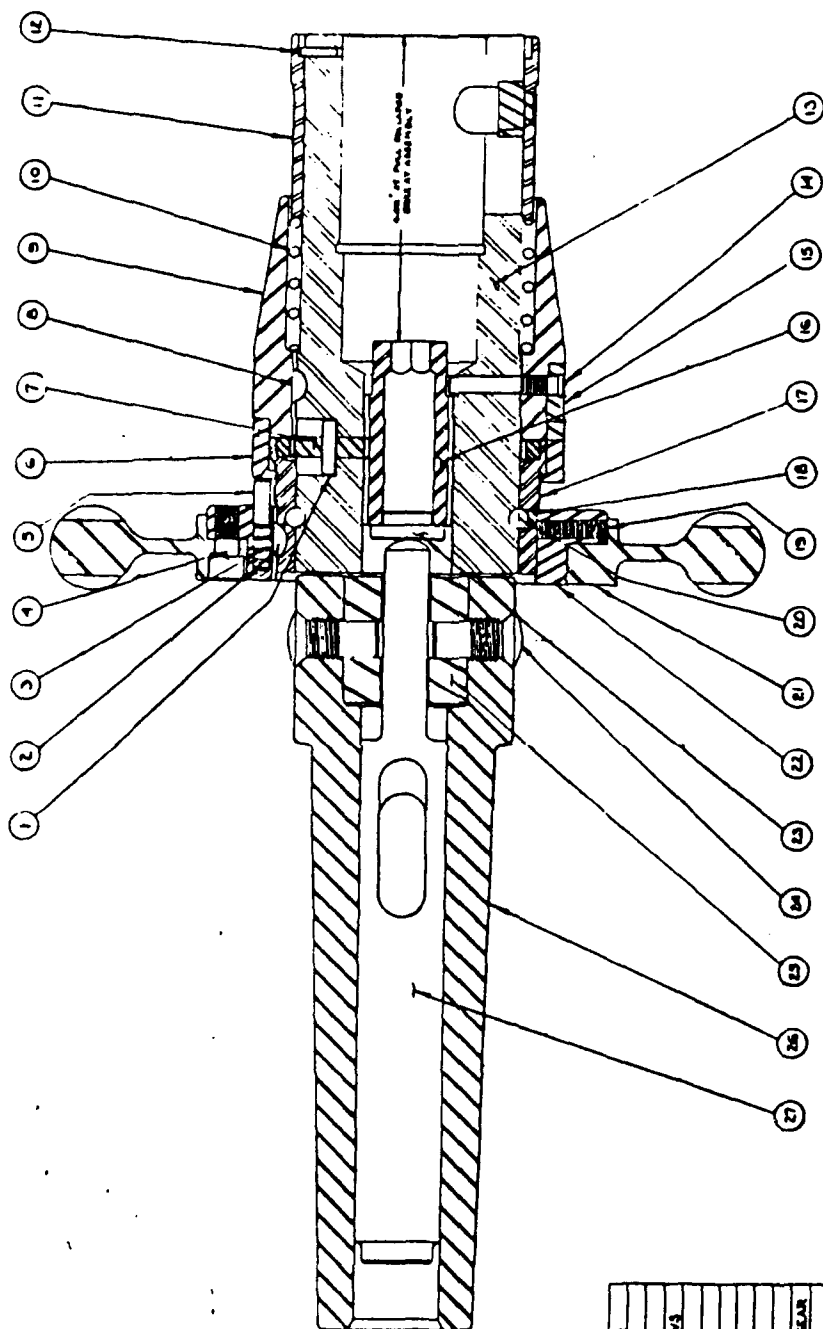
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GENERAL DATA NAME: _____ MODEL: _____ SERIAL NO.: _____ DATE: _____		DRAWING NO.: _____ SCALE: _____ SHEET NO.: _____	
MATERIAL: _____ MANUFACTURER: _____ INSPECTION: _____		APPROVED: _____ CHECKED: _____ DESIGNED: _____	



SO NO. _____
 QUANTITY REQUIRED _____
 R/R _____
 DATE _____
 BY _____
 CHECKED BY _____
 APPROVED BY _____
 SPECIAL INSTRUCTIONS _____
 PART NO. 15-15 1 15-25-15 15-25-15

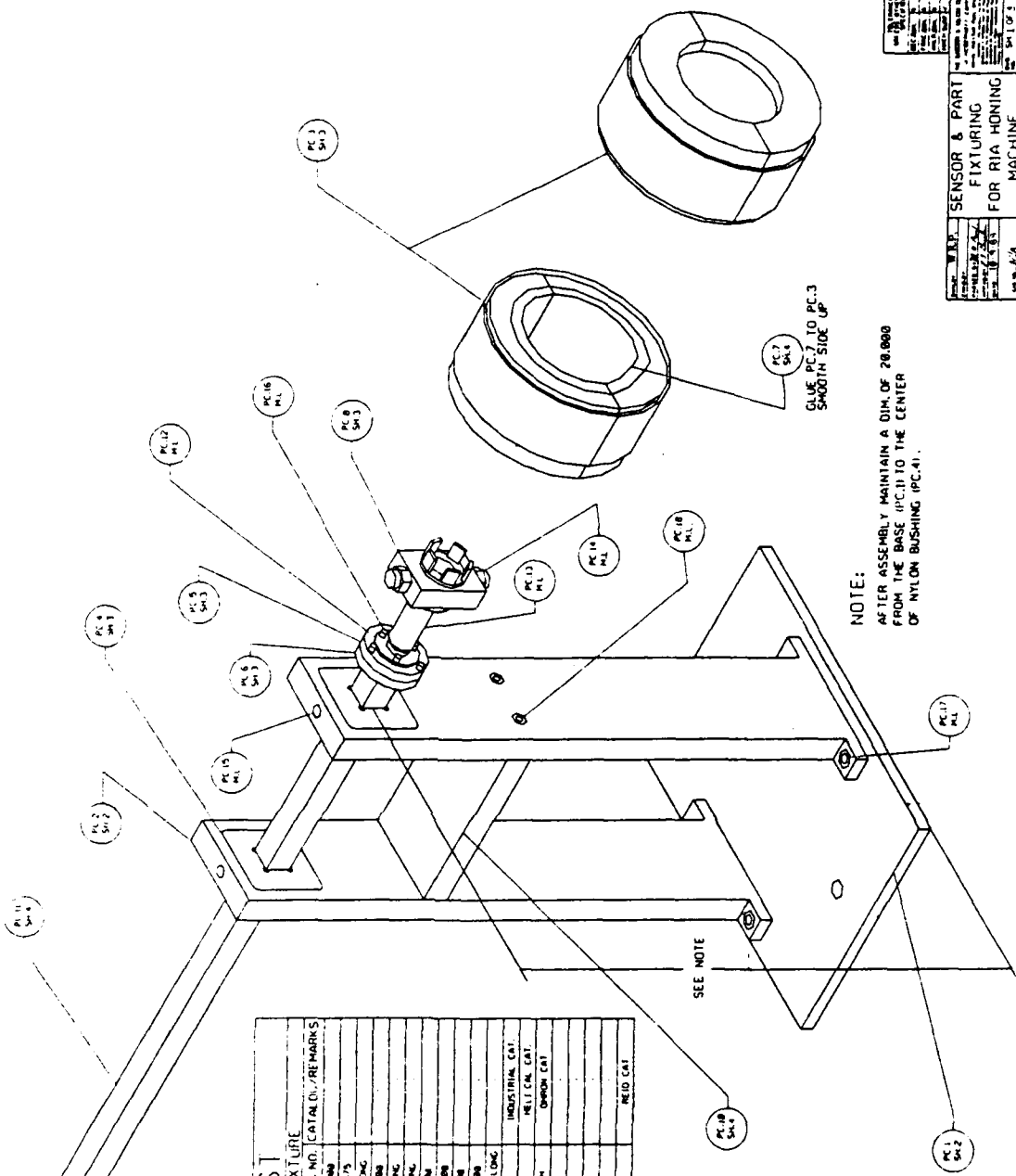


27	HYDRAULIC PUSH ROD
26	DRIVE SHAFT
25	UNIVERSAL JOINT
24	UNIVERSAL DRIVE SHAFT
23	GEAR BUTTON
22	HANDWHEEL COLLAR
21	HANDWHEEL
20	BALL BEARINGS
19	DOUBLE SET SCREWS
18	BALL BEARING
17	ADJUSTING BEARING WING GEAR
16	PISTON GEAR
15	LOCK KEY
14	LOCK SCREW
13	ROD
12	ROLL PIN
11	LOCK BUSH
10	SHAKE SPRING
9	LOCK COLLAR
8	WOODRUFF KEY
7	WELL GEAR
6	WELL COLLAR
5	PLUNGER
4	ADJUST NO. CAP SCREW
3	PLUNGER SPRING
2	WOODRUFF KEY
1	LOCK PIN
NO	DESCRIPTION

GENERAL BODE CORPORATION BIRLA OHIO U.S.A.	
DATE: 1-1-63	BY: J.E.B.
* 411 ADJUSTING HEAD - ASSEMBLY	
CJOC/03	

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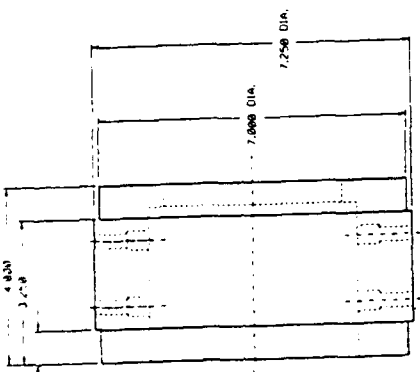
PC	SN	QTY	DESCRIPTION	PART SIZE / CAT. NO.	REMARKS
	1	2	ALUMINUM	750 X 18 000 X 14 000	
	2	2	ALUMINUM	1 000 X 6 000 X 21 375	
	3	3	W/LOH 18"	2 250 Dia X 6 000 LONG	
	4	3	W/LOH 18"	1 000 X 3 000 X 3 000	
	5	3	W/LOH 18"	2 500 Dia X 375 LONG	
	6	3	ALUMINUM	2 500 Dia X 375 LONG	
	7	3	LEADING #	125 X 3 000 X 7 750	
	8	3	ALUMINUM	2 000 X 2 000 X 3 000	
	9	2	4140 STEEL	1750 X 1 000 X 2 500	
	10	5	ALUMINUM	1 000 X 4 000 X 7 000	
	11	1	ALUMINUM TUBING	1 50 X 125 WALL X 60 LONG	
	12	1	SLIP RING	3" ID	
	13	1	WELL CAL. COMP. LING	CAT NO. 40-12-10	INDUSTRIAL CAT
	14	1	SENSORS	CAT NO. 40-12-10	WELL CAL. CAT
	15	6	SOC. SET 5/8"	3/8 16 1/8 LONG	OMRON CAT
	16	6	SOC. NO. CAP. SENSE	3/8 12 1/8 LONG	
	17	4	SOC. NO. CAP. SENSE	3/8 16 1/8 1" LONG	
	18	4	SOC. NO. CAP. SENSE	3/8 16 1/8 1 1/2" LONG	
	19	2	I-HUB	CAT NO. 14	FIELD CAT



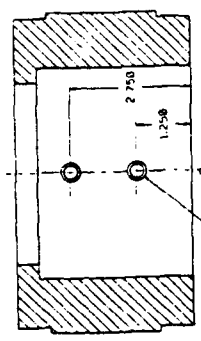
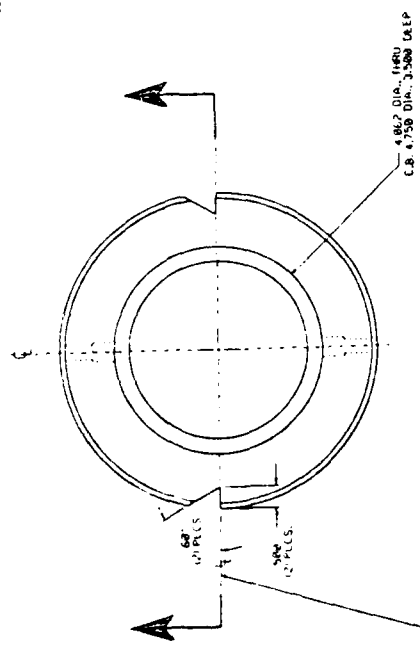
NOTE:
AFTER ASSEMBLY MAINTAIN A DIM. OF 20.000
FROM THE BASE (PC.1) TO THE CENTER
OF NYLON BUSHING (PC.4).

[illegible]

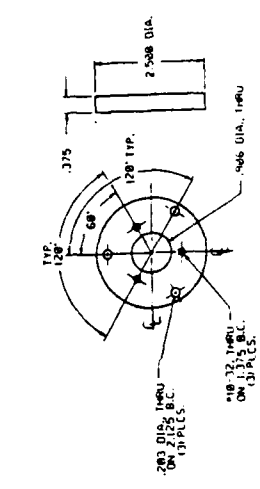
REV	DATE	BY	CHKD	APP'D	DESCRIPTION
1	10/1/68	J. J. J.			INITIAL DESIGN
2	10/1/68	J. J. J.			REVISED FOR MACHINING
3	10/1/68	J. J. J.			REVISED FOR MACHINING
4	10/1/68	J. J. J.			REVISED FOR MACHINING
5	10/1/68	J. J. J.			REVISED FOR MACHINING
6	10/1/68	J. J. J.			REVISED FOR MACHINING
7	10/1/68	J. J. J.			REVISED FOR MACHINING
8	10/1/68	J. J. J.			REVISED FOR MACHINING
9	10/1/68	J. J. J.			REVISED FOR MACHINING
10	10/1/68	J. J. J.			REVISED FOR MACHINING



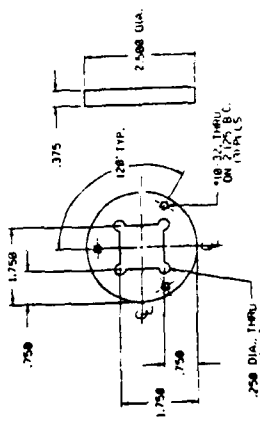
PC.3 - 4 REQ'D
MAT'L - NYLON 101



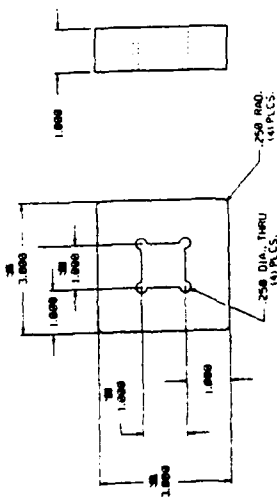
MACH FOR 1/2" SHCS
C.B. .500 DEEP
12 PLS.



PC.5 - 1 REQ'D
MAT'L - NYLON 101



PC.6 - 1 REQ'D
MAT'L - ALUMINUM



PC.4 - 2 REQ'D
MAT'L - NYLON 101

REV	DATE	BY	CHKD	APP'D	DESCRIPTION
1	10/1/68	J. J. J.			INITIAL DESIGN
2	10/1/68	J. J. J.			REVISED FOR MACHINING
3	10/1/68	J. J. J.			REVISED FOR MACHINING
4	10/1/68	J. J. J.			REVISED FOR MACHINING
5	10/1/68	J. J. J.			REVISED FOR MACHINING
6	10/1/68	J. J. J.			REVISED FOR MACHINING
7	10/1/68	J. J. J.			REVISED FOR MACHINING
8	10/1/68	J. J. J.			REVISED FOR MACHINING
9	10/1/68	J. J. J.			REVISED FOR MACHINING
10	10/1/68	J. J. J.			REVISED FOR MACHINING

SENSOR & PART
FITTING
FOR RIA MONITORING
MACHINE

1-28801

CS 212

PC.7 - 4 REQ'D
MATH - LEATHER

PC.9 - 1 REQ'D
MAT'L - 4140 STEEL

PC.10 - 1 REQ'D
MAT'L - ALUMINUM

7.000	1.000	2.000	3.000	4.000	5.000	6.000	7.000	8.000	9.000	10.000	11.000	12.000	13.000	14.000	15.000	16.000	17.000	18.000	19.000	20.000	21.000	22.000	23.000	24.000	25.000	26.000	27.000	28.000	29.000	30.000	31.000	32.000	33.000	34.000	35.000	36.000	37.000	38.000	39.000	40.000	41.000	42.000	43.000	44.000	45.000	46.000	47.000	48.000	49.000	50.000	51.000	52.000	53.000	54.000	55.000	56.000	57.000	58.000	59.000	60.000	61.000	62.000	63.000	64.000	65.000	66.000	67.000	68.000	69.000	70.000	71.000	72.000	73.000	74.000	75.000	76.000	77.000	78.000	79.000	80.000	81.000	82.000	83.000	84.000	85.000	86.000	87.000	88.000	89.000	90.000	91.000	92.000	93.000	94.000	95.000	96.000	97.000	98.000	99.000	100.000
-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	---------

PC.10 - 1 REQ'D
MAT'L - ALUMINUM

VIEW ROTATED 90°

Technical drawing of a mechanical part, showing front and top views with dimensions.

Front View (Top):

- Overall width: 3.000
- Overall height: 2.000
- Left side features a $\frac{1}{16}$ " SLOT $\frac{1}{16}$ " DEEP (12 PLCS.) and a $\frac{1}{16}$ " RAD. fillet.
- Internal features include a .375 DIA. hole and a 2.000 DIA. hole.
- Right side features a .750 DIA. 1.000 hole and a .625 dimension.

Top View (Bottom):

- Overall width: 3.000
- Overall height: 2.000
- Left side features a 1.000 dimension and a 1.400 dimension.
- Right side features a 1.000 DIA. 1.250 DEEP hole and a .750 DIA. 1.000 hole.
- Center features a 2.000 DIA. hole and a .625 dimension.
- Bottom features a 1.400 dimension and a 1.500 DIA. hole.

PC.8 - 1 REQ'D
MAT'L - ALUMINUM

2.000

1.607

2.025

375

MACH. FOR "10-32 IF AA SIDE)
C.B. FOR "10-32 SCREW (THIS SIDE)
(4) P.C.S.

Technical drawing of a square plate. The overall width is 2.000 and the overall height is 2.025. A central circular feature has a diameter of 1.607. There are four circular holes, one in each corner, with a diameter of 375. A note points to the top edge, indicating it is machined for a 10-32 screw on the AA side and contains four pieces (P.C.S.).

ASSEMBLY OF PCS.6 & 11

Technical drawing of a mechanical part, likely a bracket or support. The drawing includes the following dimensions and callouts:

- 0.15 DIA. ROSE (INSIDE SQUARE) 7.00 DEEP**: Dimension for the central square feature.
- PC. 6**: Callout for the top horizontal flange.
- PC. 11**: Callout for the vertical support structure.

PC.11 - 1 REQ'D
MAT'L - ALUMINUM TUBING

PC.11 - I REO'D
MAT'L - ALUMINUM T

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[illegible]

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Appendix II

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APPENDIX II - SOURCE CODE

```

'      AWESOME.BAS
START:
    SCREEN 9
    COLOR 15, 1
    CLS
    BASEADD = &H300
    FILENAME3$ = "STORED.DAT"
READLOOP:
    chan0 = 0
    chan2 = 0
    OUT BASEADD + &H9, 0
    OUT BASEADD + &H8, 1
READ1:
    CSR1 = (INP(BASEADD + &H9) * 256) + INP(BASEADD + &H8)
    IF ((CSR1 AND &H80) = 0) THEN GOTO READ1
    chan0 = (INP(BASEADD + &HB) * 256) + INP(BASEADD + &HA)
    OUT BASEADD + &H9, 2
    OUT BASEADD + &H8, 1
READ2:
    CSR2 = (INP(BASEADD + &H9) * 256) + INP(BASEADD + &H8)
    IF ((CSR2 AND &H80) = 0) THEN GOTO READ2
    chan2 = (INP(BASEADD + &HB) * 256) + INP(BASEADD + &HA)
    IF COLLECTFLAG = 1 THEN
        PRINT #1, chan0, chan2
        PRINT #1, USING "#####"; chan0; chan2
    END IF
    LOCATE 22, 60
    PRINT "CHANNEL 0 = "; chan0;
    LOCATE 23, 60
    PRINT "CHANNEL 2 = "; chan2;
    LOCATE 1, 66
    PRINT "(Q)UIT"
    LOCATE 3, 66
    PRINT "(C)OLLECT DATA"
    LOCATE 4, 66
    PRINT "(E)ND"
    A$ = INKEY$
    IF A$ = "" THEN GOTO READLOOP
    A$ = UCASE$(A$)
    SELECT CASE A$
    CASE "C"
        IF COLLECTFLAG = 1 THEN GOTO READLOOP
        OPEN FILENAME3$ FOR OUTPUT AS #1
        COLLECTFLAG = 1
        LOCATE 2, 60
        PRINT "COLLECTING DATA"
        GOTO READLOOP
    CASE "E"

```

```

        IF COLLECTFLAG = 0 THEN GOTO READLOOP
        COLLECTFLAG = 0
        CLS
        LOCATE 15, 20
        PRINT "DATA COLLECTION STOPPED"
        LOCATE 9, 15
        INPUT "ENTER DESCRIPTION OF FILE"; NAME$
        PRINT #1, NAME$; "  FILENAME"
        LOCATE 10, 20
        INPUT "ENTER FILENAME TO COPY DATA TO >"; NAME$
        CLOSE #1
        COPYCOMM$ = "COPY STORED.DAT " + NAME$
        SHELL COPYCOMM$
        CLS
        LOCATE 2, 60
        PRINT "
        CLS
        GOTO READLOOP
CASE "Q"
    CHAIN "HONEMENU.EXE"
END
CASE ELSE
    GOTO READLOOP
END SELECT

```

' HONEMENU.BAS

MENU:

```

SCREEN 9
COLOR 15, 1
CLS
LOCATE 8, 30
PRINT "HONE MENU";
LOCATE 10, 20
PRINT "(B)UILD LOOKUP TABLES";
LOCATE 11, 20
PRINT "(S)HOW RAW A/D DATA";
LOCATE 12, 20
PRINT "(D)ISPLAY SENSOR READINGS";
LOCATE 13, 20
PRINT "(F)AST DATA GATHERING ROUTINE";
LOCATE 14, 20
PRINT "(C)OPY COLLECTED DATA TO USER'S FILE";
LOCATE 15, 20
PRINT "(Q)UIT TO DOS";
LOCATE 16, 20
PRINT "(A)WSOME DATA ACQUISITION RATE";
LOCATE 17, 30
PRINT "ENTER CHOICE >";

```

CHOICE:

```
A$ = INKEY$
IF A$ = "" THEN GOTO CHOICE
A$ = UCASE$(A$)
SELECT CASE A$

    CASE "B"
        CHAIN "LOOKUP.EXE"

    CASE "S"
        CHAIN "HONERAW.EXE"

    CASE "D"
        CHAIN "HONEREA.D.EXE"

    CASE "F"
        CHAIN "QUIKREAD.EXE"

    CASE "C"
        CLS
        LOCATE 10, 20
        INPUT "ENTER FILENAME TO COPY DATA TO >"; NAME$
        COPYCOMM$ = "COPY STORED.DAT " + NAME$
        SHELL COPYCOMM$

    CASE "A"
        CHAIN "AWESOME.EXE"

    CASE "Q"
        END

END SELECT
GOTO MENU
```

```
' HONERAW.BAS
SCREEN 9
COLOR 15, 1
CLS
LOCATE 24, 1
BASEADD = &H300
PRINT "PRESS ANY KEY TO END DATA COLLECTION";
```

LOOPER:

```
'
' READ CHANNEL 0
'
LOCATE 10, 1
100 OUT BASEADD + &H9, 0
OUT BASEADD + &H8, 1
```

```

200  CSR1 = (INP(BASEADD + &H9) * 256) + INP(BASEADD + &H8)
      IF ((CSR1 AND &H8000) = 1) THEN 900
      IF ((CSR1 AND &H80) = 0) THEN 200
      CHAN0 = (INP(BASEADD + &HB) * 256) + INP(BASEADD + &HA)
      '
      'READ CHANNEL 2
      '
      OUT BASEADD + &H9, 2
      OUT BASEADD + &H8, 1
300  CSR2 = (INP(BASEADD + &H9) * 256) + INP(BASEADD + &H8)
      IF ((CSR2 AND &H8000) = 1) THEN 900
      IF ((CSR2 AND &H80) = 0) THEN 300
      CHAN2 = (INP(BASEADD + &HB) * 256) + INP(BASEADD + &HA)

      LOCATE 10, 20
      PRINT USING "CHANNEL 0 - #####    CHANNEL 2 - #####"; CHAN0;
                                                    CHAN2;

      A$ = INKEY$
      IF A$ = "" THEN GOTO LOOPER
      CLS
      CHAIN "HONEMENU.EXE"

900  CLS
      LOCATE 10, 20
      PRINT "THERE WAS AN A/D ERROR"
      LOCATE 12, 20
      INPUT "PRESS ENTER TO RETURN TO THE HONE MENU"; A$
      CHAIN "HONEMENU.EXE"

'      FAST DATA ACQ PROGRAM
START:
      DIM TABLE1(4096), TABLE2(4096), TIMING(180)
      SCREEN 9
      COLOR 15, 1
      CLS
      LLX = 0
      LLY = 0
      URX = 639
      URY = 349
      ULIMIT = 160
      LLIMIT = 150
      MAXX = 639
      GAGEDIAMETER = 3.54679
      ERROR1FLAG = 0
      ERROR2FLAG = 0
      ERROR3FLAG = 0
      ERROR4FLAG = 0
      ERROR5FLAG = 0
      ERROR6FLAG = 0

```

```

BASEADD = &H300
FILENAME1$ = "LOOKUP1.DAT"
FILENAME2$ = "LOOKUP2.DAT"
FILENAME3$ = "STORED.DAT"
OPEN FILENAME1$ FOR INPUT AS #1
OPEN FILENAME2$ FOR INPUT AS #2
INPUT #1, START1
INPUT #1, RANGE1
INPUT #1, DIST1
INPUT #2, START2
INPUT #2, RANGE2
INPUT #2, DIST2
CLS
ON TIMER(2) GOSUB UPDATE
TIMER ON
FOR I = 1 TO 2048
    INPUT #1, X, TABLE1(I)
NEXT I
FOR J = 1 TO 2048
    INPUT #2, X, TABLE2(J)
NEXT J
TIMER OFF
CLS
CLOSE #1
CLOSE #2
LOCATE 10, 10
INPUT "DO YOU WANT TO RECALIBRATE (Y OR N) >"; A$
CHOICE:
CLS
A$ = UCASE$(A$)
SELECT CASE A$
    CASE "Y"
        GOSUB GETOFFSET
    CASE "N"
        OPEN "OFFSET.DAT" FOR INPUT AS #1
        INPUT #1, OFFSET
        CLOSE #1
        IF OFFSET = 0 THEN
            GOSUB GETOFFSET
        ELSE
            CLS
            LOCATE 10, 10
            PRINT USING "THE PREVIOUS OFFSET WAS #.####";
            OFFSET;
            LOCATE 12, 12
            INPUT "PRESS ENTER TO CONTINUE"; A$
        END IF
    CASE ELSE
        A$ = "N"
        GOTO CHOICE

```

```

        END SELECT
    GOSUB GRAPHINIT
    N = 1
    T = 1
READLOOP:
    chan0 = 0
    chan2 = 0
        FOR K = 1 TO T
        NEXT K
        sum0 = 0
        sum2 = 0
        FOR I = 1 TO N
    OUT BASEADD + &H9, 0
    OUT BASEADD + &H8, 1
READ1:
    CSR1 = (INP(BASEADD + &H9) * 256) + INP(BASEADD + &H8)
    IF ((CSR1 AND &H80) = 0) THEN GOTO READ1
    chan0 = (INP(BASEADD + &HB) * 256) + INP(BASEADD + &HA)
    OUT BASEADD + &H9, 2
    OUT BASEADD + &H8, 1
READ2:
    CSR2 = (INP(BASEADD + &H9) * 256) + INP(BASEADD + &H8)
    IF ((CSR2 AND &H80) = 0) THEN GOTO READ2
    chan2 = (INP(BASEADD + &HB) * 256) + INP(BASEADD + &HA)
        sum0 = sum0 + chan0
        sum2 = sum2 + chan2

        NEXT I
        chan0 = FIX(sum0 / N)
        chan2 = FIX(sum2 / N)

    IF chan0 > 2048 THEN chan0 = 2048
    IF chan0 < 2 THEN chan0 = 2
NEXTSEN:
    DISP1 = TABLE1(chan0 - 1)
    IF chan2 > 2048 THEN chan2 = 2048
    IF chan2 < 2 THEN chan2 = 2
ENDCHECK:
    DISP2 = TABLE2(chan2 - 1)
    IF COLLECTFLAG = 1 THEN
        PRINT #1, USING "####.####"; (DISP1 + DISP2 + OFFSET)
    END IF
    Y = ((DISP1 + DISP2) * 1000)
    LOCATE 1, 31
    PRINT "DIAMETER";
    LOCATE 1, 40
    PRINT USING "#.####"; DISP1 + DISP2 + OFFSET
    LINE -(X, Y), 14
    X = X + 1
    IF X >= MAXX THEN GOSUB GRAPHINIT

```

```

A$ = INKEY$
IF A$ = "" THEN GOTO READLOOP
A$ = UCASE$(A$)
SELECT CASE A$
CASE "M"
    CLS
    GOSUB MENU
CASE "R"
    CLS
    GOSUB GRAPHINIT
    GOTO READLOOP
CASE ELSE
    GOTO READLOOP
END SELECT
GRAPHINIT:
CLS
WINDOW (LLX, LLY)-(URX, URY)
LINE (45, 5)-(45, 349), 13
LINE (45, 5)-(639, 5), 13
FOR I = 102 TO 602 STEP 100
    LINE (I, 0)-(I, 4), 15
NEXT I
LINE (46, LLIMIT)-(639, LLIMIT), 11
LINE (46, ULIMIT)-(639, ULIMIT), 11
IF LLY = 0 AND URY = 349 THEN LLY = LLY + 3
FOR I = LLY TO URY
    LINE (40, I)-(44, I), 12
NEXT I
IF LLY = 0 AND URY = 349 THEN LLY = LLY - 3
FOR I = (LLY + 55) TO URY STEP 50
    LINE (25, I)-(44, I), 15
NEXT I
LOCATE 1, 66
PRINT "(M)ENU"
LOCATE 2, 66
PRINT "(R)EDRAW"
LOCATE 1, 1
PRINT USING "#.###"; (URY / 1000) + OFFSET;
LOCATE 24, 1
PRINT USING "#.###"; (LLY / 1000) + OFFSET;
PSET (46, Y), 15
X = 45
RETURN
UPDATE:
LOCATE 10, 25
PRINT "READING LOOKUP TABLES";
LOCATE 12, 30
PRINT USING "###% DONE"; ((I + J) / 4096) * 100;
RETURN
MENU:

```

```

LOCATE 1, 66
PRINT "(Q)UIT"
LOCATE 3, 66
PRINT "(C)OLLECT DATA"
LOCATE 4, 66
PRINT "(E)ND"
LOCATE 9, 66
PRINT "(A)UTO SCALE"
LOCATE 10, 66
PRINT "(F)ULL SCALE"
LOCATE 11, 66
PRINT "(L)IMIT RESET"
LOCATE 12, 67
PRINT USING "LOWER = #.###"; (LLIMIT / 1000) + OFFSET;
LOCATE 13, 67
PRINT USING "UPPER = #.###"; (ULIMIT / 1000) + OFFSET;
LOCATE 5, 30
PRINT "(S)AMPLE SIZE TO AVERAGE"
LOCATE 6, 30
PRINT "(T)IME ADJUSTMENT FACTOR"
A$ = INKEY$
IF A$ = "" THEN GOTO MENU
A$ = UCASE$(A$)
SELECT CASE A$
CASE "C"
    CLS
    IF COLLECTFLAG = 1 THEN GOTO READLOOP
    OPEN FILENAME3$ FOR OUTPUT AS #1
    PRINT #1, N; " SAMPLE(S) "
    PRINT #1, T; " ADJUSTMENT NUMBER"
    COLLECTFLAG = 1
    LOCATE 7, 20
    INPUT "ENTER TEMPERATURE OF MACHINED PART >"; TEMP$
    LOCATE 8, 20
    INPUT "ENTER TEMPERATURE OF CALIBRATION STANDARD >";
                                           TOMP$

    LOCATE 9, 20
    INPUT "ENTER A SHORT DESCRIPTION OF THE FILE"; NAME$
    PRINT #1, TEMP$; " TEMPERATURE OF MACHINED PART"
    PRINT #1, TOMP$; " TEMPERATURE OF CALIBRATION STANDARD"
    PRINT #1, NAME$; " FILENAME DESCRIPTION"
    START$ = TIME$
    LOCATE 2, 60
    PRINT "COLLECTING DATA"
    GOSUB GRAPHINIT
    PRINT "COLLECTING DATA"
    GOTO READLOOP
CASE "E"
    CLS
    IF COLLECTFLAG = 0 THEN GOTO READLOOP

```

```

COLLECTFLAG = 0
CLS
LOCATE 15, 20
PRINT "DATA COLLECTION STOPPED"
FINISH$ = TIME$
STSEC = VAL(RIGHT$(START$, 2))
FINSEC = VAL(RIGHT$(FINISH$, 2))
LOCATE 12, 20
PRINT "ELAPSED TIME"; FINSEC - STSEC;
PRINT "SECONDS"
PRINT #1, FINSEC - STSEC; "  SECONDS ELAPSED TIME"
CLOSE #1
LOCATE 10, 20
INPUT "ENTER FILENAME TO COPY DATA TO >"; NAME$
COPYCOMM$ = "COPY STORED.DAT " + NAME$
SHELL COPYCOMM$
CLS
LOCATE 2, 60
PRINT "          "
CLS
GOSUB GRAPHINIT
GOTO READLOOP
CASE "Q"
TIMER OFF
CHAIN "HONEMENU.EXE"
END
CASE "R"
CLS
LOCATE 10, 20
INPUT "ENTER LOWER Y BOUNDARY >"; LLY
LLY = (LLY - OFFSET) * 1000
LOCATE 12, 20
INPUT "HI ENTER UPPER Y BOUNDARY >"; URY
URY = (URY - OFFSET) * 1000
IF LLY < 0 THEN LLY = 0
IF URY > 349 THEN URY = 349
LOCATE 14, 20
INPUT "ENTER RIGHT X VALUE (MAX - 638 MIN - 10) >"; URX
IF URX > 638 THEN URX = 638
IF URX < 10 THEN URX = 638
LOCATE 16, 20
INPUT "ENTER LEFT X VALUE (MAX - 628 MIN - 0) >"; LLX
IF LLX > 638 THEN LLX = 40
IF LLX < 0 THEN LLX = 40
IF LLX > URX THEN LLX = URX - 200
MAXX = URX
X = MAXX
GOSUB GRAPHINIT
GOTO READLOOP
CASE "A"

```

```

        CLS
        LLY = ((DISP1 + DISP2) * 1000) - 3
        URY = ((DISP1 + DISP2) * 1000) + 3
        GOSUB GRAPHINIT
        GOTO READLOOP
CASE "F"
    CLS
    LLY = 0
    URY = 349
    LLX = 0
    URX = 638
    GOSUB GRAPHINIT
    GOTO READLOOP
CASE "S"
    CLS
    LOCATE 6, 30
    INPUT "NUMBER OF SAMPLES TO AVERAGE"; N
    IF N < 1 THEN N = 1
    GOSUB GRAPHINIT
    GOTO READLOOP
CASE "T"
    CLS
    LOCATE 10, 30
    INPUT "TIME ADJUSTMENT FACTOR >"; T
    IF T < 1 THEN T = 1
    GOSUB GRAPHINIT
    GOTO READLOOP
CASE ELSE
    GOTO READLOOP
END SELECT
RETURN
GETOFFSET:
    CLS
    LOCATE 10, 10
    INPUT "PLACE SENSOR HEAD IN OFFSET RING AND PRESS RETURN"; A$
    CLS
    OUT BASEADD + &H9, 0
    OUT BASEADD + &H8, 1
OFF1:
    CSR1 = (INP(BASEADD + &H9) * 256) + INP(BASEADD + &H8)
    IF ((CSR1 AND &H80) = 0) THEN GOTO OFF1
    chan0 = (INP(BASEADD + &HB) * 256) + INP(BASEADD + &HA)
    IF chan0 > 2048 THEN chan0 = 2048
    IF chan0 < 2 THEN chan0 = 2
    DISP1 = TABLE1(chan0 - 1)
    OUT BASEADD + &H9, 2
    OUT BASEADD + &H8, 1
OFF2:
    CSR2 = (INP(BASEADD + &H9) * 256) + INP(BASEADD + &H8)
    IF ((CSR2 AND &H80) = 0) THEN GOTO OFF2

```

```

chan2 = (INP(BASEADD + &HB) * 256) + INP(BASEADD + &HA)
IF chan2 > 2048 THEN chan2 = 2048
IF chan2 < 2 THEN chan2 = 2
DISP2 = TABLE2(chan2 - 1)
OFFSET = GAGEDIAMETER - (DISP1 + DISP2)
LOCATE 10, 20
PRINT USING "THE CALCULATED SENSOR HEAD OFFSET WAS #.###";
                                                OFFSET;

OPEN "OFFSET.DAT" FOR OUTPUT AS #1
PRINT #1, OFFSET
CLOSE #1
LOCATE 12, 30
INPUT "PRESS RETURN TO CONTINUE"; A$
RETURN
ENDIT:
FOR I = 1 TO 180 STEP 6
    PRINT USING "#####.##"; TIMING(I); TIMING(I + 1);
                                TIMING(I + 2); TIMING(I + 3);
                                TIMING(I + 4); TIMING(I + 5);

NEXT I
INPUT A$
CHAIN "HONEMENU.EXE"
END

' TITLE LOOKUP.BAS
'
' This program is used to create a lookup table for a
' sensor connected to an A/D board with a 12 bit converter.
' The routine will prompt the user for the lookup table
' filename, the start of the sensor range, the total range
' of the sensor, the distance between readings, and the A/D
' channel to read from. The program will then prompt the
' user to set the mic head at the desired distance from the
' sensor and press the return key. After stepping through
' the entire range of the sensor, the program will build the
' lookup table using a linear interpolation between the actual
' values read from the mic head. There will be readings
' associated with each A/D value. It will be up to the
' responsibility of the sensor reading program to check for
' high and low limits of the sensor.

START:
'
' Initialize the table
'
DIM TABLE(4096)
MAXSUB = 4096
BASEADD = &H300

```

```

/   Get the table name and sensor info from the operator
/
SCREEN 9
COLOR 15, 1
CLS
LOCATE 2, 10
PRINT "SENSOR #1 FILENAME:  LOOKUP1.DAT"
LOCATE 4, 10
PRINT "SENSOR #2 FILENAME:  LOOKUP2.DAT"
LOCATE 10, 10
INPUT "ENTER NAME OF LOOKUP FILE >"; FILENAME$
CLS
LOCATE 10, 10
INPUT "ENTER START OF RANGE >"; START
CLS
LOCATE 10, 10
INPUT "ENTER TOTAL RANGE OF SENSOR >"; RANGE
CLS
LOCATE 10, 10
INPUT "ENTER DISTANCE BETWEEN READINGS >"; DIST
CLS
LOCATE 5, 10
PRINT "SENSOR #1 :  0"
LOCATE 7, 10
PRINT "SENSOR #2 :  2"
LOCATE 10, 10
INPUT "ENTER CHANNEL SENSOR IS CONNECTED TO >"; CHAN
/
/   Start prompting the operator for mic head settings
/
FOR I = START TO (RANGE + DIST) STEP DIST
    CLS
    LOCATE 10, 10
    PRINT USING "SET MICROMETER HEAD TO #.### AND PRESS
                                RETURN"; I;
    INPUT A$
/
/   Set the selected channel and the start bit
/
    OUT BASEADD + &H9, CHAN
    OUT BASEADD + &H8, 1
/
/   Read the A/D CSR and wait for an error or the done bit to be
/   set
/
WAIT1:
    CSR = (INP(BASEADD + &H9) * 256) + INP(BASEADD + &H8)
    IF ((CSR AND &H8000) = 1) THEN GOTO ERRMSG
    IF ((CSR AND &H80) = 0) THEN GOTO WAIT1
/

```

```

/   Read the A/D value and put it in the table
/
      RDG = (INP(BASEADD + &HB) * 256) + INP(BASEADD + &HA)
      TABLE(RDG) = I

      NEXT I
/
/   Interpolate between the mic head readings and place the
/   interpolated values in the table
/
      CLS
      ON TIMER(1) GOSUB UPDATE1
      TIMER ON
      LASTVAL = 0
      LASTSUB = 0
/
/   Skip the zeros between the readings
/
NEXTSPAN:
      FIRSTVAL = LASTVAL
      FIRSTSUB = LASTSUB + 1
      LASTSUB = FIRSTSUB
      IF LASTSUB = (MAXSUB + 1) THEN GOTO DONEINTERP
      WHILE TABLE(LASTSUB) = 0
        LASTSUB = LASTSUB + 1
        IF LASTSUB = (MAXSUB + 1) THEN GOTO LASTREAD
      WEND
      LASTVAL = TABLE(LASTSUB)
/
/   Find the distance per A/D bit for this section
/
INTERP:
      SUBSPAN = (LASTSUB - FIRSTSUB) + 1
      IF SUBSPAN = 0 THEN GOTO NEXTSPAN
      VALSPAN = LASTVAL - FIRSTVAL
      PERSUB = VALSPAN / SUBSPAN
/
/   Fill in the interpolated values
/
LASTREAD:
      TOTSUB = PERSUB
      FOR I = FIRSTSUB TO (LASTSUB - 1)
        TABLE(I) = FIRSTVAL + TOTSUB
        TOTSUB = TOTSUB + PERSUB
      NEXT I
      IF LASTSUB < MAXSUB + 1 THEN GOTO NEXTSPAN
/
/   Write the lookup table to the operator selected filename
/
DONEINTERP:

```

```

TIMER OFF
CLS
ON TIMER(1) GOSUB UPDATE2
TIMER ON
OPEN FILENAME$ FOR OUTPUT AS #1
PRINT #1, USING " #.#####"; START
PRINT #1, USING " #.#####"; RANGE
PRINT #1, USING " #.#####"; DIST
FOR I = 1 TO 2048
    PRINT #1, USING " ##### #.##### "; I; TABLE(I)
NEXT I
CLOSE #1
TIMER OFF
CHAIN "HONEMENU.EXE"
/
/   Keep the operator informed of what is going on
/
UPDATE1:
    LOCATE 10, 22
    PRINT "CONSTRUCTING LOOKUP TABLE";
    LOCATE 12, 30
    PRINT USING "###% DONE"; ((LASTSUB / MAXSUB) * 100)
    RETURN
/
UPDATE2:
    LOCATE 10, 25
    PRINT "SAVING LOOKUP TABLE";
    LOCATE 12, 30
    PRINT USING "###% DONE"; ((I / MAXSUB) * 100)
    RETURN
/
/   Inform the operator of an A/D error
/
ERRMSG:
    CLS
    LOCATE 10, 20
    PRINT "THERE WAS AN A/D ERROR"
    LOCATE 12, 20
    INPUT "PRESS ENTER TO RETURN TO THE HONE MENU"; A$
    CHAIN "HONEMENU.EXE"

/   HONEREAD.BAS
/   TITLE HONEREAD .441176 SECONDS/REVOLUTION
/
/   This program will collect the data from the hone sensors and
/   display them to the screen as graphics or as distance values.
/   Several options exist
/   *** 8 MARCH 1989 ***
START:

```

```

DIM TABLE1(4096), TABLE2(4096), TIMING(180)
SCREEN 9
COLOR 15, 1
CLS
LLX = 0
LLY = 0
URX = 639
URY = 349
ULIMIT = 160
LLIMIT = 150
MAXX = 639
GAGEDIAMETER = 3.54679
ERROR1FLAG = 0
ERROR2FLAG = 0
ERROR3FLAG = 0
ERROR4FLAG = 0
ERROR5FLAG = 0
ERROR6FLAG = 0
BASEADD = &H300
FILENAME1$ = "LOOKUP1.DAT"
FILENAME2$ = "LOOKUP2.DAT"
FILENAME3$ = "STORED.DAT"
OPEN FILENAME1$ FOR INPUT AS #1
OPEN FILENAME2$ FOR INPUT AS #2
INPUT #1, START1
INPUT #1, RANGE1
INPUT #1, DIST1
INPUT #2, START2
INPUT #2, RANGE2
INPUT #2, DIST2

CLS
ON TIMER(2) GOSUB UPDATE
TIMER ON
FOR I = 1 TO 2048
    INPUT #1, X, TABLE1(I)
NEXT I
FOR J = 1 TO 2048
    INPUT #2, X, TABLE2(J)
NEXT J
TIMER OFF

CLS
CLOSE #1
CLOSE #2

LOCATE 10, 10
INPUT "DO YOU WANT TO RECALIBRATE (Y OR N) >"; A$

```

CHOICE:

```

CLS
A$ = UCASE$(A$)
SELECT CASE A$

    CASE "Y"
        GOSUB GETOFFSET

    CASE "N"
        OPEN "OFFSET.DAT" FOR INPUT AS #1
        INPUT #1, OFFSET
        CLOSE #1
        IF OFFSET = 0 THEN
            GOSUB GETOFFSET
        ELSE
            CLS
            LOCATE 10, 10
            PRINT USING "THE PREVIOUS OFFSET WAS #.####";
                                OFFSET;
            LOCATE 12, 12
            INPUT "PRESS ENTER TO CONTINUE"; A$
        END IF
    CASE ELSE
        A$ = "N"
        GOTO CHOICE
END SELECT
GOSUB GRAPHINIT
'K = 1
N = 1
T = 1
READLOOP:
'TIMING(K) = TIMER
'K = K + 1
'IF K = 181 THEN GOTO ENDIT
chan0 = 0
chan2 = 0
    sum0 = 0
    sum2 = 0
    ADJUSTMENT LOOP
    FOR K = 1 TO T
        NEXT K

    FOR I = 1 TO N

        OUT BASEADD + &H9, 0
        OUT BASEADD + &H8, 1
READ1:
        CSR1 = (INP(BASEADD + &H9) * 256) + INP(BASEADD + &H8)
        IF ((CSR1 AND &H8000) = 1) THEN GOTO ERROR1
        IF ((CSR1 AND &H80) = 0) THEN GOTO READ1
        chan0 = chan0 + (INP(BASEADD + &HB) * 256) + INP(BASEADD

```

```

chan0 = (INP(BASEADD + &HB) * 256) + INP(BASEADD + &HA)
OUT BASEADD + &H9, 2
OUT BASEADD + &H8, 1

READ2:
CSR2 = (INP(BASEADD + &H9) * 256) + INP(BASEADD + &H8)
IF ((CSR2 AND &H8000) = 1) THEN GOTO ERROR2
IF ((CSR2 AND &H80) = 0) THEN GOTO READ2
chan2 = chan2 + (INP(BASEADD + &HB) * 256) + INP(BASEADD + &HA)
chan2 = (INP(BASEADD + &HB) * 256) + INP(BASEADD + &HA)

sum0 = sum0 + chan0
sum2 = sum2 + chan2

NEXT I

chan0 = FIX(sum0 / N)
chan2 = FIX(sum2 / N)
LOCATE 22, 60
PRINT "CHANNEL 0 = "; chan0;
LOCATE 23, 60
PRINT "CHANNEL 2 = "; chan2;

IF chan0 > 2048 THEN chan0 = 2048
IF chan0 < 2 THEN chan0 = 2
IF TABLE1(chan0 - 1) < RANGE1 AND TABLE1(chan0 - 1) >
    START1 THEN GOTO NEXTSEN
IF TABLE1(chan0 - 1) < START1 THEN
    GOSUB ERROR3
ELSE
    IF ERROR3FLAG = 1 THEN GOSUB CLRERROR3
END IF
IF TABLE1(chan0 - 1) > RANGE1 THEN
    GOSUB ERROR5
ELSE
    IF ERROR5FLAG = 1 THEN GOSUB CLRERROR5
END IF

NEXTSEN:
DISP1 = TABLE1(chan0 - 1)

IF chan2 > 2048 THEN chan2 = 2048
IF chan2 < 2 THEN chan2 = 2
IF TABLE2(chan2 - 1) < RANGE2 AND TABLE2(chan2 - 1) >
    START2 THEN GOTO ENDCHECK
IF TABLE2(chan2 - 1) < START2 THEN
    GOSUB ERROR4

```

```

ELSE
    IF ERROR4FLAG = 1 THEN GOSUB CLRERROR4
END IF
IF TABLE2(chan2 - 1) > RANGE2 THEN
    GOSUB ERROR6
ELSE
    IF ERROR6FLAG = 1 THEN GOSUB CLRERROR6
END IF

ENDCHECK:
    DISP2 = TABLE2(chan2 - 1)

    IF COLLECTFLAG = 1 THEN
        PRINT #1, USING "###.###"; (DISP1 + DISP2 + OFFSET)
    END IF

    Y = ((DISP1 + DISP2) * 1000)
    LOCATE 1, 40
    PRINT USING "#.###"; DISP1 + DISP2 + OFFSET
    LINE -(X, Y), 14
    X = X + 1
    IF X >= MAXX THEN GOSUB GRAPHINIT

    A$ = INKEY$
    IF A$ = "" THEN GOTO READLOOP
    A$ = UCASE$(A$)
    SELECT CASE A$

    CASE "C"
        IF COLLECTFLAG = 1 THEN GOTO READLOOP
        OPEN FILENAME3$ FOR OUTPUT AS #1
        PRINT #1, N; " SAMPLE(S)"
        COLLECTFLAG = 1
        LOCATE 7, 15
        INPUT "ENTER TEMPERATURE OF MACHINED PART >"; TEMP$
        LOCATE 8, 15
        INPUT "ENTER TEMPERATURE OF CALIBRATION STANDARD >";
            TOMP$

        LOCATE 9, 15
        INPUT "ENTER DESCRIPTION OF FILE"; NAME$
        PRINT #1, TEMP$; " TEMPERATURE OF MACHINED PART"
        PRINT #1, TOMP$; " TEMPERATURE OF CALIBRATION STANDARD"
        PRINT #1, NAME$; " FILENAME"
        START$ = TIME$
        LOCATE 2, 60
        PRINT "COLLECTING DATA"

        GOTO READLOOP

    CASE "E"

```

```

IF COLLECTFLAG = 0 THEN GOTO READLOOP
COLLECTFLAG = 0
CLS
LOCATE 15, 20
PRINT "DATA COLLECTION STOPPED"
FINISH$ = TIME$
STSEC = VAL(RIGHT$(START$, 2))
FINSEC = VAL(RIGHT$(FINISH$, 2))
LOCATE 12, 20
PRINT "ELAPSED TIME"; FINSEC - STSEC;
PRINT "SECONDS"
PRINT #1, FINSEC - STSEC; "  SECONDS ELAPSED TIME"
CLOSE #1
LOCATE 10, 20
INPUT "ENTER FILENAME TO COPY DATA TO >"; NAME$
COPYCOMM$ = "COPY STORED.DAT " + NAME$
SHELL COPYCOMM$
CLS
LOCATE 2, 60
PRINT " "
CLS
GOSUB GRAPHINIT
GOTO READLOOP

```

```

CASE "L"
CLS
LOCATE 10, 20
INPUT "ENTER LOWER LIMIT >"; LLIMIT
LLIMIT = (LLIMIT - OFFSET) * 1000
LOCATE 12, 20
INPUT "ENTER UPPER LIMIT >"; ULIMIT
ULIMIT = (ULIMIT - OFFSET) * 1000
GOSUB GRAPHINIT
GOTO READLOOP

```

```

CASE "Q"
TIMER OFF
CHAIN "HONEMENU.EXE"
END

```

```

CASE "R"
CLS
LOCATE 10, 20
INPUT "ENTER LOWER Y BOUNDARY >"; LLY
LLY = (LLY - OFFSET) * 1000
LOCATE 12, 20
INPUT "HI ENTER UPPER Y BOUNDARY >"; URY
URY = (URY - OFFSET) * 1000
IF LLY < 0 THEN LLY = 0
IF URY > 349 THEN URY = 349

```

```

LOCATE 14, 20
INPUT "ENTER RIGHT X VALUE (MAX - 638 MIN - 10) >"; URX
IF URX > 638 THEN URX = 638
IF URX < 10 THEN URX = 10
LOCATE 16, 20
INPUT "ENTER LEFT X VALUE (MAX - 628 MIN - 0) >"; LLX
IF LLX > 638 THEN LLX = 638
IF LLX < 0 THEN LLX = 40
IF LLX > URX THEN LLX = URX - 200
MAXX = URX
X = MAXX
GOSUB GRAPHINIT
GOTO READLOOP

```

```

CASE "Z"
  LLY = LLY + 10
  URY = URY - 10
  GOSUB GRAPHINIT
  GOTO READLOOP

```

```

CASE "B"
  LLY = LLY - 10
  URY = URY + 10
  GOSUB GRAPHINIT
  GOTO READLOOP

```

```

CASE "D"
  LLY = LLY - 2
  URY = URY - 2
  GOSUB GRAPHINIT
  GOTO READLOOP

```

```

CASE "U"
  LLY = LLY + 2
  URY = URY + 2
  GOSUB GRAPHINIT
  GOTO READLOOP

```

```

CASE "A"
  LLY = ((DISP1 + DISP2) * 1000) - 3
  URY = ((DISP1 + DISP2) * 1000) + 3
  GOSUB GRAPHINIT
  GOTO READLOOP

```

```

CASE "F"
  LLY = 0
  URY = 349
  LLX = 0
  URX = 638

```

```
GOSUB GRAPHINIT
GOTO READLOOP
```

```
CASE "S"
    LOCATE 9, 30
    INPUT "NUMBER OF SAMPLES TO AVERAGE"; N
    IF N < 1 THEN N = 1

    GOSUB GRAPHINIT
    GOTO READLOOP
CASE "T"
    LOCATE 10, 30
    INPUT "TIME ADJUSTMENT FACTOR >"; T
    IF T < 1 THEN T = 1

    GOSUB GRAPHINIT
    GOTO READLOOP
CASE "P"
    GOSUB GRAPHINIT
    GOTO READLOOP

CASE ELSE
    GOTO READLOOP
```

```
END SELECT
```

```
GRAPHINIT:
```

```
CLS
WINDOW (LLX, LLY)-(URX, URY)
LINE (45, 5)-(45, 349), 13
LINE (45, 5)-(639, 5), 13
FOR I = 102 TO 602 STEP 100
    LINE (I, 0)-(I, 4), 15
NEXT I
LINE (46, LLIMIT)-(639, LLIMIT), 11
LINE (46, ULIMIT)-(639, ULIMIT), 11
IF LLY = 0 AND URY = 349 THEN LLY = LLY + 3
FOR I = LLY TO URY
    LINE (40, I)-(44, I), 12
NEXT I
IF LLY = 0 AND URY = 349 THEN LLY = LLY - 3
FOR I = (LLY + 55) TO URY STEP 50
    LINE (25, I)-(44, I), 15
NEXT I
LOCATE 1, 66
PRINT "(Q)UIT"
LOCATE 2, 66
PRINT "(R)ESCALE"
LOCATE 3, 66
PRINT "(C)OLLECT DATA"
```

```

LOCATE 4, 66
PRINT "(E)ND"
LOCATE 5, 66
PRINT "(Z)OOM"
LOCATE 6, 66
PRINT "(B)ACKUP";
LOCATE 7, 66
PRINT "(U)P"
LOCATE 8, 66
PRINT "(D)OWN"
LOCATE 9, 66
PRINT "(A)UTO SCALE"
LOCATE 10, 66
PRINT "(F)ULL SCALE"
LOCATE 11, 66
PRINT "(L)IMIT RESET"
LOCATE 12, 67
PRINT USING "LOWER = #.###"; (LLIMIT / 1000) + OFFSET;
LOCATE 13, 67
PRINT USING "UPPER = #.###"; (ULIMIT / 1000) + OFFSET;
LOCATE 17, 60
PRINT "(P)"
LOCATE 5, 30
PRINT "(S)AMPLE SIZE TO AVERAGE"
LOCATE 6, 30
PRINT "(T)IME ADJUSTMENT FACTOR"
LOCATE 1, 31
PRINT "DIAMETER";
LOCATE 1, 1
PRINT USING "#.###"; (URY / 1000) + OFFSET;
LOCATE 24, 1
PRINT USING "#.###"; (LLY / 1000) + OFFSET;
PSET (46, Y), 15
X = 45
RETURN

```

UPDATE:

```

LOCATE 10, 25
PRINT "READING LOOKUP TABLES";
LOCATE 12, 30
PRINT USING "###% DONE"; ((I + J) / 4096) * 100;
RETURN

```

ERROR1:

```

CLS
LOCATE 10, 20
PRINT "CHANNEL 0 A/D CONVERSION ERROR";
LOCATE 24, 1
PRINT "PRESS ANY KEY TO CONTINUE";

```

```

ERROR1WAIT:
  A$ = INKEY$
  IF A$ = "" THEN GOTO ERROR1WAIT
  CHAIN "HONEMENU.EXE"

ERROR2:
  CLS
  LOCATE 10, 20
  PRINT "CHANNEL 2 A/D CONVERSION ERROR";
  LOCATE 24, 1
  PRINT "PRESS ANY KEY TO CONTINUE";

ERROR2WAIT:
  A$ = INKEY$
  IF A$ = "" THEN GOTO ERROR2WAIT
  CHAIN "HONEMENU.EXE"

ERROR3:
  LOCATE 2, 20
  ERROR3FLAG = 1
  PRINT "SENSOR 1 READS LOW";
  RETURN

ERROR4:
  LOCATE 3, 20
  ERROR4FLAG = 1
  PRINT "SENSOR 2 READS LOW";
  RETURN

ERROR5:
  LOCATE 2, 40
  ERROR5FLAG = 1
  PRINT "SENSOR 1 READS HIGH";
  RETURN

ERROR6:
  LOCATE 3, 40
  ERROR6FLAG = 1
  PRINT "SENSOR 2 READS HIGH";
  RETURN

CLRERROR3:
  LOCATE 2, 20
  ERROR3FLAG = 0
  PRINT " ";
  RETURN

CLRERROR4:
  LOCATE 3, 20
  ERROR4FLAG = 0

```

```
PRINT "                ";  
RETURN
```

```
CLRERROR5:  
  LOCATE 2, 40  
  ERROR5FLAG = 0  
  PRINT "                ";  
  RETURN
```

```
CLRERROR6:  
  LOCATE 3, 40  
  ERROR6FLAG = 0  
  PRINT "                ";  
  RETURN
```

```
GETOFFSET:  
  CLS  
  LOCATE 10, 10  
  INPUT "PLACE SENSOR HEAD IN OFFSET RING AND PRESS RETURN"; A$  
  CLS  
  OUT BASEADD + &H9, 0  
  OUT BASEADD + &H8, 1
```

```
OFF1:  
  CSR1 = (INP(BASEADD + &H9) * 256) + INP(BASEADD + &H8)  
  IF ((CSR1 AND &H8000) = 1) THEN GOTO ERROR1  
  IF ((CSR1 AND &H80) = 0) THEN GOTO OFF1  
  chan0 = (INP(BASEADD + &HB) * 256) + INP(BASEADD + &HA)  
  
  IF chan0 > 2048 THEN chan0 = 2048  
  IF chan0 < 2 THEN chan0 = 2  
  IF TABLE1(chan0 - 1) < START1 THEN  
    GOSUB ERROR3  
  ELSE  
    IF ERROR3FLAG = 1 THEN GOSUB CLRERROR3  
  END IF  
  IF TABLE1(chan0 - 1) > RANGE1 THEN  
    GOSUB ERROR5  
  ELSE  
    IF ERROR5FLAG = 1 THEN GOSUB CLRERROR5  
  END IF  
  DISP1 = TABLE1(chan0 - 1)  
  
  OUT BASEADD + &H9, 2  
  OUT BASEADD + &H8, 1
```

```
OFF2:  
  CSR2 = (INP(BASEADD + &H9) * 256) + INP(BASEADD + &H8)  
  IF ((CSR2 AND &H8000) = 1) THEN GOTO ERROR2  
  IF ((CSR2 AND &H80) = 0) THEN GOTO OFF2
```

```

chan2 = (INP(BASEADD + &HB) * 256) + INP(BASEADD + &HA)
IF chan2 > 2048 THEN chan2 = 2048
IF chan2 < 2 THEN chan2 = 2
IF TABLE2(chan2 - 1) < START2 THEN
    GOSUB ERROR4
ELSE
    IF ERROR4FLAG = 1 THEN GOSUB CLRERROR4
END IF
IF TABLE2(chan2 - 1) > RANGE2 THEN
    GOSUB ERROR6
ELSE
    IF ERROR6FLAG = 1 THEN GOSUB CLRERROR6
END IF
DISP2 = TABLE2(chan2 - 1)
OFFSET = GAGEDIAMETER - (DISP1 + DISP2)
LOCATE 10, 20
PRINT USING "THE CALCULATED SENSOR HEAD OFFSET WAS ###.###";
                                                OFFSET;

OPEN "OFFSET.DAT" FOR OUTPUT AS #1
PRINT #1, OFFSET
CLOSE #1
LOCATE 12, 30
INPUT "PRESS RETURN TO CONTINUE"; A$
RETURN

```

ENDIT:

```

FOR I = 1 TO 180 STEP 6
    PRINT USING "#####.###"; TIMING(I); TIMING(I + 1);
                                TIMING(I + 2); TIMING(I + 3);
                                TIMING(I + 4); TIMING(I + 5);
NEXT I
INPUT A$
CHAIN "HONEMENU.EXE"
END

```

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Appendix III

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APPENDIX III - BENCH TESTING CAPACITANCE SENSOR DATA

ROCK ISLAND ARSENAL
 ADVANCED TECHNOLOGY FOR ABRASIVE MACHINING
 8 SEPTEMBER 1989
 BABCOCK & WILCOX CAPACITANCE SENSOR
 FILE: CAP1.WS

DISTANCE TO TARGET (INCHES)	SENSOR OUTPUT (VOLTS)	CALCULATED OUTPUT (VOLTS)	DIFFERENCE ACT - CALC (VOLTS)	ERROR (INCHES)
0.00000	0.00000	0.00000	0.00000	0.00000
0.00500	0.00500	0.00500	0.00000	0.00000
0.01000	0.01000	0.01000	0.00000	0.00000
0.01500	0.01510	0.01500	0.00010	0.00010
0.02000	0.02020	0.02000	0.00020	0.00020
0.02500	0.02510	0.02500	0.00010	0.00010
0.03000	0.03010	0.03000	0.00010	0.00010
0.03500	0.03510	0.03500	0.00010	0.00010
0.04000	0.04000	0.04000	0.00000	0.00000
0.04500	0.04500	0.04500	0.00000	0.00000
0.05000	0.05000	0.05000	0.00000	0.00000
0.05500	0.05500	0.05500	0.00000	0.00000
0.06000	0.06000	0.06000	0.00000	0.00000
0.06500	0.06500	0.06500	0.00000	0.00000
0.07000	0.07000	0.07000	0.00000	0.00000
0.07500	0.07500	0.07500	0.00000	0.00000
0.08000	0.08000	0.08000	0.00000	0.00000
0.08500	0.08500	0.08500	0.00000	0.00000
0.09000	0.09000	0.09000	0.00000	0.00000
0.09500	0.09500	0.09500	0.00000	0.00000
0.10000	0.10000	0.10000	0.00000	0.00000
0.10500	0.10500	0.10500	0.00000	0.00000
0.11000	0.11000	0.11000	0.00000	0.00000
0.11500	0.11500	0.11500	0.00000	0.00000
0.12000	0.12000	0.12000	0.00000	0.00000
0.12500	0.12500	0.12500	0.00000	0.00000

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Appendix IV

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APPENDIX IV - BENCH TESTING INDUCTIVE SENSOR DATA

BABCOCK & WILCOX
CIM SYSTEMS
20 NOVEMBER 1989
FILE: HONE10.WS

OMRON SIGNAL CONDITIONER E2CA-AN-4E
OMRON INDUCTIVE PROXIMITY SENSOR
ANALOG OUTPUT E2CA-X5A-5M

DISTANCE TO TARGET	DATA READOUT AMPS	THEORITICAL READOUT AMPS	THEORETICAL MINUS DATA (AMPS)	ERROR INCHES
0.00000	0.00000	0.00000	0.00000	0.00000
0.00200	0.00000	0.00020	-0.00020	-0.00200
0.00400	0.00000	0.00040	-0.00040	-0.00400
0.00600	0.00000	0.00060	-0.00060	-0.00600
0.00800	0.00000	0.00080	-0.00080	-0.00800
0.01000	0.00000	0.00100	-0.00100	-0.01000
0.01200	0.00000	0.00120	-0.00120	-0.01200
0.01400	0.00176	0.00140	0.00036	0.00360
0.01600	0.00191	0.00160	0.00031	0.00310
0.01800	0.00206	0.00180	0.00026	0.00260
0.02000	0.00221	0.00200	0.00021	0.00210
0.02200	0.00238	0.00220	0.00018	0.00180
0.02400	0.00254	0.00240	0.00014	0.00140
0.02600	0.00271	0.00260	0.00011	0.00110
0.02800	0.00288	0.00280	0.00008	0.00080
0.03000	0.00306	0.00300	0.00006	0.00060
0.03200	0.00324	0.00320	0.00004	0.00040
0.03400	0.00343	0.00340	0.00003	0.00030
0.03600	0.00362	0.00360	0.00002	0.00020
0.03800	0.00381	0.00380	0.00001	0.00010
0.04000	0.00401	0.00400	0.00001	0.00010
0.04200	0.00421	0.00420	0.00001	0.00010
0.04400	0.00442	0.00440	0.00002	0.00020
0.04600	0.00463	0.00460	0.00003	0.00030
0.04800	0.00485	0.00480	0.00005	0.00050
0.05000	0.00506	0.00500	0.00006	0.00060
0.05200	0.00528	0.00520	0.00008	0.00080
0.05400	0.00551	0.00540	0.00011	0.00110
0.05600	0.00573	0.00560	0.00013	0.00130
0.05800	0.00597	0.00580	0.00017	0.00170
0.06000	0.00619	0.00600	0.00019	0.00190
0.06200	0.00641	0.00620	0.00021	0.00210
0.06400	0.00664	0.00640	0.00024	0.00240
0.06600	0.00686	0.00660	0.00026	0.00260
0.06800	0.00707	0.00680	0.00027	0.00270
0.07000	0.00728	0.00700	0.00028	0.00280
0.07200	0.00748	0.00720	0.00028	0.00280
0.07400	0.00769	0.00740	0.00029	0.00290

0.07600	0.00789	0.00760	0.00029	0.00290
0.07800	0.00809	0.00780	0.00029	0.00290
0.08000	0.00830	0.00800	0.00030	0.00300
0.08200	0.00851	0.00820	0.00031	0.00310
0.08400	0.00871	0.00840	0.00031	0.00310
0.08600	0.00892	0.00860	0.00032	0.00320
0.08800	0.00913	0.00880	0.00033	0.00330
0.09000	0.00933	0.00900	0.00033	0.00330
0.09200	0.00954	0.00920	0.00034	0.00340
0.09400	0.00975	0.00940	0.00035	0.00350
0.09600	0.00995	0.00960	0.00035	0.00350
0.09800	0.01015	0.00980	0.00035	0.00350
0.10000	0.01035	0.01000	0.00035	0.00350
0.10200	0.01055	0.01020	0.00035	0.00350
0.10400	0.01075	0.01040	0.00035	0.00350
0.10600	0.01096	0.01060	0.00036	0.00360
0.10800	0.01116	0.01080	0.00036	0.00360
0.11000	0.01136	0.01100	0.00036	0.00360
0.11200	0.01157	0.01120	0.00037	0.00370
0.11400	0.01177	0.01140	0.00037	0.00370
0.11600	0.01198	0.01160	0.00038	0.00380
0.11800	0.01218	0.01180	0.00038	0.00380
0.12000	0.01239	0.01200	0.00039	0.00390
0.12200	0.01259	0.01220	0.00039	0.00390
0.12400	0.01279	0.01240	0.00039	0.00390
0.12600	0.01299	0.01260	0.00039	0.00390
0.12800	0.01319	0.01280	0.00039	0.00390
0.13000	0.01339	0.01300	0.00039	0.00390
0.13200	0.01358	0.01320	0.00038	0.00380
0.13400	0.01378	0.01340	0.00038	0.00380
0.13600	0.01397	0.01360	0.00037	0.00370
0.13800	0.01415	0.01380	0.00035	0.00350
0.14000	0.01435	0.01400	0.00035	0.00350
0.14200	0.01454	0.01420	0.00034	0.00340
0.14400	0.01473	0.01440	0.00033	0.00330
0.14600	0.01492	0.01460	0.00032	0.00320
0.14800	0.01512	0.01480	0.00032	0.00320
0.15000	0.01531	0.01500	0.00031	0.00310
0.15200	0.01551	0.01520	0.00031	0.00310
0.15400	0.01571	0.01540	0.00031	0.00310
0.15600	0.01591	0.01560	0.00031	0.00310
0.15800	0.01611	0.01580	0.00031	0.00310
0.16000	0.01630	0.01600	0.00030	0.00300
0.16200	0.01650	0.01620	0.00030	0.00300
0.16400	0.01669	0.01640	0.00029	0.00290
0.16600	0.01689	0.01660	0.00029	0.00290
0.16800	0.01708	0.01680	0.00028	0.00280
0.17000	0.01727	0.01700	0.00027	0.00270
0.17200	0.01745	0.01720	0.00025	0.00250

0.17400	0.01764	0.01740	0.00024	0.00240
0.17600	0.01783	0.01760	0.00023	0.00230
0.17800	0.01801	0.01780	0.00021	0.00210
0.18000	0.01820	0.01800	0.00020	0.00200
0.18200	0.01838	0.01820	0.00018	0.00180
0.18400	0.01856	0.01840	0.00016	0.00160
0.18600	0.01875	0.01860	0.00015	0.00150
0.18800	0.01892	0.01880	0.00012	0.00120
0.19000	0.01911	0.01900	0.00011	0.00110
0.19200	0.01929	0.01920	0.00009	0.00090
0.19400	0.01948	0.01940	0.00008	0.00080
0.19600	0.01966	0.01960	0.00006	0.00060
0.19800	0.01984	0.01980	0.00004	0.00040
0.20000	0.02003	0.02000	0.00003	0.00030
0.20200	0.02021	0.02020	0.00001	0.00010
0.20400	0.02040	0.02040	0.00000	0.00000
0.20600	0.02058	0.02060	-0.00002	-0.00020
0.20800	0.02076	0.02080	-0.00004	-0.00040
0.21000	0.02094	0.02100	-0.00006	-0.00060
0.21200	0.02113	0.02120	-0.00007	-0.00070
0.21400	0.02131	0.02140	-0.00009	-0.00090
0.21600	0.02150	0.02160	-0.00010	-0.00100
0.21800	0.02168	0.02180	-0.00012	-0.00120
0.22000	0.02185	0.02200	-0.00015	-0.00150
0.22200	0.02203	0.02220	-0.00017	-0.00170
0.22400	0.02220	0.02240	-0.00020	-0.00200
0.22600	0.02237	0.02260	-0.00023	-0.00230
0.22800	0.02253	0.02280	-0.00027	-0.00270
0.23000	0.02270	0.02300	-0.00030	-0.00300
0.23200	0.02286	0.02320	-0.00034	-0.00340
0.23400	0.02301	0.02340	-0.00039	-0.00390
0.23600	0.02316	0.02360	-0.00044	-0.00440
0.23800	0.02332	0.02380	-0.00048	-0.00480
0.24000	0.02348	0.02400	-0.00052	-0.00520
0.24200	0.02362	0.02420	-0.00058	-0.00580
0.24400	0.02377	0.02440	-0.00063	-0.00630
0.24600	0.02390	0.02460	-0.00070	-0.00700
0.24800	0.02405	0.02480	-0.00075	-0.00750
0.25000	0.02418	0.02500	-0.00082	-0.00820

ROCK ISLAND ARSENAL
 ADVANCED TECHNOLOGY FOR ABRASIVE MACHINING
 8 SEPTEMBER 1989
 KEYENCE EDDY CURRENT SENSOR
 FILE: KEY2.WS

DISTANCE TO TARGET (INCHES)	SENSOR OUTPUT (VOLTS)	CALCULATED OUTPUT (VOLTS)	DIFFERENCE ACT - CALC (VOLTS)	ERROR (INCHES)
0.00000	-0.00100	0.00000	-0.00100	0.00004
0.00200	0.04240	0.05080	-0.00840	0.00033
0.00400	0.08710	0.10160	-0.01450	0.00057
0.00600	0.13410	0.15240	-0.01830	0.00072
0.00800	0.18190	0.20320	-0.02130	0.00084
0.01000	0.23180	0.25400	-0.02220	0.00087
0.01200	0.28270	0.30480	-0.02210	0.00087
0.01400	0.33530	0.35560	-0.02030	0.00080
0.01600	0.38870	0.40640	-0.01770	0.00070
0.01800	0.44230	0.45720	-0.01490	0.00059
0.02000	0.49560	0.50800	-0.01240	0.00049
0.02200	0.54630	0.55880	-0.01250	0.00049
0.02400	0.59480	0.60960	-0.01480	0.00058
0.02600	0.64200	0.66040	-0.01840	0.00072
0.02800	0.68980	0.71120	-0.02140	0.00084
0.03000	0.73850	0.76200	-0.02350	0.00093
0.03200	0.78810	0.81280	-0.02470	0.00097
0.03400	0.83820	0.86360	-0.02540	0.00100
0.03600	0.88940	0.91440	-0.02500	0.00098
0.03800	0.94120	0.96520	-0.02400	0.00094
0.04000	0.99390	1.01600	-0.02210	0.00087
0.04200	1.04740	1.06680	-0.01940	0.00076
0.04400	1.10050	1.11760	-0.01710	0.00067
0.04600	1.15420	1.16840	-0.01420	0.00056
0.04800	1.20780	1.21920	-0.01140	0.00045
0.05000	1.25950	1.27000	-0.01050	0.00041
0.05200	1.30900	1.32080	-0.01180	0.00046
0.05400	1.35750	1.37160	-0.01410	0.00056
0.05600	1.40700	1.42240	-0.01540	0.00061
0.05800	1.45670	1.47320	-0.01650	0.00065
0.06000	1.50600	1.52400	-0.01800	0.00071
0.06200	1.55610	1.57480	-0.01870	0.00074
0.06400	1.60650	1.62560	-0.01910	0.00075
0.06600	1.65700	1.67640	-0.01940	0.00076
0.06800	1.70760	1.72720	-0.01960	0.00077
0.07000	1.75850	1.77800	-0.01950	0.00077
0.07200	1.80850	1.82880	-0.02030	0.00080
0.07400	1.85910	1.87960	-0.02050	0.00081

0.07600	1.90940	1.93040	-0.02100	0.00083
0.07800	1.96000	1.98120	-0.02120	0.00083
0.08000	2.00980	2.03200	-0.02220	0.00087
0.08200	2.05940	2.08280	-0.02340	0.00092
0.08400	2.10890	2.13360	-0.02470	0.00097
0.08600	2.15870	2.18440	-0.02570	0.00101
0.08800	2.20820	2.23520	-0.02700	0.00106
0.09000	2.25740	2.28600	-0.02860	0.00113
0.09200	2.30610	2.33680	-0.03070	0.00121
0.09400	2.35420	2.38760	-0.03340	0.00131
0.09600	2.40200	2.43840	-0.03640	0.00143
0.09800	2.44990	2.48920	-0.03930	0.00155
0.10000	2.50100	2.54000	-0.03900	0.00154
0.10200	2.55440	2.59080	-0.03640	0.00143
0.10400	2.60790	2.64160	-0.03370	0.00133
0.10600	2.66170	2.69240	-0.03070	0.00121
0.10800	2.71500	2.74320	-0.02820	0.00111
0.11000	2.76810	2.79400	-0.02590	0.00102
0.11200	2.82020	2.84480	-0.02460	0.00097
0.11400	2.87190	2.89560	-0.02370	0.00093
0.11600	2.92350	2.94640	-0.02290	0.00090
0.11800	2.97390	2.99720	-0.02330	0.00092
0.12000	3.02380	3.04800	-0.02420	0.00095
0.12200	3.07280	3.09880	-0.02600	0.00102
0.12400	3.12110	3.14960	-0.02850	0.00112
0.12600	3.16820	3.20040	-0.03220	0.00127
0.12800	3.21480	3.25120	-0.03640	0.00143
0.13000	3.26070	3.30200	-0.04130	0.00163
0.13200	3.30610	3.35280	-0.04670	0.00184
0.13400	3.35390	3.40360	-0.04970	0.00196
0.13600	3.40470	3.45440	-0.04970	0.00196
0.13800	3.45870	3.50520	-0.04650	0.00183
0.14000	3.51340	3.55600	-0.04260	0.00168
0.14200	3.56860	3.60680	-0.03820	0.00150
0.14400	3.62360	3.65760	-0.03400	0.00134
0.14600	3.67760	3.70840	-0.03080	0.00121
0.14800	3.73110	3.75920	-0.02810	0.00111
0.15000	3.78350	3.81000	-0.02650	0.00104
0.15200	3.83510	3.86080	-0.02570	0.00101
0.15400	3.88580	3.91160	-0.02580	0.00102
0.15600	3.93570	3.96240	-0.02670	0.00105
0.15800	3.98430	4.01320	-0.02890	0.00114
0.16000	4.03240	4.06400	-0.03160	0.00124
0.16200	4.07970	4.11480	-0.03510	0.00138
0.16400	4.12690	4.16560	-0.03870	0.00152
0.16600	4.17480	4.21640	-0.04160	0.00164
0.16800	4.22340	4.26720	-0.04380	0.00172
0.17000	4.27350	4.31800	-0.04450	0.00175
0.17200	4.32390	4.36880	-0.04490	0.00177

0.17400	4.37450	4.41960	-0.04510	0.00178
0.17600	4.42490	4.47040	-0.04550	0.00179
0.17800	4.47480	4.52120	-0.04640	0.00183
0.18000	4.52360	4.57200	-0.04840	0.00191
0.18200	4.57200	4.62280	-0.05080	0.00200
0.18400	4.61930	4.67360	-0.05430	0.00214
0.18600	4.66620	4.72440	-0.05820	0.00229
0.18800	4.71220	4.77520	-0.06300	0.00248
0.19000	4.75770	4.82600	-0.06830	0.00269
0.19200	4.80300	4.87680	-0.07380	0.00291
0.19400	4.84770	4.92760	-0.07990	0.00315
0.19600	4.89270	4.97840	-0.08570	0.00337
0.19800	4.93720	5.02920	-0.09200	0.00362
0.20000	4.98290	5.08000	-0.09710	0.00382
0.20200	5.02940	5.13080	-0.10140	0.00399

ROCK ISLAND ARSENAL
 ADVANCED TECHNOLOGY FOR ABRASIVE MACHINING
 8 SEPTEMBER 1989
 OMRON EDDY CURRENT SENSOR (HIGH SENSITIVITY) E2CA-X2A
 FILE: OMRON.WS

DISTANCE TO TARGET (INCHES)	SENSOR OUTPUT (AMPS)	CALCULATED OUTPUT (AMPS)	DIFFERENCE ACT-CALC (AMPS)	ERROR (INCHES)
0.02000	0.00399	0.00400	-0.00001	-0.00004
0.02200	0.00452	0.00453	-0.00001	-0.00004
0.02400	0.00505	0.00506	-0.00001	-0.00004
0.02600	0.00560	0.00559	0.00001	0.00004
0.02800	0.00614	0.00612	0.00002	0.00008
0.03000	0.00669	0.00665	0.00004	0.00015
0.03200	0.00722	0.00718	0.00004	0.00015
0.03400	0.00775	0.00771	0.00004	0.00015
0.03600	0.00829	0.00824	0.00005	0.00019
0.03800	0.00882	0.00877	0.00005	0.00019
0.04000	0.00934	0.00930	0.00004	0.00015
0.04200	0.00988	0.00983	0.00005	0.00019
0.04400	0.01040	0.01036	0.00004	0.00015
0.04600	0.01093	0.01089	0.00004	0.00015
0.04800	0.01145	0.01142	0.00003	0.00011
0.05000	0.01199	0.01195	0.00004	0.00015
0.05200	0.01252	0.01248	0.00004	0.00015
0.05400	0.01304	0.01301	0.00003	0.00011
0.05600	0.01356	0.01354	0.00002	0.00008
0.05800	0.01408	0.01407	0.00001	0.00004
0.06000	0.01460	0.01460	0.00000	0.00000
0.06200	0.01512	0.01513	-0.00001	-0.00004
0.06400	0.01566	0.01566	0.00000	0.00000
0.06600	0.01621	0.01619	0.00002	0.00008
0.06800	0.01674	0.01672	0.00002	0.00008
0.07000	0.01729	0.01725	0.00004	0.00015
0.07200	0.01783	0.01778	0.00005	0.00019
0.07400	0.01837	0.01831	0.00006	0.00023
0.07600	0.01891	0.01884	0.00007	0.00026
0.07800	0.01946	0.01937	0.00009	0.00034
0.08000	0.02001	0.01990	0.00011	0.00041

ROCK ISLAND ARSENAL
 ADVANCED TECHNOLOGY FOR ABRASIVE MACHINING
 8 SEPTEMBER 1989
 OMRON EDDY CURRENT SENSOR (LOW SENSITIVITY) EC2A-X2A
 FILE: OMRON1.WS

DISTANCE TO TARGET (INCHES)	SENSOR OUTPUT (AMPS)	CALCULATED OUTPUT (AMPS)	DIFFERENCE (AMPS)	ERROR INCHES
0.02000	0.00401	0.00400	0.00001	0.00004
0.02200	0.00454	0.00453	0.00001	0.00004
0.02400	0.00509	0.00506	0.00003	0.00011
0.02600	0.00563	0.00559	0.00004	0.00015
0.02800	0.00618	0.00612	0.00006	0.00023
0.03000	0.00672	0.00665	0.00007	0.00026
0.03200	0.00725	0.00718	0.00007	0.00026
0.03400	0.00778	0.00771	0.00007	0.00026
0.03600	0.00832	0.00824	0.00008	0.00030
0.03800	0.00885	0.00877	0.00008	0.00030
0.04000	0.00938	0.00930	0.00008	0.00030
0.04200	0.00991	0.00983	0.00008	0.00030
0.04400	0.01043	0.01036	0.00007	0.00026
0.04600	0.01096	0.01089	0.00007	0.00026
0.04800	0.01149	0.01142	0.00007	0.00026
0.05000	0.01202	0.01195	0.00007	0.00026
0.05200	0.01255	0.01248	0.00007	0.00026
0.05400	0.01308	0.01301	0.00007	0.00026
0.05600	0.01360	0.01354	0.00006	0.00023
0.05800	0.01411	0.01407	0.00004	0.00015
0.06000	0.01464	0.01460	0.00004	0.00015
0.06200	0.01516	0.01513	0.00003	0.00011
0.06400	0.01570	0.01566	0.00004	0.00015
0.06600	0.01625	0.01619	0.00006	0.00023
0.06800	0.01679	0.01672	0.00007	0.00026
0.07000	0.01734	0.01725	0.00009	0.00034
0.07200	0.01788	0.01778	0.00010	0.00038
0.07400	0.01842	0.01831	0.00011	0.00041
0.07600	0.01897	0.01884	0.00013	0.00049
0.07800	0.01952	0.01937	0.00015	0.00056
0.08000	0.02007	0.01990	0.00017	0.00064

ROCK ISLAND ARSENAL
 ADVANCED TECHNOLOGY FOR ABRASIVE MACHINING
 30 AUGUST 1989
 KEYENCE EDDY CURRENT SENSOR TESTING (WET VS. DRY) E2CA-X2A
 FILE: RIAHONE.WS

DISP. (INCHES)	DRY (VOLTS)	WET (VOLTS)	DRY UNITS (INCHES)	DRY ERROR (INCHES)	WET UNITS (INCHES)	WET ERROR (INCHES)
0.0000	-0.0001	0.0003	0.0000	0.0000	0.0000	0.0000
0.0100	0.2368	0.2373	0.0095	-0.0005	0.0095	-0.0005
0.0200	0.5007	0.5009	0.0200	0.0000	0.0200	0.0000
0.0300	0.7424	0.7442	0.0297	-0.0003	0.0298	-0.0002
0.0400	0.9990	0.9994	0.0400	0.0000	0.0400	0.0000
0.0500	1.2639	1.2636	0.0506	0.0006	0.0505	0.0005
0.0600	1.5096	1.5097	0.0604	0.0004	0.0604	0.0004
0.0700	1.7610	1.7610	0.0704	0.0004	0.0704	0.0004
0.0800	2.0108	2.0111	0.0804	0.0004	0.0804	0.0004
0.0900	2.2570	2.2573	0.0903	0.0003	0.0903	0.0003
0.1000	2.5004	2.5006	0.1000	0.0000	0.1000	0.0000
0.1100	2.7664	2.7664	0.1107	0.0007	0.1107	0.0007
0.1200	3.0204	3.0210	0.1208	0.0008	0.1208	0.0008
0.1300	3.2563	3.2565	0.1303	0.0003	0.1303	0.0003
0.1400	3.5078	3.5086	0.1403	0.0003	0.1403	0.0003
0.1500	3.7771	3.7778	0.1511	0.0011	0.1511	0.0011
0.1600	4.0254	4.0258	0.1610	0.0010	0.1610	0.0010
0.1700	4.2651	4.2653	0.1706	0.0006	0.1706	0.0006
0.1800	4.5177	4.5179	0.1807	0.0007	0.1807	0.0007
0.1900	4.7575	4.7576	0.1903	0.0003	0.1903	0.0003
0.2000	4.9863	4.9867	0.1995	-0.0005	0.1995	-0.0005

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Appendix V

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APPENDIX V - OFFSET STANDARD ZEISS INSPECTION DATA

MEASURING RECORD

ZEISS UMESS

CYLINDER

MANUAL MEASURING

DRAWING NUMBER I ORDER NUMBER I SUPPLIER/CUSTOMER I OPERATION
N/A I N/A I B&W I ZEISS INSP.

OPERATOR I DATE I PART NO I
503938 I 08.12.89 I I

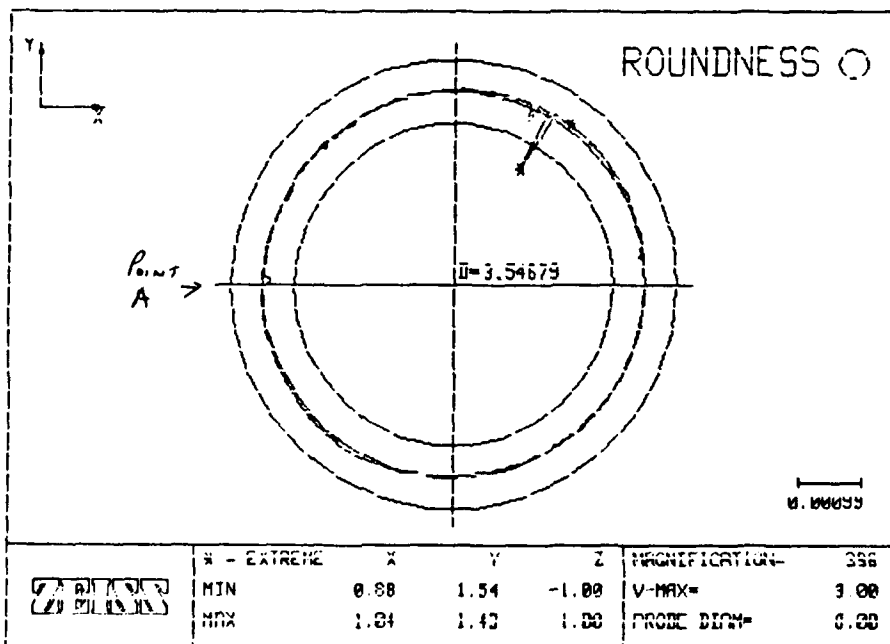
ADIREC I TASK I IDF ISYI ACTUAL I NOMINAL I U TOL I L TOL I DEV I EXC

1 COORD SYSTEM LIKE W-POS

CIRCLE AT 1.00 BELOW SURFACE "A"

2 CIRC 1 X -0.00016
 Y -0.00012
 D 3.54679
335P S/MIN/MAX 0.00006 (111) -0.00094 (117) 0.00008

FORM & POSITION INSPECTION ISO 1101



MEASURING RECORD

ZEISS UMES

CYLINDER

MANUAL MEASURING

DRAWING NUMBER
N/AORDER NUMBER
N/ASUPPLIER/CUSTOMER
B&WOPERATION
ZEISS INSP.OPERATOR
503938DATE
08.12.89PART NO
I

I

ADIR	REC	TASK	IDF	ISYI	ACTUAL	NOMINAL	U TOL	L TOL	DEV	EXC
1		COORD SYSTEM LIKE W-POS								

1 COORD SYSTEM LIKE W-POS

CIRCLE AT 1.00 BELOW SURFACE "B"

2	CIRC	I	X	-0.00033
			Y	-0.00030
			D	3.54731

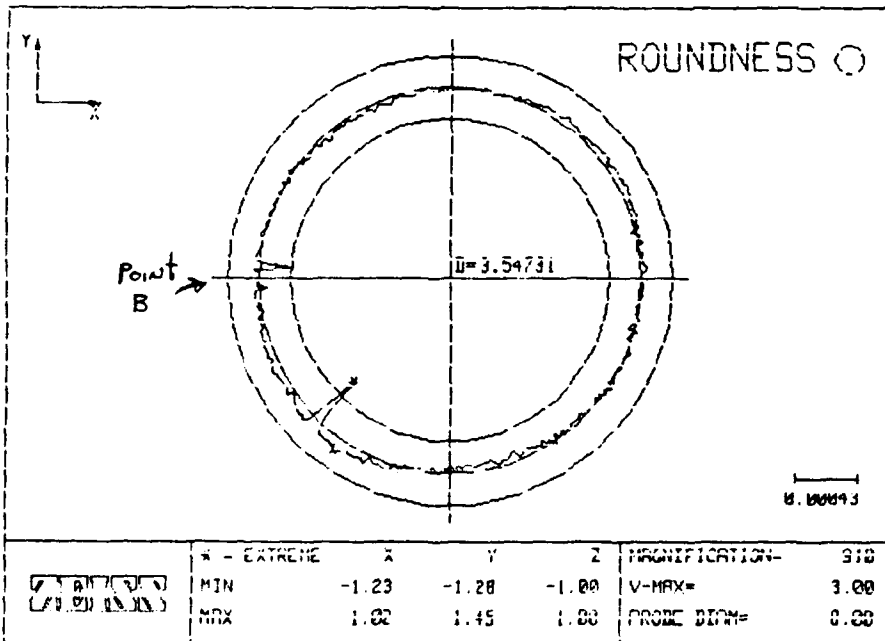
335P S/MIN/MAX

0.00004

(287) -0.00036

(279) 0.00009

FORM & POSITION INSPECTION ISO 1101



Appendix VI

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APPENDIX VI - MACHINE TESTING DATA

FILE: P1S1

Part: 1

Station: 1

Stones: Roughing

Delta Temperature: 13 F

READING	VALUE
1	3.5850
2	3.5845
3	3.5845
4	3.5850
5	3.5854
6	3.5855
7	3.5851
8	3.5850
9	3.5850
10	3.5846
11	3.5844
12	3.5843
13	3.5845
14	3.5850
15	3.5851
16	3.5849
17	3.5850
18	3.5852
19	3.5852
20	3.5848
21	3.5846
22	3.5850
23	3.5853
24	3.5852
25	3.5853
26	3.5849
27	3.5849
28	3.5849
29	3.5845
30	3.5843
31	3.5845
32	3.5848
33	3.5851
34	3.5850
35	3.5851
36	3.5850
37	3.5848
38	3.5846
39	3.5846
40	3.5850
41	3.5851
42	3.5853

43	3.5851
44	3.5851
45	3.5850
46	3.5848
47	3.5846
48	3.5843
49	3.5845
50	3.5851
51	3.5853
52	3.5850
53	3.5849
54	3.5851
55	3.5850
56	3.5848
57	3.5846
58	3.5850
59	3.5852
60	3.5852
61	3.5851
62	3.5850
63	3.5850
64	3.5846
65	3.5845
66	3.5845
67	3.5844
68	3.5850
69	3.5849
70	3.5849
71	3.5849
72	3.5851
73	3.5849
74	3.5847
75	3.5845
76	3.5853
77	3.5852
78	3.5853
79	3.5852
80	3.5849
81	3.5850
82	3.5846
83	3.5848
84	3.5843
85	3.5844
86	3.5850
87	3.5852
88	3.5849
89	3.5850
90	3.5850
91	3.5850
92	3.5846
93	3.5853
94	3.5851

95	3.5852
96	3.5853
97	3.5849
98	3.5845
99	3.5844
100	3.5844
101	3.5848
102	3.5849
103	3.5850
104	3.5850
105	3.5851
106	3.5851
107	3.5848
108	3.5845
109	3.5848
110	3.5854
111	3.5854
112	3.5851
113	3.5851
114	3.5852
115	3.5849
116	3.5846
117	3.5844
118	3.5842
119	3.5846
120	3.5849
121	3.5851
122	3.5849
123	3.5850
124	3.5850
125	3.5849
126	3.5845
127	3.5846
128	3.5850
129	3.5855
130	3.5854
131	3.5849
132	3.5852
133	3.5849
134	3.5847
135	3.5845
136	3.5844
137	3.5845
138	3.5849
139	3.5854
140	3.5851
141	3.5850
142	3.5852
143	3.5850
144	3.5845
145	3.5848
146	3.5855

147	3.5853
148	3.5851
149	3.5848
150	3.5851
151	3.5847
152	3.5847
153	3.5843
154	3.5844
155	3.5848
156	3.5849
157	3.5850
158	3.5849
159	3.5851
160	3.5848
161	3.5849
162	3.5845
163	3.5848
164	3.5853
165	3.5854
166	3.5852
167	3.5851
168	3.5850
169	3.5848
170	3.5845
171	3.5843
172	3.5843
173	3.5847
174	3.5849
175	3.5849
176	3.5850
177	3.5850
178	3.5848
179	3.5848
180	3.5846
181	3.5847
182	3.5852
183	3.5853
184	3.5851
185	3.5850
186	3.5850
187	3.5847
188	3.5846
189	3.5843
190	3.5845
191	3.5849
192	3.5849
193	3.5853
194	3.5850
195	3.5849
196	3.5848
197	3.5845
198	3.5846

199	3.5849
200	3.5851
201	3.5852
202	3.5853
203	3.5850
204	3.5851
205	3.5844
206	3.5844
207	3.5842
208	3.5845
209	3.5849
210	3.5851
211	3.5851
212	3.5849
213	3.5854
214	3.5849
215	3.5848
216	3.5845
217	3.5853
218	3.5854
219	3.5852
220	3.5854
221	3.5850
222	3.5850
223	3.5847
224	3.5845
225	3.5844
226	3.5845
227	3.5847
228	3.5852
229	3.5851
230	3.5850
231	3.5851
232	3.5848
233	3.5844
234	3.5845
235	3.5850
236	3.5855
237	3.5853
238	3.5853
239	3.5848
240	3.5848
241	3.5846
242	3.5846
243	3.5843
244	3.5842
245	3.5847
246	3.5850
247	3.5849
248	3.5851
249	3.5851

8

SECONDS ELAPSED TIME

31 READINGS PER SECOND
3.5842 MINIMUM DIAMETER READING
3.5855 MAXIMUM DIAMETER READING
3.5849 AVERAGE DIAMETER READING

FILE: P1S2

Part: 1

Station: 2

Stones: Finishing

Delta Temperature: 7 F

READING	VALUE
1.00	3.5852
2.00	3.5853
3.00	3.5850
4.00	3.5852
5.00	3.5852
6.00	3.5850
7.00	3.5851
8.00	3.5849
9.00	3.5851
10.00	3.5854
11.00	3.5854
12.00	3.5853
13.00	3.5851
14.00	3.5850
15.00	3.5847
16.00	3.5846
17.00	3.5845
18.00	3.5848
19.00	3.5850
20.00	3.5850
21.00	3.5852
22.00	3.5852
23.00	3.5852
24.00	3.5849
25.00	3.5851
26.00	3.5850
27.00	3.5852
28.00	3.5852
29.00	3.5853
30.00	3.5855
31.00	3.5852
32.00	3.5849
33.00	3.5845
34.00	3.5845
35.00	3.5847
36.00	3.5848
37.00	3.5851
38.00	3.5850
39.00	3.5852
40.00	3.5851
41.00	3.5850
42.00	3.5849
43.00	3.5849

44.00	3.5849
45.00	3.5852
46.00	3.5851
47.00	3.5854
48.00	3.5855
49.00	3.5853
50.00	3.5849
51.00	3.5846
52.00	3.5844
53.00	3.5848
54.00	3.5850
55.00	3.5851
56.00	3.5852
57.00	3.5852
58.00	3.5852
59.00	3.5851
60.00	3.5849
61.00	3.5849
62.00	3.5851
63.00	3.5851
64.00	3.5856
65.00	3.5854
66.00	3.5856
67.00	3.5851
68.00	3.5851
69.00	3.5847
70.00	3.5843
71.00	3.5847
72.00	3.5848
73.00	3.5852
74.00	3.5849
75.00	3.5852

2.2	SECONDS ELAPSED TIME
34.0	READINGS PER SECOND
3.5843	MINIMUM DIAMETER READING
3.5856	MAXIMUM DIAMETER READING
3.5850	AVERAGE DIAMETER READING

FILE: P2S1

Part:2

Station: 1

Stones: Finishing

Ambient Temperature: 69 F

Part Temperature: 78 F

Delta Temperature: 9 F

READING	DIAMETER
1	3.5472
2	3.5473
3	3.5473
4	3.5471
5	3.5467
6	3.5467
7	3.5463
8	3.5462
9	3.5463
10	3.5469
11	3.5468
12	3.5473
13	3.5472
14	3.5473
15	3.5472
16	3.5469
17	3.5469
18	3.5468
19	3.5472
20	3.5475
21	3.5473
22	3.5472
23	3.5466
24	3.5468
25	3.5463
26	3.5464
27	3.5463
28	3.5466
29	3.5470
30	3.5474
31	3.5474
32	3.5472
33	3.5473
34	3.5469
35	3.5467
36	3.5467
37	3.5472
38	3.5473
39	3.5462
40	3.5464
41	3.5465

42	3.5467
43	3.5470
44	3.5475
45	3.5474
46	3.5471
47	3.5473
48	3.5471
49	3.5470
50	3.5468
51	3.5470
52	3.5472
53	3.5475
54	3.5471
55	3.5466
56	3.5468
57	3.5465
58	3.5464
59	3.5464
60	3.5468
61	3.5469
62	3.5473
63	3.5474
64	3.5474
65	3.5475
66	3.5471
67	3.5471
68	3.5470
69	3.5468
70	3.5472
71	3.5473
72	3.5473
73	3.5467
74	3.5468
75	3.5464
76	3.5461
77	3.5463
78	3.5467
79	3.5469
80	3.5472
81	3.5475
82	3.5472
83	3.5474
84	3.5471
85	3.5469
86	3.5468
87	3.5470
88	3.5473
89	3.5473
90	3.5462
91	3.5465
92	3.5466
93	3.5470

94	3.5473
95	3.5474
96	3.5473
97	3.5474
98	3.5471
99	3.5471
100	3.5467
101	3.5472
102	3.5472
103	3.5474
104	3.5472
105	3.5467
106	3.5468
107	3.5462
108	3.5463
109	3.5463
110	3.5468
111	3.5470
112	3.5474
113	3.5474
114	3.5472
115	3.5475
116	3.5470
117	3.5471
118	3.5468
119	3.5470
120	3.5472
121	3.5474
122	3.5472
123	3.5468
124	3.5465
125	3.5465
126	3.5461
127	3.5464
128	3.5466
129	3.5469
130	3.5472
131	3.5475
132	3.5473
133	3.5474
134	3.5472
135	3.5468
136	3.5470
137	3.5469
138	3.5473
139	3.5472
140	3.5472
141	3.5468
142	3.5468
143	3.5463
144	3.5466
145	3.5466

146	3.5468
147	3.5473
148	3.5475
149	3.5474
150	3.5475
151	3.5474
152	3.5471
153	3.5470
154	3.5469
155	3.5469
156	3.5474
157	3.5473
158	3.5470
159	3.5468
160	3.5466
161	3.5463
162	3.5466
163	3.5466
164	3.5469
165	3.5473
166	3.5475
167	3.5474
168	3.5474
169	3.5471
170	3.5471
171	3.5470
172	3.5468
173	3.5471
174	3.5474
175	3.5475
176	3.5469
177	3.5466
178	3.5467
179	3.5463
180	3.5463
181	3.5465
182	3.5467
183	3.5472
184	3.5476
185	3.5474
186	3.5472
187	3.5473
188	3.5471
189	3.5469
190	3.5468
191	3.5471
192	3.5474
193	3.5473
194	3.5468
195	3.5468
196	3.5464
197	3.5463

198	3.5464
199	3.5466
200	3.5471
201	3.5472
202	3.5475
203	3.5473
204	3.5474
205	3.5471
206	3.5469
207	3.5469
208	3.5471
209	3.5473
210	3.5474
211	3.5474
212	3.5468
213	3.5468
214	3.5466
215	3.5460
216	3.5462
217	3.5467
218	3.5470
219	3.5474
220	3.5476
221	3.5472
222	3.5474
223	3.5472
224	3.5468
225	3.5469
226	3.5468
227	3.5471
228	3.5474
229	3.5473
230	3.5469
231	3.5467
232	3.5464
233	3.5462
234	3.5464
235	3.5468
236	3.5471
237	3.5472
238	3.5474
239	3.5471
240	3.5474
241	3.5470
242	3.5469
243	3.5468
244	3.5470
245	3.5472
246	3.5473
247	3.5471
248	3.5467
249	3.5468

	7	SECONDS ELAPSED TIME
	34	READINGS PER SECOND
Minimum	3.5460	MINIMUM DIAMETER READING
Maximum	3.5476	MAXIMUM DIAMETER READING
Average	3.5470	AVERAGE DIAMETER READING

FILE: P2S2

Part: 2

Station: 2

Stones: Finishing

Ambient Temperature: 69 F

Part Temperature: 83 F

Delta Temperature: 14 F

READING	DIAMETER
1	3.5480
2	3.5475
3	3.5477
4	3.5474
5	3.5478
6	3.5475
7	3.5473
8	3.5472
9	3.5473
10	3.5477
11	3.5475
12	3.5477
13	3.5477
14	3.5481
15	3.5481
16	3.5480
17	3.5477
18	3.5477
19	3.5480
20	3.5475
21	3.5475
22	3.5473
23	3.5479
24	3.5477
25	3.5472
26	3.5472
27	3.5474
28	3.5477
29	3.5475
30	3.5475
31	3.5478
32	3.5482
33	3.5481
34	3.5477
35	3.5478
36	3.5475
37	3.5479
38	3.5475
39	3.5474
40	3.5474
41	3.5478

42	3.5474
43	3.5474
44	3.5471
45	3.5476
46	3.5479
47	3.5476
48	3.5475
49	3.5480
50	3.5481
51	3.5482
52	3.5478
53	3.5475
54	3.5478
55	3.5479
56	3.5475
57	3.5476
58	3.5474
59	3.5478
60	3.5477
61	3.5474
62	3.5472
63	3.5473
64	3.5478
65	3.5477
66	3.5476
67	3.5479
68	3.5481
69	3.5481
70	3.5478
71	3.5475
72	3.5476
73	3.5478
74	3.5474
75	3.5476
76	3.5475
77	3.5478
78	3.5477
79	3.5474
80	3.5472
81	3.5474
82	3.5476
83	3.5475
84	3.5476
85	3.5478
86	3.5480
87	3.5481
88	3.5479
89	3.5477
90	3.5473
91	3.5474
92	3.5476
93	3.5477

94	3.5478
95	3.5474
96	3.5472
97	3.5474
98	3.5475
99	3.5472
100	3.5478
101	3.5480
102	3.5483
103	3.5479
104	3.5477
105	3.5474
106	3.5475
107	3.5477
108	3.5476
109	3.5477
110	3.5476
111	3.5476
112	3.5477
113	3.5472
114	3.5472
115	3.5475
116	3.5473
117	3.5475
118	3.5477
119	3.5480
120	3.5483
121	3.5480
122	3.5478
123	3.5473
124	3.5477
125	3.5476
126	3.5473
127	3.5477
128	3.5478
129	3.5476
130	3.5477
131	3.5471
132	3.5472
133	3.5474
134	3.5478
135	3.5474
136	3.5477
137	3.5478
138	3.5482
139	3.5480
140	3.5478
141	3.5475
142	3.5477
143	3.5476
144	3.5473
145	3.5475

146	3.5476
147	3.5477
148	3.5474
149	3.5470
150	3.5473
151	3.5473
152	3.5476
153	3.5474
154	3.5478
155	3.5483
156	3.5478
157	3.5477
158	3.5478
159	3.5476
160	3.5476
161	3.5475
162	3.5474
163	3.5476
164	3.5477
165	3.5474
166	3.5474
167	3.5472
168	3.5474
169	3.5473
170	3.5475
171	3.5474
172	3.5477
173	3.5481
174	3.5482
175	3.5477
176	3.5474
177	3.5477
178	3.5476
179	3.5478
180	3.5471
181	3.5474
182	3.5478
183	3.5477
184	3.5474
185	3.5472
186	3.5470
187	3.5475
188	3.5477
189	3.5475
190	3.5475
191	3.5482
192	3.5481
193	3.5480
194	3.5474
195	3.5476
196	3.5478
197	3.5475

198	3.5476
199	3.5474
200	3.5478
201	3.5477
202	3.5474
203	3.5471
204	3.5474
205	3.5477
206	3.5476
207	3.5476
208	3.5478
209	3.5481
210	3.5482
211	3.5480
212	3.5475
213	3.5478
214	3.5480
215	3.5475
216	3.5476
217	3.5475
218	3.5477
219	3.5475
220	3.5473
221	3.5471
222	3.5473
223	3.5477
224	3.5475
225	3.5476
226	3.5479
227	3.5480
228	3.5480
229	3.5480
230	3.5477
231	3.5474
232	3.5479
233	3.5475
234	3.5478
235	3.5474
236	3.5476
237	3.5476
238	3.5472
239	3.5471
240	3.5472
241	3.5475
242	3.5474
243	3.5478
244	3.5479
245	3.5480
246	3.5481
247	3.5478
248	3.5474
249	3.5476

250	3.5477
251	3.5474
252	3.5476
253	3.5477
254	3.5476
255	3.5478
256	3.5473
257	3.5469
258	3.5474
259	3.5477
260	3.5476
261	3.5476
262	3.5481
263	3.5481
264	3.5483
265	3.5477
266	3.5474
267	3.5476
268	3.5478
269	3.5474
270	3.5476
271	3.5476
272	3.5475
273	3.5477
274	3.5473
275	3.5470
276	3.5475
277	3.5477
278	3.5474
279	3.5478
280	3.5480
281	3.5482
282	3.5481
283	3.5477
284	3.5475
285	3.5477
286	3.5479
287	3.5475
288	3.5474
289	3.5477
290	3.5474
291	3.5477
292	3.5472
293	3.5472
294	3.5477
295	3.5475
296	3.5474
297	3.5477
298	3.5483
299	3.5482
300	3.5479
301	3.5475

302	3.5475
303	3.5478
304	3.5477
305	3.5474
306	3.5473
307	3.5479
308	3.5475
309	3.5476
310	3.5472
311	3.5473
312	3.5476
313	3.5476
314	3.5476
315	3.5476
316	3.5482
317	3.5483
318	3.5480
319	3.5478
320	3.5476
321	3.5478
322	3.5476
323	3.5474
324	3.5475
325	3.5478
326	3.5476
327	3.5473
328	3.5474
329	3.5475
330	3.5477
331	3.5475
332	3.5475
333	3.5476
334	3.5480
335	3.5480
336	3.5481
337	3.5477
338	3.5475
339	3.5479
340	3.5476

10 SECONDS ELAPSED TIME

33 READINGS PER SECOND

3.5469 MINIMUM DIAMETER READING

3.5483 MAXIMUM DIAMETER READING

3.5476 AVERAGE DIAMETER READING

FILE: P2S3

Part: 1

Station: 3

Stones: Finishing

Ambient Temperature: 69 F

Part Temperature: 77 F

Delta Temperature: 8 F

READING	DIAMETER
1	3.5475
2	3.5475
3	3.5474
4	3.5476
5	3.5478
6	3.5477
7	3.5477
8	3.5474
9	3.5477
10	3.5472
11	3.5474
12	3.5472
13	3.5471
14	3.5476
15	3.5475
16	3.5476
17	3.5472
18	3.5474
19	3.5471
20	3.5474
21	3.5475
22	3.5475
23	3.5480
24	3.5478
25	3.5477
26	3.5473
27	3.5476
28	3.5473
29	3.5472
30	3.5474
31	3.5470
32	3.5474
33	3.5475
34	3.5473
35	3.5472
36	3.5475
37	3.5472
38	3.5474
39	3.5474
40	3.5475
41	3.5479

42	3.5479
43	3.5476
44	3.5475
45	3.5476
46	3.5471
47	3.5471
48	3.5473
49	3.5471
50	3.5474
51	3.5473
52	3.5473
53	3.5472
54	3.5472
55	3.5473
56	3.5476
57	3.5474
58	3.5477
59	3.5478
60	3.5479
61	3.5476
62	3.5474
63	3.5475
64	3.5471
65	3.5474
66	3.5471
67	3.5471
68	3.5472
69	3.5476
70	3.5474
71	3.5473
72	3.5473
73	3.5476
74	3.5474
75	3.5475
76	3.5477
77	3.5478
78	3.5478
79	3.5477
80	3.5475
81	3.5475
82	3.5473
83	3.5471
84	3.5470
85	3.5472
86	3.5474
87	3.5474
88	3.5474
89	3.5472
90	3.5475
91	3.5472
92	3.5475
93	3.5477

94	3.5477
95	3.5482
96	3.5482
97	3.5477
98	3.5476
99	3.5473
100	3.5473
101	3.5474
102	3.5471
103	3.5473
104	3.5476
105	3.5477
106	3.5471
107	3.5473
108	3.5475
109	3.5473
110	3.5476
111	3.5477
112	3.5478
113	3.5483
114	3.5480
115	3.5478
116	3.5476
117	3.5474
118	3.5471
119	3.5475
120	3.5472
121	3.5471
122	3.5477
123	3.5476
124	3.5471
125	3.5473
126	3.5474
127	3.5472
128	3.5473
129	3.5477
130	3.5478
131	3.5485
132	3.5481
133	3.5477
134	3.5476
135	3.5474
136	3.5473
137	3.5472
138	3.5470
139	3.5473
140	3.5478
141	3.5476
142	3.5472
143	3.5473
144	3.5474
145	3.5474

146	3.5476
147	3.5476
148	3.5478
149	3.5481
150	3.5479
151	3.5475
152	3.5473
153	3.5473
154	3.5473
155	3.5472
156	3.5470
157	3.5472
158	3.5474
159	3.5476
160	3.5473
161	3.5474
162	3.5473
163	3.5474
164	3.5474
165	3.5477
166	3.5478
167	3.5480
168	3.5480
169	3.5475
170	3.5472
171	3.5473
172	3.5471
173	3.5474
174	3.5472
175	3.5472
176	3.5475
177	3.5476
178	3.5472
179	3.5471
180	3.5472
181	3.5473
182	3.5475
183	3.5477
184	3.5477
185	3.5481
186	3.5482
187	3.5474
188	3.5473
189	3.5472
190	3.5472
191	3.5475
192	3.5470
193	3.5477
194	3.5475
195	3.5471
196	3.5472
197	3.5473

198	3.5473
199	3.5477
200	3.5475
201	3.5477
202	3.5482
203	3.5479
204	3.5473
205	3.5475
206	3.5475
207	3.5473
208	3.5474
209	3.5472
210	3.5471
211	3.5478
212	3.5474
213	3.5471
214	3.5473
215	3.5471
216	3.5475
217	3.5474
218	3.5476
219	3.5477
220	3.5483
221	3.5479
222	3.5474
223	3.5474
224	3.5475
225	3.5471
226	3.5475
227	3.5473
228	3.5471
229	3.5477
230	3.5474
231	3.5472
232	3.5473
233	3.5473
234	3.5473
235	3.5478
236	3.5474
237	3.5476
238	3.5481
239	3.5479
240	3.5475
241	3.5475
242	3.5476
243	3.5472
244	3.5474
245	3.5469
246	3.5475
247	3.5480
248	3.5477
249	3.5472

250	3.5473
251	3.5478
252	3.5473
253	3.5478
254	3.5475
255	3.5478
256	3.5483
257	3.5481
258	3.5476
259	3.5476
260	3.5474
261	3.5471
262	3.5474
263	3.5470
264	3.5473
265	3.5479
266	3.5473
267	3.5472
268	3.5473
269	3.5474
270	3.5473
271	3.5477
272	3.5475
273	3.5479
274	3.5483
275	3.5480
276	3.5476
277	3.5478
278	3.5474
279	3.5472
280	3.5473
281	3.5470
282	3.5474
283	3.5479
284	3.5477
285	3.5472
286	3.5474

SECONDS ELAPSED TIME

READINGS PER SECOND

3.5469 MINIMUM DIAMETER READING

3.5485 MAXIMUM DIAMETER READING

3.5475 AVERAGE DIAMETER READING

FILE: P2S4

Part: 2

Station: 4

Stones: Finishing

Ambient Temperature: 69 F

Part Temperature: 77 F

Delta Temperature: 8 F

READING	DIAMETER
1	3.5474
2	3.5475
3	3.5475
4	3.5477
5	3.5478
6	3.5481
7	3.5480
8	3.5475
9	3.5477
10	3.5475
11	3.5475
12	3.5476
13	3.5476
14	3.5471
15	3.5474
16	3.5473
17	3.5470
18	3.5470
19	3.5474
20	3.5474
21	3.5475
22	3.5477
23	3.5474
24	3.5481
25	3.5481
26	3.5475
27	3.5478
28	3.5473
29	3.5475
30	3.5475
31	3.5475
32	3.5471
33	3.5472
34	3.5475
35	3.5470
36	3.5471
37	3.5471
38	3.5473
39	3.5475
40	3.5472
41	3.5476

42	3.5481
43	3.5480
44	3.5475
45	3.5478
46	3.5475
47	3.5475
48	3.5473
49	3.5474
50	3.5472
51	3.5473
52	3.5474
53	3.5470
54	3.5472
55	3.5471
56	3.5474
57	3.5476
58	3.5476
59	3.5477
60	3.5480
61	3.5479
62	3.5477
63	3.5477
64	3.5476
65	3.5473
66	3.5475
67	3.5474
68	3.5473
69	3.5476
70	3.5473
71	3.5472
72	3.5472
73	3.5471
74	3.5473
75	3.5473
76	3.5478
77	3.5476
78	3.5479
79	3.5481
80	3.5474
81	3.5475
82	3.5474
83	3.5473
84	3.5476
85	3.5472
86	3.5472
87	3.5473
88	3.5476
89	3.5470
90	3.5473
91	3.5476
92	3.5478
93	3.5478

94	3.5481
95	3.5475
96	3.5478
97	3.5474
98	3.5475
99	3.5478
100	3.5472
101	3.5472
102	3.5477
103	3.5475
104	3.5471
105	3.5472
106	3.5470
107	3.5472
108	3.5475
109	3.5475
110	3.5478
111	3.5479
112	3.5480
113	3.5476
114	3.5477
115	3.5476
116	3.5474
117	3.5478
118	3.5475
119	3.5470
120	3.5476
121	3.5474
122	3.5471
123	3.5471
124	3.5470
125	3.5475
126	3.5474
127	3.5476
128	3.5477
129	3.5480
130	3.5482
131	3.5475
132	3.5476
133	3.5476
134	3.5474
135	3.5475
136	3.5474
137	3.5473
138	3.5475
139	3.5477
140	3.5472
141	3.5471
142	3.5471
143	3.5471
144	3.5474
145	3.5475

146	3.5477
147	3.5478
148	3.5481
149	3.5476
150	3.5475
151	3.5473
152	3.5473
153	3.5475
154	3.5476
155	3.5473
156	3.5473
157	3.5474
158	3.5471
159	3.5471
160	3.5471
161	3.5473
162	3.5472
163	3.5476
164	3.5478
165	3.5477
166	3.5480
167	3.5476
168	3.5477
169	3.5475
170	3.5472
171	3.5473
172	3.5474
173	3.5474
174	3.5476
175	3.5474
176	3.5471
177	3.5473
178	3.5469
179	3.5472
180	3.5473
181	3.5476
182	3.5477
183	3.5478
184	3.5480
185	3.5476
186	3.5475
187	3.5474
188	3.5473
189	3.5473
190	3.5476
191	3.5473
192	3.5474
193	3.5472
194	3.5469
195	3.5472
196	3.5472
197	3.5473

198	3.5475
199	3.5475
200	3.5479
201	3.5480
202	3.5477
203	3.5476
204	3.5476
205	3.5476
206	3.5476
207	3.5474
208	3.5472
209	3.5475
210	3.5475
211	3.5474
212	3.5471
213	3.5472
214	3.5469
215	3.5474
216	3.5475
217	3.5475
218	3.5479
219	3.5480
220	3.5478
221	3.5475
222	3.5476
223	3.5476
224	3.5475
225	3.5476
226	3.5473
227	3.5476
228	3.5476
229	3.5473
230	3.5472
231	3.5471
232	3.5470
233	3.5473
234	3.5475
235	3.5475
236	3.5478
237	3.5481
238	3.5478
239	3.5476
240	3.5474
241	3.5473
242	3.5476
243	3.5476
244	3.5473
245	3.5475
246	3.5476
247	3.5471
248	3.5470
249	3.5472

250	3.5472
251	3.5475
252	3.5476
253	3.5473
254	3.5480
255	3.5481
256	3.5476
257	3.5476
258	3.5477
259	3.5473
260	3.5477
261	3.5476
262	3.5473
263	3.5475
264	3.5476
265	3.5470
266	3.5471
267	3.5475
268	3.5473
269	3.5474
270	3.5475
271	3.5474
272	3.5480
273	3.5480
274	3.5475
275	3.5478
276	3.5477
277	3.5475
278	3.5476
279	3.5474
280	3.5474
281	3.5475
282	3.5476
283	3.5470
284	3.5470
285	3.5475
286	3.5474
287	3.5475
288	3.5479

9

SECONDS ELAPSED TIME

32

READINGS PER SECOND

3.5469

MINIMUM DIAMETER READING

3.5482

MAXIMUM DIAMETER READING

3.5475

AVERAGE DIAMETER READING

FILE: P2S5

Part: 2

Station: 5

Stones: Finishing

Ambient Temperature: 69 F

Part Temperature: 76 F

Delta Temperature: 8 F

READING	DIAMETER
---------	----------

1	3.5467
2	3.5468
3	3.5473
4	3.5470
5	3.5470
6	3.5474
7	3.5473
8	3.5474
9	3.5474
10	3.5472
11	3.5470
12	3.5470
13	3.5467
14	3.5468
15	3.5468
16	3.5465
17	3.5467
18	3.5468
19	3.5466
20	3.5466
21	3.5473
22	3.5472
23	3.5472
24	3.5473
25	3.5474
26	3.5474
27	3.5474
28	3.5470
29	3.5471
30	3.5467
31	3.5470
32	3.5467
33	3.5468
34	3.5467
35	3.5468
36	3.5467
37	3.5470
38	3.5473
39	3.5472
40	3.5472
41	3.5471

42	3.5475
43	3.5473
44	3.5474
45	3.5474
46	3.5473
47	3.5470
48	3.5471
49	3.5465
50	3.5467
51	3.5472
52	3.5469
53	3.5465
54	3.5466
55	3.5467
56	3.5468
57	3.5473
58	3.5470
59	3.5473
60	3.5474
61	3.5472
62	3.5473
63	3.5474
64	3.5470
65	3.5473
66	3.5469
67	3.5470
68	3.5467
69	3.5468
70	3.5466
71	3.5467
72	3.5467
73	3.5467
74	3.5465
75	3.5471
76	3.5470
77	3.5471
78	3.5473
79	3.5473
80	3.5474
81	3.5473
82	3.5470
83	3.5472
84	3.5470
85	3.5469
86	3.5467
87	3.5466
88	3.5468
89	3.5468
90	3.5472
91	3.5471
92	3.5478
93	3.5476

94	3.5475
95	3.5474
96	3.5474
97	3.5471
98	3.5473
99	3.5472
100	3.5469
101	3.5472
102	3.5467
103	3.5468
104	3.5466
105	3.5467
106	3.5465
107	3.5467
108	3.5473
109	3.5470
110	3.5471
111	3.5475
112	3.5476
113	3.5474
114	3.5472
115	3.5471
116	3.5471
117	3.5472
118	3.5469
119	3.5470
120	3.5467
121	3.5470
122	3.5468
123	3.5466
124	3.5466
125	3.5468
126	3.5473
127	3.5472
128	3.5472
129	3.5475
130	3.5475
131	3.5475
132	3.5470
133	3.5472
134	3.5474
135	3.5474
136	3.5469
137	3.5470
138	3.5469
139	3.5470
140	3.5468
141	3.5468
142	3.5469
143	3.5469
144	3.5472
145	3.5467

146	3.5473
147	3.5476
148	3.5474
149	3.5474
150	3.5473
151	3.5469
152	3.5472
153	3.5472
154	3.5467
155	3.5467
156	3.5470
157	3.5466
158	3.5468
159	3.5467
160	3.5468
161	3.5471
162	3.5472
163	3.5471
164	3.5473
165	3.5473
166	3.5472
167	3.5472
168	3.5474
169	3.5470
170	3.5470
171	3.5472
172	3.5468
173	3.5469
174	3.5468
175	3.5467
176	3.5467
177	3.5466
178	3.5465
179	3.5467
180	3.5470
181	3.5471
182	3.5472
183	3.5475
184	3.5472
185	3.5473
186	3.5474
187	3.5471
188	3.5470
189	3.5471
190	3.5469
191	3.5469
192	3.5471
193	3.5467
194	3.5463
195	3.5465
196	3.5467
197	3.5470

198	3.5471
199	3.5471
200	3.5468
201	3.5473
202	3.5474
203	3.5471
204	3.5471
205	3.5471
206	3.5472
207	3.5471
208	3.5469
209	3.5468
210	3.5469
211	3.5466
212	3.5465
213	3.5468
214	3.5466
215	3.5469
216	3.5474
217	3.5472
218	3.5471
219	3.5474
220	3.5475
221	3.5470
222	3.5473
223	3.5473
224	3.5471
225	3.5469
226	3.5468
227	3.5466
228	3.5472
229	3.5467
230	3.5463
231	3.5466
232	3.5468
233	3.5468
234	3.5472
235	3.5474
236	3.5471
237	3.5474
238	3.5474
239	3.5471
240	3.5473
241	3.5470
242	3.5472
243	3.5469
244	3.5470
245	3.5470
246	3.5468
247	3.5469
248	3.5465
249	3.5466

250	3.5468
251	3.5473
252	3.5471
253	3.5471
254	3.5473
255	3.5474
256	3.5475
257	3.5470
258	3.5469
259	3.5471

8

SECONDS ELAPSED TIME

31

READINGS PER SECOND

3.5463

MINIMUM DIAMETER READING

3.5478

MAXIMUM DIAMETER READING

3.5470

AVERAGE DIAMETER READING

Part 1, with roughing stones
Full part profile
File: P1PRO.dat

1.0000	3.5643	0.0003
2.0000	3.5647	0.0007
3.0000	3.5649	0.0009
4.0000	3.5650	0.0010
5.0000	3.5648	0.0008
6.0000	3.5646	0.0006
7.0000	3.5645	0.0005
8.0000	3.5645	0.0005
9.0000	3.5644	0.0004
10.0000	3.5643	0.0003
11.0000	3.5643	0.0003
12.0000	3.5643	0.0003
13.0000	3.5642	0.0002
14.0000	3.5642	0.0002
15.0000	3.5647	0.0007
16.0000	3.5645	0.0005
17.0000	3.5648	0.0008
18.0000	3.5647	0.0007
19.0000	3.5649	0.0009
20.0000	3.5646	0.0006
21.0000	3.5647	0.0007
22.0000	3.5646	0.0006
23.0000	3.5647	0.0007
24.0000	3.5648	0.0008
25.0000	3.5647	0.0007
26.0000	3.5643	0.0003
27.0000	3.5645	0.0005
28.0000	3.5647	0.0007
29.0000	3.5650	0.0010
30.0000	3.5652	0.0012
31.0000	3.5651	0.0011
32.0000	3.5651	0.0011
33.0000	3.5648	0.0008
34.0000	3.5648	0.0008
35.0000	3.5647	0.0007
36.0000	3.5648	0.0008
37.0000	3.5645	0.0005
38.0000	3.5645	0.0005
39.0000	3.5645	0.0005
40.0000	3.5646	0.0006
41.0000	3.5646	0.0006
42.0000	3.5650	0.0010
43.0000	3.5649	0.0009
44.0000	3.5650	0.0010
45.0000	3.5648	0.0008
46.0000	3.5648	0.0008
47.0000	3.5651	0.0011

48.0000	3.5647	0.0007
49.0000	3.5649	0.0009
50.0000	3.5646	0.0006
51.0000	3.5649	0.0009
52.0000	3.5645	0.0005
53.0000	3.5651	0.0011
54.0000	3.5647	0.0007
55.0000	3.5647	0.0007
56.0000	3.5647	0.0007
57.0000	3.5645	0.0005
58.0000	3.5644	0.0004
59.0000	3.5647	0.0007
60.0000	3.5645	0.0005
61.0000	3.5649	0.0009
62.0000	3.5651	0.0011
63.0000	3.5650	0.0010
64.0000	3.5651	0.0011
65.0000	3.5651	0.0011
66.0000	3.5650	0.0010
67.0000	3.5650	0.0010
68.0000	3.5650	0.0010
69.0000	3.5648	0.0008
70.0000	3.5649	0.0009
71.0000	3.5645	0.0005
72.0000	3.5648	0.0008
73.0000	3.5646	0.0006
74.0000	3.5649	0.0009
75.0000	3.5649	0.0009
76.0000	3.5654	0.0014
77.0000	3.5653	0.0013
78.0000	3.5653	0.0013
79.0000	3.5651	0.0011
80.0000	3.5650	0.0010
81.0000	3.5649	0.0009
82.0000	3.5648	0.0008
83.0000	3.5649	0.0009
84.0000	3.5650	0.0010
85.0000	3.5648	0.0008
86.0000	3.5650	0.0010
87.0000	3.5649	0.0009
88.0000	3.5648	0.0008
89.0000	3.5648	0.0008
90.0000	3.5654	0.0014
91.0000	3.5652	0.0012
92.0000	3.5653	0.0013
93.0000	3.5653	0.0013
94.0000	3.5654	0.0014
95.0000	3.5654	0.0014
96.0000	3.5651	0.0011
97.0000	3.5654	0.0014
98.0000	3.5651	0.0011
99.0000	3.5650	0.0010

100.0000	3.5650	0.0010
101.0000	3.5649	0.0009
102.0000	3.5646	0.0006
103.0000	3.5650	0.0010
104.0000	3.5655	0.0015
105.0000	3.5655	0.0015
106.0000	3.5652	0.0012
107.0000	3.5653	0.0013
108.0000	3.5650	0.0010
109.0000	3.5651	0.0011
110.0000	3.5649	0.0009
111.0000	3.5652	0.0012
112.0000	3.5647	0.0007
113.0000	3.5649	0.0009
114.0000	3.5647	0.0007
115.0000	3.5653	0.0013
116.0000	3.5655	0.0015
117.0000	3.5659	0.0019
118.0000	3.5656	0.0016
119.0000	3.5656	0.0016
120.0000	3.5655	0.0015
121.0000	3.5654	0.0014
122.0000	3.5657	0.0017
123.0000	3.5659	0.0019
124.0000	3.5659	0.0019
125.0000	3.5658	0.0018
126.0000	3.5659	0.0019
127.0000	3.5660	0.0020
128.0000	3.5664	0.0024
129.0000	3.5668	0.0028
130.0000	3.5673	0.0033
131.0000	3.5675	0.0035
132.0000	3.5672	0.0032
133.0000	3.5671	0.0031
134.0000	3.5674	0.0034
135.0000	3.5691	0.0051
136.0000	3.5790	0.0150
137.0000	3.6064	0.0424
138.0000	3.6611	0.0971
139.0000	3.7692	0.2052
140.0000	3.7920	0.2280
141.0000	3.7920	0.2280
142.0000	3.7920	0.2280
143.0000	3.7920	0.2280
144.0000	3.7920	0.2280
145.0000	3.7920	0.2280
146.0000	3.7920	0.2280
147.0000	3.7920	0.2280
148.0000	3.7920	0.2280
149.0000	3.7920	0.2280
150.0000	3.7920	0.2280
151.0000	3.7920	0.2280

152.0000	3.7920	0.2280
153.0000	3.7920	0.2280
154.0000	3.7920	0.2280
155.0000	3.7920	0.2280
156.0000	3.7920	0.2280
157.0000	3.7920	0.2280
158.0000	3.7920	0.2280
159.0000	3.7920	0.2280
160.0000	3.7920	0.2280
161.0000	3.7920	0.2280
162.0000	3.7920	0.2280
163.0000	3.7920	0.2280
164.0000	3.7920	0.2280
165.0000	3.7920	0.2280
166.0000	3.7920	0.2280
167.0000	3.7920	0.2280
168.0000	3.7920	0.2280
169.0000	3.7920	0.2280
170.0000	3.7920	0.2280
171.0000	3.7920	0.2280
172.0000	3.7920	0.2280
173.0000	3.7920	0.2280
174.0000	3.7920	0.2280
175.0000	3.7920	0.2280
176.0000	3.7920	0.2280
177.0000	3.7920	0.2280
178.0000	3.7920	0.2280
179.0000	3.7920	0.2280
180.0000	3.7920	0.2280
181.0000	3.7920	0.2280
182.0000	3.7920	0.2280
183.0000	3.7920	0.2280
184.0000	3.7920	0.2280
185.0000	3.7920	0.2280
186.0000	3.7920	0.2280
187.0000	3.7920	0.2280

DATA SHOWN IN GRAPH (CONNECTED POINTS)

1.00	188.0000	3.7571	0.1931
2.00	189.0000	3.6133	0.0493
3.00	190.0000	3.5715	0.0075
4.00	191.0000	3.5683	0.0043
5.00	192.0000	3.5676	0.0036
6.00	193.0000	3.5670	0.0030
7.00	194.0000	3.5671	0.0031
8.00	195.0000	3.5672	0.0032
9.00	196.0000	3.5670	0.0030
10.00	197.0000	3.5668	0.0028
11.00	198.0000	3.5662	0.0022
12.00	199.0000	3.5659	0.0019
13.00	200.0000	3.5655	0.0015
14.00	201.0000	3.5656	0.0016

15.00	202.0000	3.5656	0.0016
16.00	203.0000	3.5657	0.0017
17.00	204.0000	3.5653	0.0013
18.00	205.0000	3.5649	0.0009
19.00	206.0000	3.5653	0.0013
20.00	207.0000	3.5657	0.0017
21.00	208.0000	3.5659	0.0019
22.00	209.0000	3.5657	0.0017
23.00	210.0000	3.5657	0.0017
24.00	211.0000	3.5650	0.0010
25.00	212.0000	3.5653	0.0013
26.00	213.0000	3.5654	0.0014
27.00	214.0000	3.5652	0.0012
28.00	215.0000	3.5649	0.0009
29.00	216.0000	3.5651	0.0011
30.00	217.0000	3.5651	0.0011
31.00	218.0000	3.5653	0.0013
32.00	219.0000	3.5656	0.0016
33.00	220.0000	3.5656	0.0016
34.00	221.0000	3.5655	0.0015
35.00	222.0000	3.5653	0.0013
36.00	223.0000	3.5652	0.0012
37.00	224.0000	3.5652	0.0012
38.00	225.0000	3.5650	0.0010
39.00	226.0000	3.5647	0.0007
40.00	227.0000	3.5650	0.0010
41.00	228.0000	3.5647	0.0007
42.00	229.0000	3.5648	0.0008
43.00	230.0000	3.5652	0.0012
44.00	231.0000	3.5654	0.0014
45.00	232.0000	3.5652	0.0012
46.00	233.0000	3.5656	0.0016
47.00	234.0000	3.5653	0.0013
48.00	235.0000	3.5653	0.0013
49.00	236.0000	3.5652	0.0012
50.00	237.0000	3.5655	0.0015
51.00	238.0000	3.5650	0.0010
52.00	239.0000	3.5652	0.0012
53.00	240.0000	3.5650	0.0010
54.00	241.0000	3.5652	0.0012
55.00	242.0000	3.5656	0.0016
56.00	243.0000	3.5654	0.0014
57.00	244.0000	3.5654	0.0014
58.00	245.0000	3.5653	0.0013
59.00	246.0000	3.5652	0.0012
60.00	247.0000	3.5650	0.0010
61.00	248.0000	3.5649	0.0009
62.00	249.0000	3.5647	0.0007
63.00	250.0000	3.5648	0.0008
64.00	251.0000	3.5642	0.0002
65.00	252.0000	3.5647	0.0007
66.00	253.0000	3.5650	0.0010

67.00	254.0000	3.5653	0.0013
68.00	255.0000	3.5654	0.0014
69.00	256.0000	3.5655	0.0015
70.00	257.0000	3.5652	0.0012
71.00	258.0000	3.5649	0.0009
72.00	259.0000	3.5647	0.0007
73.00	260.0000	3.5647	0.0007
74.00	261.0000	3.5648	0.0008
75.00	262.0000	3.5648	0.0008
76.00	263.0000	3.5652	0.0012
77.00	264.0000	3.5651	0.0011
78.00	265.0000	3.5655	0.0015
79.00	266.0000	3.5652	0.0012
80.00	267.0000	3.5653	0.0013
81.00	268.0000	3.5650	0.0010
82.00	269.0000	3.5648	0.0008
83.00	270.0000	3.5648	0.0008
84.00	271.0000	3.5651	0.0011
85.00	272.0000	3.5647	0.0007
86.00	273.0000	3.5650	0.0010
87.00	274.0000	3.5647	0.0007
88.00	275.0000	3.5649	0.0009
89.00	276.0000	3.5648	0.0008
90.00	277.0000	3.5654	0.0014
91.00	278.0000	3.5652	0.0012
92.00	279.0000	3.5651	0.0011
93.00	280.0000	3.5650	0.0010
94.00	281.0000	3.5649	0.0009
95.00	282.0000	3.5651	0.0011
96.00	283.0000	3.5649	0.0009
97.00	284.0000	3.5651	0.0011
98.00	285.0000	3.5649	0.0009
99.00	286.0000	3.5649	0.0009
100.00	287.0000	3.5649	0.0009
101.00	288.0000	3.5651	0.0011
102.00	289.0000	3.5649	0.0009
103.00	290.0000	3.5652	0.0012
104.00	291.0000	3.5652	0.0012
105.00	292.0000	3.5653	0.0013
106.00	293.0000	3.5652	0.0012
107.00	294.0000	3.5649	0.0009
108.00	295.0000	3.5649	0.0009
109.00	296.0000	3.5649	0.0009
110.00	297.0000	3.5648	0.0008
111.00	298.0000	3.5647	0.0007
112.00	299.0000	3.5645	0.0005
113.00	300.0000	3.5643	0.0003
114.00	301.0000	3.5647	0.0007
115.00	302.0000	3.5647	0.0007
116.00	303.0000	3.5652	0.0012
117.00	304.0000	3.5652	0.0012
118.00	305.0000	3.5651	0.0011

119.00	306.0000	3.5648	0.0008
120.00	307.0000	3.5650	0.0010
121.00	308.0000	3.5647	0.0007
122.00	309.0000	3.5647	0.0007
123.00	310.0000	3.5647	0.0007
124.00	311.0000	3.5646	0.0006
125.00	312.0000	3.5646	0.0006
126.00	313.0000	3.5649	0.0009
127.00	314.0000	3.5653	0.0013
128.00	315.0000	3.5653	0.0013
129.00	316.0000	3.5649	0.0009
130.00	317.0000	3.5650	0.0010
131.00	318.0000	3.5646	0.0006
132.00	319.0000	3.5647	0.0007
133.00	320.0000	3.5648	0.0008
134.00	321.0000	3.5645	0.0005
135.00	322.0000	3.5642	0.0002
136.00	323.0000	3.5644	0.0004
137.00	324.0000	3.5644	0.0004
138.00	325.0000	3.5648	0.0008
139.00	326.0000	3.5648	0.0008
140.00	327.0000	3.5652	0.0012
141.00	328.0000	3.5651	0.0011
142.00	329.0000	3.5650	0.0010
143.00	330.0000	3.5648	0.0008
144.00	331.0000	3.5647	0.0007
145.00	332.0000	3.5647	0.0007
146.00	333.0000	3.5647	0.0007
147.00	334.0000	3.5643	0.0003
148.00	335.0000	3.5647	0.0007
149.00	336.0000	3.5647	0.0007
150.00	337.0000	3.5648	0.0008
151.00	338.0000	3.5649	0.0009
152.00	339.0000	3.5651	0.0011
153.00	340.0000	3.5652	0.0012
154.00	341.0000	3.5651	0.0011
155.00	342.0000	3.5647	0.0007
156.00	343.0000	3.5645	0.0005
157.00	344.0000	3.5645	0.0005
158.00	345.0000	3.5644	0.0004
159.00	346.0000	3.5647	0.0007
160.00	347.0000	3.5643	0.0003
161.00	348.0000	3.5643	0.0003
162.00	349.0000	3.5643	0.0003
163.00	350.0000	3.5644	0.0004
164.00	351.0000	3.5647	0.0007
165.00	352.0000	3.5650	0.0010
166.00	353.0000	3.5648	0.0008
167.00	354.0000	3.5649	0.0009
168.00	355.0000	3.5644	0.0004
169.00	356.0000	3.5646	0.0006
170.00	357.0000	3.5645	0.0005

171.00	358.0000	3.5649	0.0009
172.00	359.0000	3.5645	0.0005
173.00	360.0000	3.5644	0.0004
174.00	361.0000	3.5646	0.0006
175.00	362.0000	3.5645	0.0005
176.00	363.0000	3.5645	0.0005
177.00	364.0000	3.5648	0.0008
178.00	365.0000	3.5651	0.0011
179.00	366.0000	3.5648	0.0008
180.00	367.0000	3.5645	0.0005
181.00	368.0000	3.5645	0.0005
182.00	369.0000	3.5644	0.0004
183.00	370.0000	3.5646	0.0006
184.00	371.0000	3.5644	0.0004
185.00	372.0000	3.5643	0.0003
186.00	373.0000	3.5640	0.0000
187.00	374.0000	3.5642	0.0002
188.00	375.0000	3.5644	0.0004
189.00	376.0000	3.5646	0.0006
190.00	377.0000	3.5649	0.0009
191.00	378.0000	3.5653	0.0013
192.00	379.0000	3.5649	0.0009
193.00	380.0000	3.5652	0.0012
194.00	381.0000	3.5647	0.0007
195.00	382.0000	3.5651	0.0011
196.00	383.0000	3.5648	0.0008
197.00	384.0000	3.5648	0.0008
198.00	385.0000	3.5645	0.0005
199.00	386.0000	3.5645	0.0005
200.00	387.0000	3.5645	0.0005
201.00	388.0000	3.5648	0.0008
202.00	389.0000	3.5650	0.0010
203.00	390.0000	3.5653	0.0013
204.00	391.0000	3.5652	0.0012
205.00	392.0000	3.5650	0.0010
206.00	393.0000	3.5651	0.0011
207.00	394.0000	3.5648	0.0008
208.00	395.0000	3.5650	0.0010
209.00	396.0000	3.5646	0.0006
210.00	397.0000	3.5647	0.0007
211.00	398.0000	3.5644	0.0004
212.00	399.0000	3.5647	0.0007
213.00	400.0000	3.5643	0.0003
214.00	401.0000	3.5648	0.0008
215.00	402.0000	3.5650	0.0010
216.00	403.0000	3.5653	0.0013
217.00	404.0000	3.5652	0.0012
218.00	405.0000	3.5653	0.0013
219.00	406.0000	3.5652	0.0012
220.00	407.0000	3.5654	0.0014
221.00	408.0000	3.5652	0.0012
222.00	409.0000	3.5651	0.0011

223.00	410.0000	3.5650	0.0010
224.00	411.0000	3.5650	0.0010
225.00	412.0000	3.5650	0.0010
226.00	413.0000	3.5650	0.0010
227.00	414.0000	3.5653	0.0013
228.00	415.0000	3.5653	0.0013
229.00	416.0000	3.5653	0.0013
230.00	417.0000	3.5652	0.0012
231.00	418.0000	3.5655	0.0015
232.00	419.0000	3.5653	0.0013
233.00	420.0000	3.5653	0.0013
234.00	421.0000	3.5652	0.0012
235.00	422.0000	3.5653	0.0013
236.00	423.0000	3.5649	0.0009
237.00	424.0000	3.5649	0.0009
238.00	425.0000	3.5647	0.0007
239.00	426.0000	3.5646	0.0006
240.00	427.0000	3.5649	0.0009
241.00	428.0000	3.5651	0.0011
242.00	429.0000	3.5653	0.0013
243.00	430.0000	3.5655	0.0015
244.00	431.0000	3.5655	0.0015
245.00	432.0000	3.5656	0.0016
246.00	433.0000	3.5656	0.0016
247.00	434.0000	3.5653	0.0013
248.00	435.0000	3.5655	0.0015
249.00	436.0000	3.5652	0.0012
250.00	437.0000	3.5652	0.0012
251.00	438.0000	3.5648	0.0008
252.00	439.0000	3.5652	0.0012
253.00	440.0000	3.5653	0.0013
254.00	441.0000	3.5657	0.0017
255.00	442.0000	3.5657	0.0017
256.00	443.0000	3.5658	0.0018
257.00	444.0000	3.5655	0.0015
258.00	445.0000	3.5658	0.0018
259.00	446.0000	3.5654	0.0014
260.00	447.0000	3.5656	0.0016
261.00	448.0000	3.5653	0.0013
262.00	449.0000	3.5651	0.0011
263.00	450.0000	3.5648	0.0008
264.00	451.0000	3.5651	0.0011
265.00	452.0000	3.5654	0.0014
266.00	453.0000	3.5656	0.0016
267.00	454.0000	3.5654	0.0014
268.00	455.0000	3.5656	0.0016
269.00	456.0000	3.5655	0.0015
270.00	457.0000	3.5658	0.0018
271.00	458.0000	3.5656	0.0016
272.00	459.0000	3.5658	0.0018
273.00	460.0000	3.5655	0.0015
274.00	461.0000	3.5654	0.0014

	275.00	462.0000	3.5655	0.0015
	276.00	463.0000	3.5654	0.0014
	277.00	464.0000	3.5655	0.0015
	278.00	465.0000	3.5658	0.0018
	279.00	466.0000	3.5658	0.0018
	280.00	467.0000	3.5657	0.0017
	281.00	468.0000	3.5657	0.0017
	282.00	469.0000	3.5657	0.0017
	283.00	470.0000	3.5656	0.0016
	284.00	471.0000	3.5654	0.0014
	285.00	472.0000	3.5653	0.0013
	286.00	473.0000	3.5657	0.0017
	287.00	474.0000	3.5652	0.0012
	288.00	475.0000	3.5653	0.0013
	289.00	476.0000	3.5652	0.0012
	290.00	477.0000	3.5654	0.0014
	291.00	478.0000	3.5654	0.0014
	292.00	479.0000	3.5657	0.0017
	293.00	480.0000	3.5656	0.0016
292.00	294.00	481.0000	3.5660	0.0020
291.00	295.00	482.0000	3.5657	0.0017
290.00	296.00	483.0000	3.5663	0.0023

GRAPHED DATA (NON-CONNECTED POINTS)

289.00	484.0000	3.5660	0.0020
288.00	485.0000	3.5653	0.0013
287.00	486.0000	3.5662	0.0022
286.00	487.0000	3.5657	0.0017
285.00	488.0000	3.5657	0.0017
284.00	489.0000	3.5655	0.0015
283.00	490.0000	3.5662	0.0022
282.00	491.0000	3.5660	0.0020
281.00	492.0000	3.5659	0.0019
280.00	493.0000	3.5657	0.0017
279.00	494.0000	3.5659	0.0019
278.00	495.0000	3.5658	0.0018
277.00	496.0000	3.5656	0.0016
276.00	497.0000	3.5655	0.0015
275.00	498.0000	3.5658	0.0018
274.00	499.0000	3.5653	0.0013
273.00	500.0000	3.5654	0.0014
272.00	501.0000	3.5654	0.0014
271.00	502.0000	3.5651	0.0011
270.00	503.0000	3.5656	0.0016
269.00	504.0000	3.5652	0.0012
268.00	505.0000	3.5654	0.0014
267.00	506.0000	3.5656	0.0016
266.00	507.0000	3.5658	0.0018
265.00	508.0000	3.5655	0.0015
264.00	509.0000	3.5660	0.0020
263.00	510.0000	3.5654	0.0014
262.00	511.0000	3.5656	0.0016

261.00	512.0000	3.5652	0.0012
260.00	513.0000	3.5656	0.0016
259.00	514.0000	3.5651	0.0011
258.00	515.0000	3.5657	0.0017
257.00	516.0000	3.5656	0.0016
256.00	517.0000	3.5658	0.0018
255.00	518.0000	3.5658	0.0018
254.00	519.0000	3.5654	0.0014
253.00	520.0000	3.5657	0.0017
252.00	521.0000	3.5654	0.0014
251.00	522.0000	3.5649	0.0009
250.00	523.0000	3.5650	0.0010
249.00	524.0000	3.5648	0.0008
248.00	525.0000	3.5650	0.0010
247.00	526.0000	3.5651	0.0011
246.00	527.0000	3.5654	0.0014
245.00	528.0000	3.5656	0.0016
244.00	529.0000	3.5655	0.0015
243.00	530.0000	3.5654	0.0014
242.00	531.0000	3.5652	0.0012
241.00	532.0000	3.5652	0.0012
240.00	533.0000	3.5653	0.0013
239.00	534.0000	3.5647	0.0007
238.00	535.0000	3.5648	0.0008
237.00	536.0000	3.5646	0.0006
236.00	537.0000	3.5646	0.0006
235.00	538.0000	3.5646	0.0006
234.00	539.0000	3.5650	0.0010
233.00	540.0000	3.5652	0.0012
232.00	541.0000	3.5651	0.0011
231.00	542.0000	3.5653	0.0013
230.00	543.0000	3.5654	0.0014
229.00	544.0000	3.5653	0.0013
228.00	545.0000	3.5650	0.0010
227.00	546.0000	3.5652	0.0012
226.00	547.0000	3.5649	0.0009
225.00	548.0000	3.5648	0.0008
224.00	549.0000	3.5647	0.0007
223.00	550.0000	3.5649	0.0009
222.00	551.0000	3.5650	0.0010
221.00	552.0000	3.5653	0.0013
220.00	553.0000	3.5653	0.0013
219.00	554.0000	3.5651	0.0011
218.00	555.0000	3.5653	0.0013
217.00	556.0000	3.5650	0.0010
216.00	557.0000	3.5650	0.0010
215.00	558.0000	3.5648	0.0008
214.00	559.0000	3.5645	0.0005
213.00	560.0000	3.5644	0.0004
212.00	561.0000	3.5646	0.0006
211.00	562.0000	3.5645	0.0005
210.00	563.0000	3.5648	0.0008

209.00	564.0000	3.5647	0.0007
208.00	565.0000	3.5651	0.0011
207.00	566.0000	3.5650	0.0010
206.00	567.0000	3.5648	0.0008
205.00	568.0000	3.5645	0.0005
204.00	569.0000	3.5647	0.0007
203.00	570.0000	3.5647	0.0007
202.00	571.0000	3.5647	0.0007
201.00	572.0000	3.5647	0.0007
200.00	573.0000	3.5645	0.0005
199.00	574.0000	3.5646	0.0006
198.00	575.0000	3.5646	0.0006
197.00	576.0000	3.5647	0.0007
196.00	577.0000	3.5650	0.0010
195.00	578.0000	3.5650	0.0010
194.00	579.0000	3.5649	0.0009
193.00	580.0000	3.5645	0.0005
192.00	581.0000	3.5646	0.0006
191.00	582.0000	3.5644	0.0004
190.00	583.0000	3.5643	0.0003
189.00	584.0000	3.5643	0.0003
188.00	585.0000	3.5644	0.0004
187.00	586.0000	3.5641	0.0001
186.00	587.0000	3.5641	0.0001
185.00	588.0000	3.5643	0.0003
184.00	589.0000	3.5647	0.0007
183.00	590.0000	3.5648	0.0008
182.00	591.0000	3.5649	0.0009
181.00	592.0000	3.5643	0.0003
180.00	593.0000	3.5644	0.0004
179.00	594.0000	3.5644	0.0004
178.00	595.0000	3.5643	0.0003
177.00	596.0000	3.5645	0.0005
176.00	597.0000	3.5640	0.0000
175.00	598.0000	3.5644	0.0004
174.00	599.0000	3.5641	0.0001
173.00	600.0000	3.5643	0.0003
172.00	601.0000	3.5644	0.0004
171.00	602.0000	3.5648	0.0008
170.00	603.0000	3.5648	0.0008
169.00	604.0000	3.5643	0.0003
168.00	605.0000	3.5642	0.0002
167.00	606.0000	3.5642	0.0002
166.00	607.0000	3.5643	0.0003
165.00	608.0000	3.5644	0.0004
164.00	609.0000	3.5645	0.0005
163.00	610.0000	3.5642	0.0002
162.00	611.0000	3.5641	0.0001
161.00	612.0000	3.5643	0.0003
160.00	613.0000	3.5646	0.0006
159.00	614.0000	3.5644	0.0004
158.00	615.0000	3.5646	0.0006

157.00	616.0000	3.5647	0.0007
156.00	617.0000	3.5645	0.0005
155.00	618.0000	3.5643	0.0003
154.00	619.0000	3.5643	0.0003
153.00	620.0000	3.5643	0.0003
152.00	621.0000	3.5646	0.0006
151.00	622.0000	3.5642	0.0002
150.00	623.0000	3.5645	0.0005
149.00	624.0000	3.5644	0.0004
148.00	625.0000	3.5649	0.0009
147.00	626.0000	3.5648	0.0008
146.00	627.0000	3.5649	0.0009
145.00	628.0000	3.5651	0.0011
144.00	629.0000	3.5648	0.0008
143.00	630.0000	3.5646	0.0006
142.00	631.0000	3.5642	0.0002
141.00	632.0000	3.5643	0.0003
140.00	633.0000	3.5643	0.0003
139.00	634.0000	3.5643	0.0003
138.00	635.0000	3.5642	0.0002
137.00	636.0000	3.5644	0.0004
136.00	637.0000	3.5645	0.0005
135.00	638.0000	3.5648	0.0008
134.00	639.0000	3.5646	0.0006
133.00	640.0000	3.5648	0.0008
132.00	641.0000	3.5649	0.0009
131.00	642.0000	3.5649	0.0009
130.00	643.0000	3.5647	0.0007
129.00	644.0000	3.5645	0.0005
128.00	645.0000	3.5644	0.0004
127.00	646.0000	3.5645	0.0005
126.00	647.0000	3.5645	0.0005
125.00	648.0000	3.5647	0.0007
124.00	649.0000	3.5643	0.0003
123.00	650.0000	3.5646	0.0006
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121.00	652.0000	3.5648	0.0008
120.00	653.0000	3.5653	0.0013
119.00	654.0000	3.5650	0.0010
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115.00	658.0000	3.5646	0.0006
114.00	659.0000	3.5649	0.0009
113.00	660.0000	3.5645	0.0005
112.00	661.0000	3.5645	0.0005
111.00	662.0000	3.5645	0.0005
110.00	663.0000	3.5644	0.0004
109.00	664.0000	3.5646	0.0006
108.00	665.0000	3.5647	0.0007
107.00	666.0000	3.5650	0.0010
106.00	667.0000	3.5648	0.0008

105.00	668.0000	3.5648	0.0008
104.00	669.0000	3.5649	0.0009
103.00	670.0000	3.5648	0.0008
102.00	671.0000	3.5648	0.0008
101.00	672.0000	3.5647	0.0007
100.00	673.0000	3.5646	0.0006
99.00	674.0000	3.5650	0.0010
98.00	675.0000	3.5649	0.0009
97.00	676.0000	3.5653	0.0013
96.00	677.0000	3.5650	0.0010
95.00	678.0000	3.5648	0.0008
94.00	679.0000	3.5648	0.0008
93.00	680.0000	3.5646	0.0006
92.00	681.0000	3.5648	0.0008
91.00	682.0000	3.5649	0.0009
90.00	683.0000	3.5646	0.0006
89.00	684.0000	3.5648	0.0008
88.00	685.0000	3.5647	0.0007
87.00	686.0000	3.5649	0.0009
86.00	687.0000	3.5648	0.0008
85.00	688.0000	3.5649	0.0009
84.00	689.0000	3.5652	0.0012
83.00	690.0000	3.5651	0.0011
82.00	691.0000	3.5650	0.0010
81.00	692.0000	3.5651	0.0011
80.00	693.0000	3.5648	0.0008
79.00	694.0000	3.5649	0.0009
78.00	695.0000	3.5650	0.0010
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76.00	697.0000	3.5649	0.0009
75.00	698.0000	3.5648	0.0008
74.00	699.0000	3.5652	0.0012
73.00	700.0000	3.5650	0.0010
72.00	701.0000	3.5654	0.0014
71.00	702.0000	3.5651	0.0011
70.00	703.0000	3.5652	0.0012
69.00	704.0000	3.5652	0.0012
68.00	705.0000	3.5652	0.0012
67.00	706.0000	3.5649	0.0009
66.00	707.0000	3.5648	0.0008
65.00	708.0000	3.5648	0.0008
64.00	709.0000	3.5645	0.0005
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62.00	711.0000	3.5646	0.0006
61.00	712.0000	3.5649	0.0009
60.00	713.0000	3.5648	0.0008
59.00	714.0000	3.5650	0.0010
58.00	715.0000	3.5653	0.0013
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56.00	717.0000	3.5652	0.0012
55.00	718.0000	3.5654	0.0014
54.00	719.0000	3.5652	0.0012

53.00	720.0000	3.5654	0.0014
52.00	721.0000	3.5651	0.0011
51.00	722.0000	3.5650	0.0010
50.00	723.0000	3.5647	0.0007
49.00	724.0000	3.5653	0.0013
48.00	725.0000	3.5649	0.0009
47.00	726.0000	3.5652	0.0012
46.00	727.0000	3.5654	0.0014
45.00	728.0000	3.5653	0.0013
44.00	729.0000	3.5654	0.0014
43.00	730.0000	3.5653	0.0013
42.00	731.0000	3.5652	0.0012
41.00	732.0000	3.5652	0.0012
40.00	733.0000	3.5651	0.0011
39.00	734.0000	3.5651	0.0011
38.00	735.0000	3.5652	0.0012
37.00	736.0000	3.5649	0.0009
36.00	737.0000	3.5648	0.0008
35.00	738.0000	3.5645	0.0005
34.00	739.0000	3.5649	0.0009
33.00	740.0000	3.5649	0.0009
32.00	741.0000	3.5656	0.0016
31.00	742.0000	3.5654	0.0014
30.00	743.0000	3.5657	0.0017
29.00	744.0000	3.5656	0.0016
28.00	745.0000	3.5653	0.0013
27.00	746.0000	3.5654	0.0014
26.00	747.0000	3.5652	0.0012
25.00	748.0000	3.5652	0.0012
24.00	749.0000	3.5656	0.0016
23.00	750.0000	3.5654	0.0014
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21.00	752.0000	3.5653	0.0013
20.00	753.0000	3.5652	0.0012
19.00	754.0000	3.5660	0.0020
18.00	755.0000	3.5662	0.0022
17.00	756.0000	3.5661	0.0021
16.00	757.0000	3.5660	0.0020
15.00	758.0000	3.5658	0.0018
14.00	759.0000	3.5657	0.0017
13.00	760.0000	3.5657	0.0017
12.00	761.0000	3.5656	0.0016
11.00	762.0000	3.5663	0.0023
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9.00	764.0000	3.5666	0.0026
8.00	765.0000	3.5665	0.0025
7.00	766.0000	3.5663	0.0023
6.00	767.0000	3.5673	0.0033
5.00	768.0000	3.5683	0.0043
4.00	769.0000	3.5700	0.0000
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2.00	771.0000	3.6061	0.0000

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817.0000	3.7920	0.2280
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819.0000	3.7920	0.2280
820.0000	3.7920	0.2280
821.0000	3.7920	0.2280
822.0000	3.7213	0.1573
823.0000	3.6090	0.0450

824.0000	3.5690	0.0050
825.0000	3.5671	0.0031
826.0000	3.5665	0.0025
827.0000	3.5670	0.0030
828.0000	3.5666	0.0026
829.0000	3.5665	0.0025
830.0000	3.5661	0.0021
831.0000	3.5659	0.0019
832.0000	3.5662	0.0022
833.0000	3.5664	0.0024
834.0000	3.5664	0.0024
835.0000	3.5661	0.0021
836.0000	3.5658	0.0018
837.0000	3.5656	0.0016
838.0000	3.5653	0.0013
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843.0000	3.5653	0.0013
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845.0000	3.5656	0.0016
846.0000	3.5658	0.0018
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848.0000	3.5652	0.0012
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851.0000	3.5648	0.0008
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853.0000	3.5649	0.0009
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856.0000	3.5650	0.0010
857.0000	3.5653	0.0013
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873.0000	3.5648	0.0008
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875.0000	3.5649	0.0009

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881.0000	3.5652	0.0012
882.0000	3.5654	0.0014
883.0000	3.5650	0.0010
884.0000	3.5650	0.0010
885.0000	3.5644	0.0004
886.0000	3.5649	0.0009
887.0000	3.5647	0.0007
888.0000	3.5652	0.0012
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890.0000	3.5655	0.0015
891.0000	3.5656	0.0016
892.0000	3.5653	0.0013
893.0000	3.5653	0.0013
894.0000	3.5652	0.0012
895.0000	3.5649	0.0009
896.0000	3.5650	0.0010
897.0000	3.5648	0.0008
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899.0000	3.5649	0.0009
900.0000	3.5646	0.0006
901.0000	3.5650	0.0010
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923.0000	3.5647	0.0007
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925.0000	3.5647	0.0007
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927.0000	3.5650	0.0010

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932.0000	3.5651	0.0011
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935.0000	3.5646	0.0006
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937.0000	3.5644	0.0004
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940.0000	3.5653	0.0013
941.0000	3.5653	0.0013
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943.0000	3.5651	0.0011
944.0000	3.5650	0.0010
945.0000	3.5646	0.0006
946.0000	3.5647	0.0007
947.0000	3.5646	0.0006
948.0000	3.5643	0.0003
949.0000	3.5644	0.0004
950.0000	3.5643	0.0003
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953.0000	3.5651	0.0011
954.0000	3.5650	0.0010
955.0000	3.5651	0.0011
956.0000	3.5647	0.0007
957.0000	3.5647	0.0007
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961.0000	3.5648	0.0008
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963.0000	3.5647	0.0007
964.0000	3.5650	0.0010
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967.0000	3.5651	0.0011
968.0000	3.5652	0.0012
969.0000	3.5649	0.0009
970.0000	3.5646	0.0006
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973.0000	3.5643	0.0003
974.0000	3.5645	0.0005
975.0000	3.5646	0.0006
976.0000	3.5649	0.0009
977.0000	3.5647	0.0007
978.0000	3.5650	0.0010
979.0000	3.5652	0.0012

980.0000	3.5650	0.0010
981.0000	3.5645	0.0005
982.0000	3.5649	0.0009
983.0000	3.5646	0.0006
984.0000	3.5645	0.0005
985.0000	3.5645	0.0005
986.0000	3.5645	0.0005
987.0000	3.5646	0.0006
988.0000	3.5648	0.0008
989.0000	3.5649	0.0009
990.0000	3.5648	0.0008
991.0000	3.5649	0.0009
992.0000	3.5648	0.0008
993.0000	3.5645	0.0005
994.0000	3.5644	0.0004
995.0000	3.5647	0.0007
996.0000	3.5646	0.0006
997.0000	3.5646	0.0006
998.0000	3.5643	0.0003
999.0000	3.5643	0.0003
1000.0000	3.5643	0.0003
1001.0000	3.5642	0.0002
1002.0000	3.5645	0.0005
1003.0000	3.5648	0.0008
1004.0000	3.5652	0.0012
1005.0000	3.5652	0.0012
1006.0000	3.5648	0.0008
1007.0000	3.5647	0.0007
1008.0000	3.5650	0.0010
1009.0000	3.5648	0.0008
1010.0000	3.5647	0.0007
1011.0000	3.5644	0.0004
1012.0000	3.5646	0.0006
1013.0000	3.5645	0.0005
1014.0000	3.5646	0.0006
1015.0000	3.5650	0.0010
1016.0000	3.5653	0.0013
1017.0000	3.5652	0.0012
1018.0000	3.5652	0.0012
1019.0000	3.5652	0.0012
1020.0000	3.5648	0.0008
1021.0000	3.5650	0.0010
1022.0000	3.5648	0.0008
1023.0000	3.5647	0.0007
1024.0000	3.5644	0.0004
1025.0000	3.5644	0.0004
1026.0000	3.5649	0.0009
1027.0000	3.5649	0.0009
1028.0000	3.5649	0.0009
1029.0000	3.5653	0.0013
1030.0000	3.5653	0.0013
1031.0000	3.5655	0.0015

1032.0000	3.5651	0.0011
1033.0000	3.5653	0.0013
1034.0000	3.5651	0.0011
1035.0000	3.5651	0.0011
1036.0000	3.5647	0.0007
1037.0000	3.5648	0.0008
1038.0000	3.5648	0.0008
1039.0000	3.5653	0.0013
1040.0000	3.5653	0.0013
1041.0000	3.5654	0.0014
1042.0000	3.5655	0.0015
1043.0000	3.5651	0.0011
1044.0000	3.5653	0.0013
1045.0000	3.5653	0.0013
1046.0000	3.5652	0.0012
1047.0000	3.5650	0.0010
1048.0000	3.5651	0.0011
1049.0000	3.5647	0.0007
1050.0000	3.5649	0.0009
1051.0000	3.5646	0.0006
1052.0000	3.5652	0.0012
1053.0000	3.5649	0.0009
1054.0000	3.5651	0.0011
1055.0000	3.5653	0.0013
1056.0000	3.5655	0.0015
1057.0000	3.5654	0.0014
1058.0000	3.5655	0.0015
1059.0000	3.5654	0.0014
1060.0000	3.5654	0.0014
1061.0000	3.5652	0.0012
1062.0000	3.5653	0.0013
1063.0000	3.5650	0.0010
1064.0000	3.5650	0.0010
1065.0000	3.5651	0.0011
1066.0000	3.5653	0.0013
1067.0000	3.5658	0.0018
1068.0000	3.5656	0.0016
1069.0000	3.5655	0.0015
1070.0000	3.5655	0.0015
1071.0000	3.5657	0.0017
1072.0000	3.5653	0.0013
1073.0000	3.5653	0.0013
1074.0000	3.5652	0.0012
1075.0000	3.5652	0.0012
1076.0000	3.5650	0.0010
1077.0000	3.5647	0.0007
1078.0000	3.5651	0.0011
1079.0000	3.5654	0.0014
1080.0000	3.5656	0.0016
1081.0000	3.5658	0.0018
1082.0000	3.5658	0.0018
1083.0000	3.5658	0.0018

1084.0000	3.5656	0.0016
1085.0000	3.5657	0.0017
1086.0000	3.5657	0.0017
1087.0000	3.5654	0.0014
1088.0000	3.5655	0.0015
1089.0000	3.5655	0.0015
1090.0000	3.5654	0.0014
1091.0000	3.5656	0.0016
1092.0000	3.5661	0.0021
1093.0000	3.5659	0.0019
1094.0000	3.5657	0.0017
1095.0000	3.5657	0.0017
1096.0000	3.5656	0.0016
1097.0000	3.5657	0.0017
1098.0000	3.5654	0.0014
1099.0000	3.5651	0.0011
1100.0000	3.5654	0.0014
1101.0000	3.5651	0.0011
1102.0000	3.5651	0.0011
1103.0000	3.5654	0.0014
1104.0000	3.5655	0.0015
1105.0000	3.5658	0.0018
1106.0000	3.5657	0.0017
1107.0000	3.5655	0.0015
1108.0000	3.5657	0.0017
1109.0000	3.5660	0.0020
1110.0000	3.5657	0.0017
1111.0000	3.5659	0.0019
1112.0000	3.5659	0.0019
1113.0000	3.5658	0.0018
1114.0000	3.5653	0.0013
1115.0000	3.5660	0.0020
1116.0000	3.5660	0.0020
1117.0000	3.5661	0.0021
1118.0000	3.5661	0.0021
1119.0000	3.5660	0.0020
1120.0000	3.5656	0.0016
1121.0000	3.5663	0.0023
1122.0000	3.5656	0.0016
1123.0000	3.5660	0.0020
1124.0000	3.5654	0.0014
1125.0000	3.5659	0.0019
1126.0000	3.5660	0.0020
1127.0000	3.5658	0.0018
1128.0000	3.5659	0.0019
1129.0000	3.5656	0.0016
1130.0000	3.5657	0.0017
1131.0000	3.5656	0.0016
1132.0000	3.5653	0.0013
1133.0000	3.5652	0.0012
1134.0000	3.5655	0.0015
1135.0000	3.5653	0.0013

1136.0000	3.5651	0.0011
1137.0000	3.5651	0.0011
1138.0000	3.5650	0.0010
1139.0000	3.5656	0.0016
1140.0000	3.5657	0.0017
1141.0000	3.5657	0.0017
1142.0000	3.5658	0.0018
1143.0000	3.5659	0.0019
1144.0000	3.5655	0.0015
1145.0000	3.5659	0.0019
1146.0000	3.5656	0.0016
1147.0000	3.5655	0.0015
1148.0000	3.5652	0.0012
1149.0000	3.5654	0.0014
1150.0000	3.5651	0.0011
1151.0000	3.5653	0.0013
1152.0000	3.5653	0.0013
1153.0000	3.5653	0.0013
1154.0000	3.5656	0.0016
1155.0000	3.5657	0.0017
1156.0000	3.5655	0.0015
1157.0000	3.5654	0.0014
1158.0000	3.5656	0.0016
1159.0000	3.5653	0.0013
1160.0000	3.5650	0.0010
1161.0000	3.5649	0.0009
1162.0000	3.5648	0.0008
1163.0000	3.5648	0.0008

Appendix VII

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APPENDIX VII - Error Analysis Tables

ACCURACY ANALYSIS ON PART I, WITH ROUGHING STONES

S(1)=Standard deviation for all data at all station without filtering
S(f)=Standard deviation using all data but filtered by averaging (f)
data points.

$$S(f)=\sqrt{V(f)}$$

$V(f)=\sum(D(f))/(n/f-1)$ where

f=the number of data points averaged for the reading and

n=the total number of data points used in the analysis and

$D(f)=(X(f)-X'')^2$ where

X(f)=the reading error and X''=the average error (bias), $\sum(X(f))/n/f$.

n=32

f=1 (Un-filtered)

f=2

f=16

STATION 1:

	f=1	f=2	f=16				f=1	f=2	f=16	f=1	f=1	f=2	f=2	f=16	f=16	
READING SYSTEM	SYSTEM	SYSTEM	GAUGE	GAUGE	OFFSET	GAUGE	GAUGE	GAUGE	READING	AVERAGE	DEVIAT.	READING	DEVIAT.	READING	DEVIAT.	
NUMBER	READING	READING	READING	ANGLE	READINGSTANDARD	READING	READING	READING	ERROR	ERROR	SQUARED	ERROR	SQUARED	ERROR	SQUARED	
	(P1S1)								(X(1))	(X'')	(D(1))	(X(2))	(D(2))	(X(3))	(D(16))	
31	3.5845			22.5	0.0374	3.54679	3.5842		0.0003	0.0002	1.21E-08					
32	3.5848	3.5847		45.0	0.0378	3.54679	3.5846	3.5844	0.0002	0.0002	1.00E-10	0.0003	4.E-09			
33	3.5851			67.5	0.0383	3.54679	3.5851		0.0000	0.0002	3.61E-08					
34	3.5850	3.5851		90.0	0.0384	3.54679	3.5852	3.5851	-0.0002	0.0002	1.52E-07	-0.0001	8.E-08			
35	3.5851			112.5	0.0383	3.54679	3.5851		0.0000	0.0002	3.61E-08					
36	3.5850	3.5851		135.0	0.0378	3.54679	3.5846	3.5848	0.0004	0.0002	4.41E-08	0.0002	1.E-10			
37	3.5848			157.5	0.0375	3.54679	3.5843		0.0005	0.0002	9.61E-08					
38	3.5846	3.5847		180.0	0.0374	3.54679	3.5842	3.5842	0.0004	0.0002	4.41E-08	0.0005	7.E-08			
39	3.5846			202.5	0.0374	3.54679	3.5842		0.0004	0.0002	4.41E-08					
40	3.5850	3.5848		225.0	0.0378	3.54679	3.5846	3.5844	0.0004	0.0002	4.41E-08	0.0004	4.E-08			
41	3.5851			247.5	0.0383	3.54679	3.5851		0.0000	0.0002	3.61E-08					
42	3.5853	3.5852		270.0	0.0384	3.54679	3.5852	3.5851	0.0001	0.0002	8.10E-09	0.0001	2.E-08			
43	3.5851			292.5	0.0383	3.54679	3.5851		0.0000	0.0002	3.61E-08					
44	3.5851	3.5851		315.0	0.0378	3.54679	3.5846	3.5848	0.0005	0.0002	9.61E-08	0.0003	4.E-09			
45	3.5850			337.5	0.0375	3.54679	3.5843		0.0007	0.0002	2.81E-07					
46	3.5848	3.5849	3.5849	360.0	0.0374	3.54679	3.5842	3.5842	3.5847	0.0006	0.0002	1.68E-07	0.0007	2.E-07	0.0003	6.40E-09

STATION 2:

	f=1	f=2	f=16				f=1	f=2	f=16	f=1	f=1	f=2	f=2	f=16	f=16	
READING SYSTEM	SYSTEM	SYSTEM	GAUGE	GAUGE	OFFSET	GAUGE	GAUGE	GAUGE	GAUGE	READING	AVERAGE	DEVIAT.	READING	DEVIAT.	READING	DEVIAT.
NUMBER	READING	READING	READING	ANGLE	READINGSTANDARD	READING	AVG.	AVG.	AVG.	ERROR	ERROR	SQUARED	ERROR	SQUARED	ERROR	SQUARED
	(P1S2)									(X(1))	(X'')	(D(1))	(X(2))	(D(2))	(X(3))	(D(16))
17	3.5845			22.5	0.0381	3.54679	3.5849			-0.0004	0.0002	3.48E-07				
18	3.5848	3.5847		45.0	0.0381	3.54679	3.5849	3.5849		-0.0001	0.0002	8.41E-08	-0.0002	2.E-07		

19	3.5850		67.5	0.0382	3.54679	3.5850		0.0000	0.0002	3.61E-08	
20	3.5850	3.5850	90.0	0.0382	3.54679	3.5850	3.5850	0.0000	0.0002	3.61E-08	0.0000 4.E-08
21	3.5852		112.5	0.0382	3.54679	3.5850		0.0002	0.0002	1.00E-10	
22	3.5852	3.5852	135.0	0.0382	3.54679	3.5850	3.5850	0.0002	0.0002	1.00E-10	0.0002 1.E-10
23	3.5852		157.5	0.0382	3.54679	3.5850		0.0002	0.0002	1.00E-10	
24	3.5849	3.5851	180.0	0.0381	3.54679	3.5849	3.5849	0.0000	0.0002	3.61E-08	0.0001 8.E-09
25	3.5851		202.5	0.0381	3.54679	3.5849		0.0002	0.0002	1.00E-10	
26	3.5850	3.5851	225.0	0.0381	3.54679	3.5849	3.5849	0.0001	0.0002	8.10E-09	0.0002 2.E-09
27	3.5852		247.5	0.0382	3.54679	3.5850		0.0002	0.0002	1.00E-10	
28	3.5852	3.5852	270.0	0.0382	3.54679	3.5850	3.5850	0.0002	0.0002	1.00E-10	0.0002 1.E-10
29	3.5853		292.5	0.0382	3.54679	3.5850		0.0003	0.0002	1.21E-08	
30	3.5855	3.5854	315.0	0.0382	3.54679	3.5850	3.5850	0.0005	0.0002	9.61E-08	0.0004 4.E-08
31	3.5852		337.5	0.0382	3.54679	3.5850		0.0002	0.0002	1.00E-10	
32	3.5849	3.5851 3.5851	360.0	0.0381	3.54679	3.5849	3.5849 3.5850	0.0000	0.0002	3.61E-08	0.0001 8.1E-09 0.0001 6.01E-09

AVERAGE ERROR X" (BIAS) 0.00020

V(1)= 5.90E-08	S(1)= 0.00024
V(2)= 4.90E-08	S(2)= 0.00022
V(16)= 1.24E-08	S(16)= 0.00011

ACCURACY ANALYSIS ON PART 2, WITH FINISHING STONES

S(1)=Standard deviation for all data at all station without filtering
S(f)=Standard deviation using all data but filtered by averaging (f)
data points.

$$S(f)=\sqrt{V(f)}$$

$$V(f)=\sum(D(f))/(n/f-1) \text{ where}$$

f=the number of data points averaged for the reading and

n=the total number of data points used in the analysis and

$$D(f)=[X(f)-X'']^2 \text{ where}$$

X(f)=the reading error and X''=the average error (bias), $\sum(X(f))/n/f$.

n=80

f=1 (Un-filtered)

f=2

f=16

STATION 1:

	f=1	f=2	f=16				f=1	f=2	f=16	f=1	f=1,2,16	f=1	f=2	f=2	f=16	f=16
READING SYSTEM	SYSTEM	SYSTEM	SYSTEM	GAUGE	GAUGE	OFFSET	GAUGE	GAUGE	GAUGE	READING	AVERAGE	DEVIAT.	READING	DEVIAT.	READING	DEVIAT.
NUMBER	READING	READING	READING	ANGLE	VALUE	STANDARD	READING	READING	READING	ERROR	ERROR	SQUARED	ERROR	SQUARED	ERROR	SQUARED
(P2S1)										(X(1))	(X'')	(D(1))	(X(2))	(D(2))	(X(3))	(D(16))
59	3.5464			22.5	0.0017	3.54679	3.5485			-0.0021	-0.0020	8.1E-09				
60	3.5468	3.5466		45.0	0.0020	3.54679	3.5488	3.5486		-0.0020	-0.0020	1.0E-10	-0.0020	1.6E-09		
61	3.5469			67.5	0.0024	3.54679	3.5492			-0.0023	-0.0020	8.4E-08				
62	3.5473	3.5471		90.0	0.0025	3.54679	3.5493	3.5492		-0.0020	-0.0020	1.0E-10	-0.0021	2.0E-08		
63	3.5474			112.5	0.0023	3.54679	3.5491			-0.0017	-0.0020	9.6E-08				
64	3.5474	3.5474		135.0	0.0021	3.54679	3.5489	3.5490		-0.0015	-0.0020	2.6E-07	-0.0016	1.7E-07		
65	3.5475			157.5	0.0019	3.54679	3.5487			-0.0012	-0.0020	6.6E-07				
66	3.5471	3.5473		180.0	0.0017	3.54679	3.5485	3.5486		-0.0014	-0.0020	3.7E-07	-0.0013	5.0E-07		
67	3.5471			202.5	0.0017	3.54679	3.5485			-0.0014	-0.0020	3.7E-07				
68	3.5470	3.5471		225.0	0.0020	3.54679	3.5488	3.5486		-0.0018	-0.0020	4.4E-08	-0.0016	1.7E-07		
69	3.5468			247.5	0.0024	3.54679	3.5492			-0.0024	-0.0020	1.5E-07				
70	3.5472	3.5470		270.0	0.0025	3.54679	3.5493	3.5492		-0.0021	-0.0020	8.1E-09	-0.0022	5.8E-08		
71	3.5473			292.5	0.0023	3.54679	3.5491			-0.0018	-0.0020	4.4E-08				
72	3.5473	3.5473		315.0	0.0021	3.54679	3.5489	3.5490		-0.0016	-0.0020	1.7E-07	-0.0017	9.6E-08		
73	3.5467			337.5	0.0019	3.54679	3.5487			-0.0020	-0.0020	1.0E-10				
74	3.5468	3.5468	3.5471	360.0	0.0017	3.54679	3.5485	3.5486	3.5489	-0.0017	-0.0020	9.6E-08	-0.0018	2.6E-08	-0.0018	3.9E-08

STATION 2:

	f=1	f=2	f=16				f=1	f=2	f=16	f=1	f=1,2,16	f=1	f=2	f=2	f=16	f=16
READING SYSTEM	SYSTEM	SYSTEM	SYSTEM	GAUGE	GAUGE	OFFSET	GAUGE	GAUGE	GAUGE	READING	AVERAGE	DEVIAT.	READING	DEVIAT.	READING	DEVIAT.
NUMBER	READING	READING	READING	ANGLE	VALUE	STANDARD	READING	AVG.	AVG.	ERROR	ERROR	SQUARED	ERROR	SQUARED	ERROR	SQUARED
(P2S2)										(X(1))	(X'')	(D(1))	(X(2))	(D(2))	(X(3))	(D(16))
75	3.5476			22.5	0.0025	3.54679	3.5493			-0.0017	-0.0020	9.6E-08				
76	3.5475	3.5476		45.0	0.0026	3.54679	3.5494	3.5493		-0.0019	-0.0020	1.2E-08	-0.0018	4.4E-08		

77	3.5478			67.5	0.0026	3.54679	3.5494				-0.0016	-0.0020	1.7E-07
78	3.5477	3.5478		90.0	0.0026	3.54679	3.5494	3.5494			-0.0017	-0.0020	9.6E-08 -0.0016 1.3E-07
79	3.5474			112.5	0.0027	3.54679	3.5495				-0.0021	-0.0020	8.1E-09
80	3.5472	3.5473		135.0	0.0026	3.54679	3.5494	3.5494			-0.0022	-0.0020	3.6E-08 -0.0021 2.0E-08
81	3.5474			157.5	0.0026	3.54679	3.5494				-0.0020	-0.0020	1.0E-10
82	3.5476	3.5475		180.0	0.0026	3.54679	3.5494	3.5494			-0.0018	-0.0020	4.4E-08 -0.0019 1.2E-08
83	3.5475			202.5	0.0025	3.54679	3.5493				-0.0018	-0.0020	4.4E-08
84	3.5476	3.5476		225.0	0.0026	3.54679	3.5494	3.5493			-0.0018	-0.0020	4.4E-08 -0.0018 4.4E-08
85	3.5478			247.5	0.0026	3.54679	3.5494				-0.0016	-0.0020	1.7E-07
86	3.5480	3.5479		270.0	0.0026	3.54679	3.5494	3.5494			-0.0014	-0.0020	3.7E-07 -0.0015 2.6E-07
87	3.5481			292.5	0.0027	3.54679	3.5495				-0.0014	-0.0020	3.7E-07
88	3.5479	3.5480		315.0	0.0026	3.54679	3.5494	3.5494			-0.0015	-0.0020	2.6E-07 -0.0014 3.1E-07
89	3.5477			337.5	0.0026	3.54679	3.5494				-0.0017	-0.0020	9.6E-08
90	3.5473	3.5475	3.5476	360.0	0.0026	3.54679	3.5494	3.5494	3.5494		-0.0021	-0.0020	8.1E-09 -0.0019 1.2E-08 -0.0018 5.8E-08

STATION 3:

	f=1	f=2	f=16				f=1	f=2	f=16		f=1	f=1,2,16	f=1	f=2	f=2	f=16	f=16
READING SYSTEM SYSTEM SYSTEM GAUGE GAUGE OFFSET GAUGE GAUGE GAUGE	READING	READING	READING	ANGLE	VALUE	STANDARD	READING	AVG.	AVG.	READING AVERAGE DEVIAT.	READING DEVIAT.	READING DEVIAT.	READING DEVIAT.	READING DEVIAT.	READING DEVIAT.	READING DEVIAT.	READING DEVIAT.
NUMBER	READING	READING	READING	ANGLE	VALUE	STANDARD	READING	AVG.	AVG.	ERROR	ERROR SQUARED	ERROR SQUARED	ERROR SQUARED	ERROR SQUARED	ERROR SQUARED	ERROR SQUARED	ERROR SQUARED
	(P253)									(X(1))	(X ²)	(D(1))	(X(2))	(D(2))	(X(3))	(D(16))	
31	3.5470			22.5	0.0027	3.54679	3.5495			-0.0025	-0.0020	2.4E-07					
32	3.5474	3.5472		45.0	0.0027	3.54679	3.5495	3.5495		-0.0021	-0.0020	8.1E-09	-0.0023	8.4E-08			
33	3.5475			67.5	0.0028	3.54679	3.5496			-0.0021	-0.0020	8.1E-09					
34	3.5473	3.5474		90.0	0.0028	3.54679	3.5496	3.5496		-0.0023	-0.0020	8.4E-08	-0.0022	3.6E-08			
35	3.5472			112.5	0.0028	3.54679	3.5496			-0.0024	-0.0020	1.5E-07					
36	3.5475	3.5474		135.0	0.0028	3.54679	3.5496	3.5496		-0.0021	-0.0020	8.1E-09	-0.0022	5.8E-08			
37	3.5472			157.5	0.0027	3.54679	3.5495			-0.0023	-0.0020	8.4E-08					
38	3.5474	3.5473		180.0	0.0027	3.54679	3.5495	3.5495		-0.0021	-0.0020	8.1E-09	-0.0022	3.6E-08			
39	3.5474			202.5	0.0027	3.54679	3.5495			-0.0021	-0.0020	8.1E-09					
40	3.5475	3.5475		225.0	0.0027	3.54679	3.5495	3.5495		-0.0020	-0.0020	1.0E-10	-0.0020	1.6E-09			
41	3.5479			247.5	0.0028	3.54679	3.5496			-0.0017	-0.0020	9.6E-08					
42	3.5479	3.5479		270.0	0.0028	3.54679	3.5496	3.5496		-0.0017	-0.0020	9.6E-08	-0.0017	9.6E-08			
43	3.5476			292.5	0.0028	3.54679	3.5496			-0.0020	-0.0020	1.6E-09					
44	3.5475	3.5476		315.0	0.0028	3.54679	3.5496	3.5496		-0.0021	-0.0020	8.1E-09	-0.0020	6.2E-10			
45	3.5476			337.5	0.0027	3.54679	3.5495			-0.0019	-0.0020	1.2E-08					
46	3.5471	3.5474	3.5474	360.0	0.0027	3.54679	3.5495	3.5495	3.5495	-0.0024	-0.0020	1.5E-07	-0.0021	2.0E-08	-0.0021	1.0E-08	

STATION 4:

	f=1	f=2	f=16				f=1	f=2	f=16		f=1	f=1,2,16	f=1	f=2	f=2	f=16	f=16
READING SYSTEM SYSTEM SYSTEM GAUGE GAUGE OFFSET GAUGE GAUGE GAUGE	READING	READING	READING	ANGLE	VALUE	STANDARD	READING	AVG.	AVG.	READING AVERAGE DEVIAT.	READING DEVIAT.	READING DEVIAT.	READING DEVIAT.	READING DEVIAT.	READING DEVIAT.	READING DEVIAT.	READING DEVIAT.
NUMBER	READING	READING	READING	ANGLE	VALUE	STANDARD	READING	AVG.	AVG.	ERROR	ERROR SQUARED	ERROR SQUARED	ERROR SQUARED	ERROR SQUARED	ERROR SQUARED	ERROR SQUARED	ERROR SQUARED
	(P254)									(X(1))	(X ²)	(D(1))	(X(2))	(D(2))	(X(3))	(D(16))	
40	3.5472			22.5	0.0028	3.54679	3.5496			-0.0024	-0.0020	1.5E-07					
41	3.5476	3.5474		45.0	0.0028	3.54679	3.5496	3.5496		-0.0020	-0.0020	1.0E-10	-0.0022	3.6E-08			
42	3.5481			67.5	0.0029	3.54679	3.5497			-0.0016	-0.0020	1.7E-07					
43	3.5480	3.5481		90.0	0.0029	3.54679	3.5497	3.5497		-0.0017	-0.0020	9.6E-08	-0.0016	1.3E-07			
44	3.5475			112.5	0.0029	3.54679	3.5497			-0.0022	-0.0020	3.6E-08					
45	3.5478	3.5477		135.0	0.0029	3.54679	3.5497	3.5497		-0.0019	-0.0020	1.2E-08	-0.0020	1.6E-09			
46	3.5475			157.5	0.0028	3.54679	3.5496			-0.0021	-0.0020	8.1E-09					

47	3.5475	3.5475		180.0	0.0028	3.54679	3.5496	3.5496		-0.0021	-0.0020	8.1E-09	-0.0021	8.1E-09
48	3.5473			202.5	0.0028	3.54679	3.5496			-0.0023	-0.0020	8.4E-08		
49	3.5474	3.5474		225.0	0.0028	3.54679	3.5496	3.5496		-0.0022	-0.0020	3.6E-08	-0.0022	5.8E-08
50	3.5472			247.5	0.0029	3.54679	3.5497			-0.0025	-0.0020	2.4E-07		
51	3.5473	3.5473		270.0	0.0029	3.54679	3.5497	3.5497		-0.0024	-0.0020	1.5E-07	-0.0024	1.9E-07
52	3.5474			292.5	0.0029	3.54679	3.5497			-0.0023	-0.0020	8.4E-08		
53	3.5470	3.5472		315.0	0.0029	3.54679	3.5497	3.5497		-0.0027	-0.0020	4.8E-07	-0.0025	2.4E-07
54	3.5472			337.5	0.0028	3.54679	3.5496			-0.0024	-0.0020	1.5E-07		
55	3.5471	3.5472	3.5474	360.0	0.0028	3.54679	3.5496	3.5496	3.5496	-0.0025	-0.0020	2.4E-07	-0.0024	1.9E-07 -0.0022 3.9E-08

STATION 5:

	f=1	f=2	f=16				f=1	f=2	f=16		f=1	f=1,2,16	f=1	f=2	f=2	f=16	f=16
READING SYSTEM	SYSTEM	SYSTEM	SYSTEM	GAUGE	GAUGE	OFFSET	GAUGE	GAUGE	GAUGE	READING AVERAGE	READING AVERAGE	DEVIAT.	READING AVERAGE	DEVIAT.	READING AVERAGE	DEVIAT.	READING AVERAGE
NUMBER	READING	READING	READING	ANGLE	VALUE	STANDARD	READING	AVG.	AVG.	ERROR	ERROR	SQUARED	ERROR	SQUARED	ERROR	SQUARED	SQUARED
(P255)										(X(1))	(X")	(D(1))	(X(2))	(D(2))	(X(3))	(D(16))	
49	3.5465			22.5	0.0021	3.54679	3.5489			-0.0024	-0.0020	1.5E-07					
50	3.5467	3.5466		45.0	0.0021	3.54679	3.5489	3.5489		-0.0022	-0.0020	3.6E-08	-0.0023	8.4E-08			
51	3.5472			67.5	0.0021	3.54679	3.5489			-0.0017	-0.0020	9.6E-08					
52	3.5469	3.5471		90.0	0.0021	3.54679	3.5489	3.5489		-0.0020	-0.0020	1.0E-10	-0.0018	2.6E-08			
53	3.5465			112.5	0.0021	3.54679	3.5489			-0.0024	-0.0020	1.5E-07					
54	3.5466	3.5466		135.0	0.0021	3.54679	3.5489	3.5489		-0.0023	-0.0020	8.4E-08	-0.0023	1.2E-07			
55	3.5467			157.5	0.0021	3.54679	3.5489			-0.0022	-0.0020	3.6E-08					
56	3.5468	3.5468		180.0	0.0021	3.54679	3.5489	3.5489		-0.0021	-0.0020	8.1E-09	-0.0021	2.0E-08			
57	3.5473			202.5	0.0021	3.54679	3.5489			-0.0016	-0.0020	1.7E-07					
58	3.5470	3.5472		225.0	0.0021	3.54679	3.5489	3.5489		-0.0019	-0.0020	1.2E-08	-0.0017	6.8E-08			
59	3.5473			247.5	0.0021	3.54679	3.5489			-0.0016	-0.0020	1.7E-07					
60	3.5474	3.5474		270.0	0.0021	3.54679	3.5489	3.5489		-0.0015	-0.0020	2.6E-07	-0.0015	2.1E-07			
61	3.5472			292.5	0.0021	3.54679	3.5489			-0.0017	-0.0020	9.6E-08					
62	3.5473	3.5473		315.0	0.0021	3.54679	3.5489	3.5489		-0.0016	-0.0020	1.7E-07	-0.0016	1.3E-07			
63	3.5474			337.5	0.0021	3.54679	3.5489			-0.0015	-0.0020	2.6E-07					
64	3.5470	3.5472	3.5470	360.0	0.0021	3.54679	3.5489	3.5489	3.5489	-0.0019	-0.0020	1.2E-08	-0.0017	9.6E-08	-0.0019	9.5E-09	

AVERAGE ERROR X" (BIAS) -0.0020

V(1)= 1.12E-07	S(1)= 0.00033
V(2)= 9.79E-08	S(2)= 0.00031
V(16)= 3.88E-08	S(16)= 0.00020

REPEATABILITY ANALYSIS ON PART 1, STATION 1, WITH ROUGHING STONES

File: Repeat1.us

S = Standard deviation for all data points

$S = \sqrt{V}$

$V = \sum(X^2)/n$ where

n = the total number of data points used in the analysis and

X = the reading error

Note: $\bar{X}$ = The average error (bias) which for a repeatability analysis is assumed to be zero.

n=72

COMPARISON 1:

READING NUMBER	READING VALUE	READING NUMBER	READING VALUE	READING ERROR (X)	ERROR SQUARED (X)**2
30	3.5843	12	3.5843	0.0000	0.0E+00
31	3.5845	13	3.5845	0.0000	0.0E+00
32	3.5848	14	3.5850	0.0002	4.0E-08
33	3.5851	15	3.5851	0.0000	0.0E+00
34	3.5850	16	3.5849	-0.0001	1.0E-08
35	3.5851	17	3.5850	-0.0001	1.0E-08
36	3.5850	18	3.5852	0.0002	4.0E-08
37	3.5848	19	3.5852	0.0004	1.6E-07
38	3.5846	20	3.5848	0.0002	4.0E-08
39	3.5846	21	3.5846	0.0000	0.0E+00
40	3.5850	22	3.5850	0.0000	0.0E+00
41	3.5851	23	3.5853	0.0002	4.0E-08
42	3.5853	24	3.5852	-0.0001	1.0E-08
43	3.5851	25	3.5853	0.0002	4.0E-08
44	3.5851	26	3.5849	-0.0002	4.0E-08
45	3.5850	27	3.5849	-0.0001	1.4E-08
46	3.5848	28	3.5849	0.0001	1.0E-08
47	3.5846	29	3.5845	-0.0001	1.0E-08

COMPARISON 2:

READING NUMBER	READING VALUE	READING NUMBER	READING VALUE	READING ERROR (X)	ERROR SQUARED (X)**2
30	3.5843	48	3.5843	0.0000	0.0E+00
31	3.5845	49	3.5845	0.0000	0.0E+00
32	3.5848	50	3.5851	0.0003	9.0E-08
33	3.5851	51	3.5853	0.0002	4.0E-08
34	3.5850	52	3.5850	0.0000	0.0E+00
35	3.5851	53	3.5849	-0.0002	4.0E-08
36	3.5850	54	3.5851	0.0001	1.0E-08
37	3.5848	55	3.5850	0.0002	4.0E-08
38	3.5846	56	3.5848	0.0002	4.0E-08
39	3.5846	57	3.5846	0.0000	0.0E+00
40	3.5850	58	3.5850	0.0000	0.0E+00
41	3.5851	59	3.5852	0.0001	1.0E-08
42	3.5853	60	3.5852	-0.0001	1.0E-08
43	3.5851	61	3.5851	0.0000	0.0E+00
44	3.5851	62	3.5850	-0.0001	1.0E-08
45	3.5850	63	3.5850	0.0000	4.0E-10
46	3.5848	64	3.5846	-0.0002	4.0E-08
47	3.5846	65	3.5845	-0.0001	1.0E-08

COMPARISON 3:

READING NUMBER	READING VALUE	READING NUMBER	READING VALUE	READING ERROR	ERROR SQUARED
				(X)	(X)**2
30	3.5843	153	3.5843	0.0000	0.0E+00
31	3.5845	154	3.5844	-0.0001	1.0E-08
32	3.5848	155	3.5848	0.0000	0.0E+00
33	3.5851	156	3.5849	-0.0002	4.0E-08
34	3.5850	157	3.5850	0.0000	0.0E+00
35	3.5851	158	3.5849	-0.0002	4.0E-08
36	3.5850	159	3.5851	0.0001	1.0E-08
37	3.5848	160	3.5848	0.0000	0.0E+00
38	3.5846	161	3.5849	0.0003	9.0E-08
39	3.5846	162	3.5845	-0.0001	1.0E-08
40	3.5850	163	3.5848	-0.0002	4.0E-08
41	3.5851	164	3.5853	0.0002	4.0E-08
42	3.5853	165	3.5854	0.0001	1.0E-08
43	3.5851	166	3.5852	0.0001	1.0E-08
44	3.5851	167	3.5851	0.0000	0.0E+00
45	3.5850	168	3.5850	0.0000	4.0E-10
46	3.5848	169	3.5848	0.0000	0.0E+00
47	3.5846	170	3.5845	-0.0001	1.0E-08

COMARISON 4:

READING NUMBER	READING VALUE	READING NUMBER	READING VALUE	READING ERROR	ERROR SQUARED
				(X)	(X)**2
30	3.5843	171	3.5843	0.0000	0.0E+00
31	3.5845	172	3.5843	-0.0002	4.0E-08
32	3.5848	173	3.5847	-0.0001	1.0E-08
33	3.5851	174	3.5849	-0.0002	4.0E-08
34	3.5850	175	3.5849	-0.0001	1.0E-08
35	3.5851	176	3.5850	-0.0001	1.0E-08
36	3.5850	177	3.5850	0.0000	0.0E+00
37	3.5848	178	3.5848	0.0000	0.0E+00
38	3.5846	179	3.5848	0.0002	4.0E-08
39	3.5846	180	3.5846	0.0000	0.0E+00
40	3.5850	181	3.5847	-0.0003	9.0E-08
41	3.5851	182	3.5852	0.0001	1.0E-08
42	3.5853	183	3.5853	0.0000	0.0E+00
43	3.5851	184	3.5851	0.0000	0.0E+00
44	3.5851	185	3.5850	-0.0001	1.0E-08
45	3.5850	186	3.5850	0.0000	4.0E-10
46	3.5848	187	3.5847	-0.0001	1.0E-08
47	3.5846	188	3.5846	0.0000	0.0E+00

V = 1.92E-08

S = 0.00014

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Appendix VIII

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APPENDIX VIII - BENCH TESTING OPTICAL SENSOR DATA

VOLTAGE vs DISPLACEMENT output from Fotonic Sensor

Displacement	Voltage
0.000	0.2027
0.001	0.4493
0.002	1.7851
0.003	2.8596
0.004	4.1929
0.005	5.2527
0.006	6.1709
0.007	6.8083
0.008	7.8144
0.009	8.2369
0.010	8.6618
0.011	9.0110
0.012	9.2063
0.013	9.4188
0.014	9.5433
0.015	9.6752
0.016	9.7509
0.017	9.8315
0.018	9.8901
0.019	9.9267
0.020	9.9609
0.021	9.9805
0.022	9.9976
0.023	10.0049
0.024	10.0049
0.025	10.0049
0.026	9.9951
0.027	9.9829
0.028	9.9658
0.029	9.9536
0.030	9.9389
0.031	9.9048
0.032	9.8852
0.033	9.8559
0.034	9.8242
0.035	9.7949
0.036	9.7656
0.037	9.7289
0.038	9.6923
0.039	9.6557
0.040	9.6264
0.041	9.5873
0.042	9.5531
0.043	9.5067
0.044	9.4750
0.045	9.4310

0.046	9.3895
0.047	9.3480
0.048	9.3114
0.049	9.2625
0.050	9.2430
0.051	9.1844
0.052	9.1380
0.053	9.1013
0.054	9.0525
0.055	9.0110
0.056	8.9792
0.057	8.9255
0.058	8.8913
0.059	8.8327
0.060	8.7937
0.061	8.7570
0.062	8.7057
0.063	8.6618
0.064	8.6203
0.065	8.5788
0.066	8.5348
0.067	8.5104
0.068	8.4518
0.069	8.4054
0.070	8.3761
0.071	8.3199
0.072	8.2833
0.073	8.2320
0.074	8.1954
0.075	8.1563
0.076	8.1319
0.077	8.0635
0.078	8.0342
0.079	7.9927
0.080	7.9390
0.081	7.8950
0.082	7.8510
0.083	7.8095
0.084	7.7680
0.085	7.7265
0.086	7.6850
0.087	7.6435
0.088	7.6068
0.089	7.5629
0.090	7.5287
0.091	7.4872
0.092	7.4457
0.093	7.4090
0.094	7.3651
0.095	7.3211
0.096	7.2918

0.097	7.2454
0.098	7.2064
0.099	7.1673
0.100	7.1453
0.101	7.0891
0.102	7.0476
0.103	7.0134
0.104	6.9841
0.105	6.9377
0.106	6.9060
0.107	6.8620
0.108	6.8230
0.109	6.7863
0.110	6.7521
0.111	6.7131
0.112	6.6838
0.113	6.6374
0.114	6.6056
0.115	6.5641
0.116	6.5299
0.117	6.4982
0.118	6.4640
0.119	6.4225
0.120	6.3907
0.121	6.3541
0.122	6.3248
0.123	6.3101
0.124	6.2491
0.125	6.2198
0.126	6.1807
0.127	6.1490
0.128	6.1197
0.129	6.0781
0.130	6.0488
0.131	6.0122
0.132	5.9780
0.133	5.9487
0.134	5.9194
0.135	5.8828
0.136	5.8535
0.137	5.8193
0.138	5.7875
0.139	5.7558
0.140	5.7241
0.141	5.6996
0.142	5.6752
0.143	5.6337
0.144	5.6020
0.145	5.5775
0.146	5.5409
0.147	5.5189

0.148	5.4896
0.149	5.4505
0.150	5.4237
0.151	5.3968
0.152	5.3700
0.153	5.3455
0.154	5.3114
0.155	5.2796
0.156	5.2527
0.157	5.2259
0.158	5.1941
0.159	5.1722
0.160	5.1380
0.161	5.1184
0.162	5.0842
0.163	5.0574
0.164	5.0305
0.165	5.0012
0.166	4.9768
0.167	4.9499
0.168	4.9280
0.169	4.8962
0.170	4.8694
0.171	4.8474
0.172	4.8181
0.173	4.7961
0.174	4.7766
0.175	4.7424
0.176	4.7179
0.177	4.6960
0.178	4.6691
0.179	4.6447
0.180	4.6276
0.181	4.5958
0.182	4.5690
0.183	4.5519
0.184	4.5348
0.185	4.4982
0.186	4.4811
0.187	4.4518
0.188	4.4274
0.189	4.4054
0.190	4.3956
0.191	4.3590
0.192	4.3370
0.193	4.3126
0.194	4.2906
0.195	4.2686
0.196	4.2491
0.197	4.2247
0.198	4.2027

0.199	4.1807
0.200	4.1587
0.201	4.1368
0.202	4.1197
0.203	4.0977
0.204	4.0733
0.205	4.0562
0.206	4.0317
0.207	4.0098
0.208	3.9927
0.209	3.9707
0.210	3.9536
0.211	3.9365
0.212	3.9096
0.213	3.8926
0.214	3.8681
0.215	3.8486
0.216	3.8291
0.217	3.8169
0.218	3.7900
0.219	3.7705
0.220	3.7509
0.221	3.7338
0.222	3.7167
0.223	3.6996
0.224	3.6874
0.225	3.6606
0.226	3.6410
0.227	3.6264
0.228	3.6044
0.229	3.5873
0.230	3.5727
0.231	3.5507
0.232	3.5311
0.233	3.5165
0.234	3.4969
0.235	3.4823
0.236	3.4725
0.237	3.4481
0.238	3.4286
0.239	3.4115
0.240	3.3944
0.241	3.3797
0.242	3.3626
0.243	3.3480
0.244	3.3333
0.245	3.3114
0.246	3.2967
0.247	3.2821
0.248	3.2650
0.249	3.2503

0.250	3.2332
0.251	3.2210
0.252	3.2015
0.253	3.1844
0.254	3.1697
0.255	3.1551
0.256	3.1429
0.257	3.1258
0.258	3.1111
0.259	3.0965
0.260	3.0794
0.261	3.0647
0.262	3.0525
0.263	3.0379
0.264	3.0256
0.265	3.0085
0.266	2.9963
0.267	2.9792
0.268	2.9695
0.269	2.9524
0.270	2.9377
0.271	2.9231
0.272	2.9109
0.273	2.8962
0.274	2.8816
0.275	2.8694
0.276	2.8596
0.277	2.8498
0.278	2.8303
0.279	2.8181
0.280	2.8034
0.281	2.7912
0.282	2.7790
0.283	2.7766
0.284	2.7521
0.285	2.7424
0.286	2.7277
0.287	2.7155
0.288	2.7009
0.289	2.6911
0.290	2.6789
0.291	2.6691
0.292	2.6520
0.293	2.6422
0.294	2.6300
0.295	2.6227
0.296	2.6056
0.297	2.5934
0.298	2.5812
0.299	2.5690

FOTONIC SENSOR BENCH TESTING DATA:

AIR MEDIUM BETWEEN BETWEEN SENSOR AND SURFACE
(SENSOR CALIBRATED FOR 10 VOLT OPTICAL PEAK
USING 2L AS A REFERENCE):

SURFACE FINISH	VOLTAGE
-----	-----
2L	9.739
4L	9.306
8L	7.468
8G	7.145
16G	5.433
16BL	7.096
32G	4.676
32BL	6.938
32ST	6.657

NOTE: NUMBER REPRESENTS SURFACE FINISH IN MICROINCHES

L - LAPPED
G - GROUND
BL - BLANCHARD
ST - SHAPE-TURN

AIR MEDIUM BETWEEN BETWEEN SENSOR AND SURFACE
FOR CALIBRATION (SENSOR CALIBRATED FOR 10 VOLT
OPTICAL PEAK USING 2L AS A REFERENCE);
TESTING DONE WITH AN AIR MEDIUM AND A "CLEAN"
OIL FILM (.020 INCH) ON THE INSPECTION SURFACE:

SURFACE FINISH	VOLTAGE
-----	-----
2L	8.739
4L	7.900
8L	6.241
8G	6.115
16G	4.730
16BL	5.849
32G	4.130
32BL	6.172
32ST	5.670

NOTE: NUMBER REPRESENTS SURFACE FINISH IN MICROINCHES

L - LAPPED
G - GROUND
BL - BLANCHARD
ST - SHAPE-TURN

AIR MEDIUM BETWEEN BETWEEN SENSOR AND SURFACE
FOR CALIBRATION (SENSOR CALIBRATED FOR 10 VOLT
OPTICAL PEAK USING 2L AS A REFERENCE):
TESTING DONE WITH WITH "CLEAN" OIL MEDIUM BETWEEN
THE SENSOR FACE AND THE INSPECTION SURFACE:

SURFACE FINISH -----	VOLTAGE -----
2L	7.253
4L	6.918
8L	5.287
8G	5.065
16G	3.778
16BL	5.079
32G	3.390
32BL	4.757
32ST	4.071

NOTE: NUMBER REPRESENTS SURFACE FINISH IN MICROINCHES

L - LAPPED
G - GROUND
BL - BLANCHARD
ST - SHAPE-TURN

AIR MEDIUM BETWEEN BETWEEN SENSOR AND SURFACE
FOR CALIBRATION (SENSOR CALIBRATED FOR 10 VOLT
OPTICAL PEAK USING 2L AS A REFERENCE):
TESTING DONE WITH WITH "CLEAN" OIL MEDIUM BETWEEN
THE SENSOR FACE AND THE INSPECTION SURFACE:
A POSITIVE .005 INCH OFFSET WAS USED VERSES
PREVIOUS TESTING AT THE OPTICAL PEAK:

SURFACE FINISH -----	VOLTAGE -----
2L	6.703
4L	6.923
8L	5.289
8G	5.238
16G	3.990
16BL	4.879
32G	3.448
32BL	4.478
32ST	3.709

NOTE: NUMBER REPRESENTS SURFACE FINISH IN MICROINCHES

L - LAPPED
G - GROUND
BL - BLANCHARD
ST - SHAPE-TURN

Appendix IX

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APPENDIX IX - COMPUTER SCREENS

A9 - 1

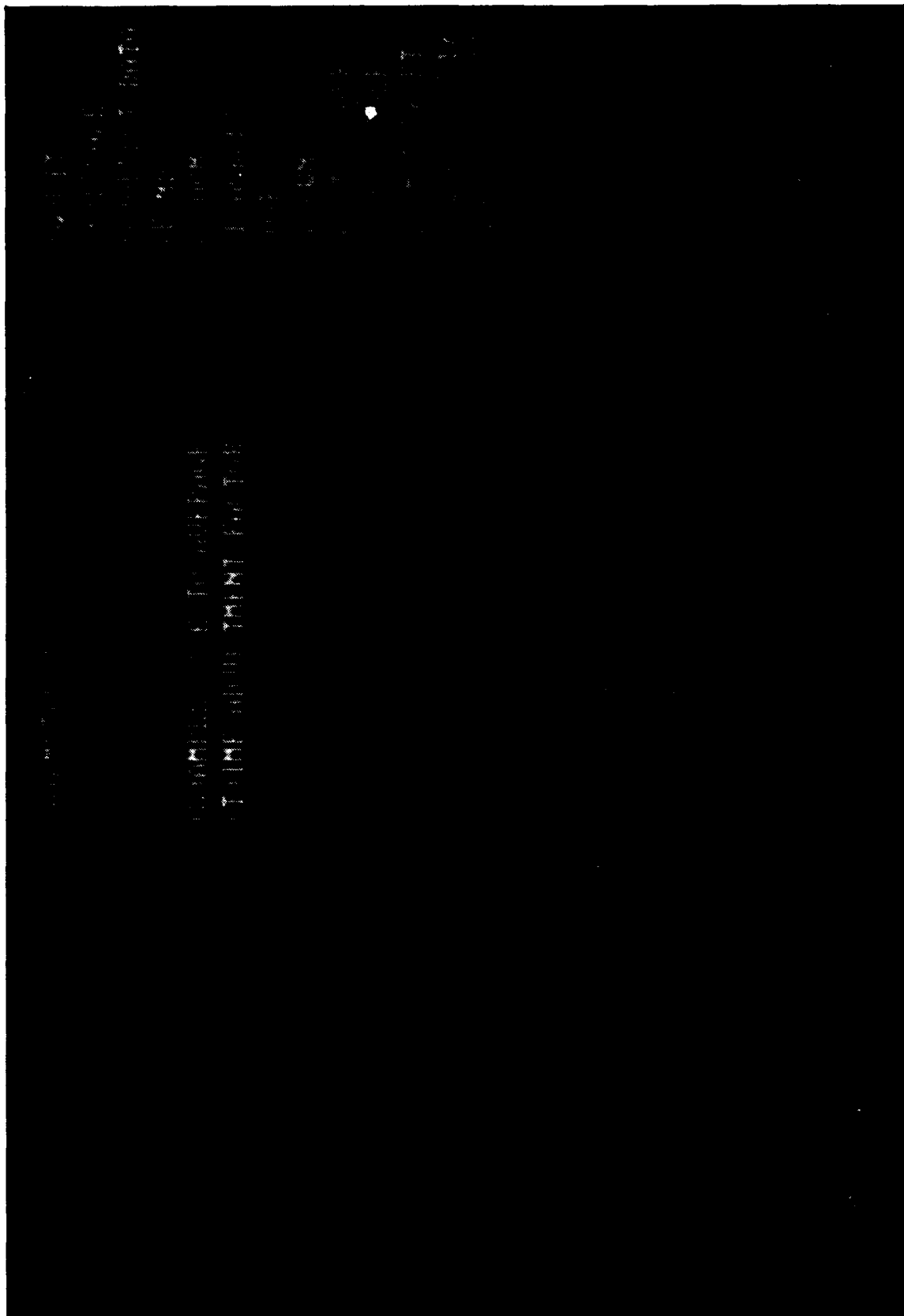
HONE MENU

(B)UILD LOOKUP TABLES
(S)HOW RAW A/D DATA
(D)ISPLAY SENSOR READINGS
(F)AST DATA GATHERING ROUTINE
(C)OPY COLLECTED DATA TO USER'S FILE
(Q)UIT TO DOS

ENTER CHOICE >

CHANNEL 0 - 1889 CHANNEL 2 - 689

PRESS ANY KEY TO END DATA COLLECTION



ENTER LOWER Y BOUNDARY >? 3.570

HI ENTER UPPER Y BOUNDARY >? 3.580

ENTER RIGHT X VALUE (MAX - 638 MIN - 10) >? 638

ENTER LEFT X VALUE (MAX - 628 MIN - 0) >? 40

3.578

DIAMETER 3.7753

SENSOR 1 READS HIGH

SENSOR 2 READS HIGH

(S)AMPLE SIZE TO AVERAGE

(T)IME ADJUSTMENT FACTOR

NUMBER OF SAMPLES TO AVERAGE? ☐

(Q)UIT
(R)ESCALE
(C)OLLECT DATA
(E)ND
(Z)OOM
(B)ACKUP
(U)P
(D)OWN
(A)UTO SCALE
(F)ULL SCALE
(L)IMIT RESET
LOWER = 3.574
UPPER = 3.576

3.573

3.588

DIAMETER 3.5789

(Q)UIT
(R)ESCALE
(C)OLLECT DATA
(E)ND
(Z)OOM
(B)ACKUP
(U)P
(D)OWN
(A)UTO SCALE
(F)ULL SCALE
(L)IMIT RESET
LOWER = 3.577
UPPER = 3.579

(S)AMPLE SIZE TO AVERAGE
(T)IME ADJUSTMENT FACTOR

3.575

3.580

DIAMETER 3.5781

(Q)UIT
(R)ESCALE
(C)OLLECT DATA
(E)ND
(Z)OOM
(B)ACKUP
(U)P
(D)OWN
(A)UTO SCALE
(F)ULL SCALE
(L)IMIT RESET
LOWER = 3.577
UPPER = 3.579

(S)AMPLE SIZE TO AVERAGE

(T)IME ADJUSTMENT FACTOR

ENTER TEMPERATURE OF MACHINED PART >? 70

ENTER TEMPERATURE OF CALIBRATION STANDARD >? 68

3.575

Appendix X

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APPENDIX X - VENDOR LIST

Omron Electronics, Inc.
One East Commerce Drive
Schaumburg, IL 60173
Phone (312) 843-7900
Fax (312) 843-7787

Kaman Instrumentation Corporation
1500 Garden of the Gods Road
P.O. Box 7463
Colorado Springs, CO 80933
Phone (719) 599-1825

ADAC Corporation
70 Tower Office Park
Woburn, MA 01801
Phone (617) 935-6668
Fax (617) 938-6553

Babcock & Wilcox
Naval Nuclear Fuel Division
P.O. Box 785
Lynchburg, VA 24505
Phone (804) 522-6000

Hewlett Packard
P.O. Box 3640
Sunnyvale, CA 94088-3640

Keyence Corporation of America
17-17 Route 128, North
Fair Lawn, NJ 07410
Phone (201) 791-8811
Fax (201) 791-5791

Litton Poly-Scientific
Slip Ring Products
1213 North Main Street
Blacksburg, VA 24060-3100
Phone (703) 953-4751
Fax (703) 953-1841

General Hone Corporation
471 U.S. 250 East, Route 2
Ashland, Ohio 44805
Phone (419) 289-3000

United States Department of Commerce
National Institute of Standards & Technology
Gaithersburg, Md 20899
Attention: Automated Production Technology Division
Phone (301) 975-6624

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Assistant Secretary of Army
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Dr. L. Lehn
Pentagon
Washington, DC 21310

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ODCSRDA
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Room 3C400, The Pentagon
Washington, DC 20310

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Aberdeen Proving Ground, MD 21010-5423

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Rock Island, IL 61299-7200

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Rock Island, IL 61299-5000

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Watervliet Arsenal
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Watervliet, NY 12189

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Champaign, IL 61820

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Naval Material Industrial Resources Office
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Code 277
Philadelphia Naval Base
Philadelphia, PA 19112

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Commander
Air Force Materials Laboratory
ATTN: LTM
Wright Patterson AFB, OH 45433

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Commander, Rock Island Arsenal
ATTN: SHCRI-SE
Rock Island, IL 61299-5000

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2. Inspection

3. Honing

4. In-process

5. Eddy Current

IN-PROCESS INSPECTION STUDY (IPIS) FOR
ABRASIVE MACHINING (HONING)

Michael A. Paul, V. Ed Stubbs, Michael W. Minnick,
Babcock and Wilcox, and Donald G. Eitzen, National
Institute of Standards and Technology

Report SE-91-03, 271 p. incl. illus. tables,
(AMS Code 3297.06.8248) Unclassified Report.

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This study was to prove the feasibility of in-process inspection of parts being honed on the inside diameter. Capacitance and inductive (eddy current) sensors were bench tested for accuracy and for the sensitivities of these measurements to honing oil. Unlike capacitance sensing, eddy current sensing was insensitive to the oil, so a honing machine was set up that had two eddy current sensors diagonally opposed to each other in a fixture screwed to the honing head. The wires were fed through flexible coupling to a slip ring, where the signals were routed through a signal conditioner to a 12 bit analog voltage to digital conversion (data acquisition) board in a computer. A look-up table was automatically used to correct for deviations from linearity of the sensors. A color monitor enabled graphical displays of individual

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SUPPLEMENTARY

INFORMATION

91-17

ERRATA SHEET

IN-PROCESS INSPECTION STUDY (IPIS) FOR ABRASIVE MACHINING (HONING)
REPORT SE-91-03, 9 NOV 90

AUTHORS

MICHAEL A. PAUL
V. ED STUBBS
MICHAEL W. MINNICK
DONALD G. EITZEN

1. Page 6-4, third paragraph, last sentence: delete in its entirety.
2. Page 6-4, fourth paragraph, first sentence: delete 'In conclusion'.
3. Page 7-7, third paragraph, first sentence: replace in entirety with
'Note: B&W does not recommend pursuing in-process, i.e., continuous, 'surface
finish' inspection for honing, where the potential benefits do not justify the
extensive development effort still required to prove feasibility for a
production system.'

AD-A-236244