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**OAK RIDGE
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MARTIN MARIETTA

CRADA Final Report
for
CRADA Number ORNL92-0090

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**FINAL REPORT
BROWN AND SHARPE CRADA
CRADA 92-0090**

**V. J. TENNERY
R. J. PARTEN**

**HIGH TEMPERATURE MATERIALS LABORATORY
OAK RIDGE NATIONAL LABORATORY
DECEMBER 31, 1994**

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INTRODUCTION

This CRADA technically started in October 1992, for a two year period, and the major component of the agreement was for the Brown and Sharpe company to provide a Leitz Model 654 Coordinate Measuring Machine for installation in the HTML and for HTML staff to conduct a series of studies to demonstrate the capabilities of this sophisticated metrology instrument. Mr. Mike Majlak was the contact at Brown and Sharpe. V. J. Tennery was the contact at ORNL. The CRADA agreement included two major phases, Phase I and Phase II. Phase I included instrument delivery, set up and calibration, plus the start of a series of repetitive measurements on reference bars to determine long term stability of the instrument. The instrument delivery occurred late and installation was only completed on April 30, 1993, therefore useful work during the first six months of this agreement was greatly reduced compared to the planned rate of progress.

ORGANIZATION AND RESULTS

In Phase I, beneficial work started in May 1993 when the Brown and Sharpe field engineer set up the instrument and certified it ready for use on May 21. In addition, a series of daily check measurements was initiated to determine the long term stability of the instrument. Early results showed that the temperature control in the laboratory room was totally inadequate for an instrument of this type, and a month and substantial funds were spent in modifying the air flow in the laboratory room so as to provide the environmental control necessary. When these modifications were completed, the room air temperature varied less than 0.1 °F during several hours of running time.

Phase II included a set of demonstration and evaluation studies for the purpose of demonstrating the capability of this instrument. The Phase I daily repetitive measurements rapidly demonstrated that this instrument was capable of a long term ability to measure dimensions in the range of 1 to 2 μm . These studies which resulted in preparation of technical reports for the partner included; (1) the determination of the effect of applying large masses to the working table design limits to the machine upon its ability to measure the length of a temperature compensated gage bar having various orientations in space - this work was designed using a full factorial design and the report title is, "A STUDY OF THE EFFECTS OF MASS LOADING AND ORIENTATION ON THE ACCURACY OF A BROWN AND SHARPE LEITZ MODEL 654 COORDINATE MEASURING MACHINE"; (2) demonstration of the instrument's capabilities in characterizing the surfaces of 22 large diesel engine cylinders obtained from the Detroit Diesel Corporation - the report title is, "MEASUREMENT OF DIESEL CYLINDER LINERS WITH A LEITZ MODEL 654 COORDINATE MEASURING MACHINE"; (3) demonstration of the instrument's capabilities in measuring a standard sphere using a statistically designed experiment (standard spheres are a commonly used artifact in calibrating such instruments) - the report title is, "A STUDY OF DEFINED PATH SCANNING OF A STANDARD SPHERE USING A LEITZ MODEL 654 COORDINATE MEASURING MACHINE"; (4) complete dimensional characterization of a series of 10 production silicon nitride cam rollers used in the Detroit Diesel Series 60 engine - the report title is, "CHARACTERIZATION OF

SILICON NITRIDE CAM ROLLER SURFACES USING BROWN AND SHARPE (LEITZ) MODEL 654 COORDINATE MEASURING MACHINE"; (5) complete dimensional and orientation characterization of a Ford state-of-the-art aluminum engine block with case in place iron cylinder liners - this work was designed using a full factorial design - the report title is, "DIMENSIONAL CHARACTERIZATION OF AN ALUMINUM V-6 ENGINE BLOCK WITH A LEITZ MODEL 654 COORDINATE MEASURING MACHINE"; and (6) a survey of the experiences among the Y-12 facility metrology staff with the latest Brown and Sharpe graphical interface software for use with the Model 654 instrument - the report title is, "EVALUATION OF THE QUINDOS GRAPHICAL USER INTERFACE."

In addition to these six major studies conducted as part of this CRADA, there was a major survey made to determine how the CMM might be adapted to measuring the characteristics of "small holes" i.e. those have diameters of the order of 5 to 10 μm , which are becoming of major importance in fuel injector technology. If such a technology could be found in the Defense Programs complex, at least preliminary studies were to be made within the framework of this CRADA to determine how the hole locations could be identified for the instrument and how the characteristics of the holes might be measured by use of a very small probe attached to the instrument. A survey was made of the entire Defense Programs complex by a committee chaired by Jim Hensley. The conclusion was that this technology does not exist in the complex and therefore this subtask was essentially terminated with negative results. This CRADA did not have the resources to initiate the development of small hole measurement technology as a stand alone task.

A task in this CRADA for which only very preliminary results could be obtained was the demonstration of near real time feedback between a machine tool and the CMM. The machine tool selected was the new Cincinnati Milacron centerless grinder recently installed in the HTML. The work piece for the demonstration was a tensile specimen. The grinding wheel was dressed with the negative shape of the ASTM standard ceramic tensile specimen and steel specimens were used for this demonstration to minimize the costs. Special software was written which allowed the CMM computer to interface with the centerless grinder controller. A limited series of runs in mid-December showed that critical dimensions of the tensile specimen could be systematically be improved by grinding a specimen using a given set up on the grinder then measuring the dimensions on the CMM and subsequently sending correction data from the CMM computer to the centerless grinder controller. Insufficient time was available to complete a statistically designed set of runs to quantitatively demonstrate this capability for three critical dimensions of this work piece, including the gage section diameter, the taper between the gage section and the shank, and the critical fillet between the shank and the button head.

One final requirement in this CRADA was to hold a workshop with industrial participants to demonstrate some of the results from this work for the purpose of showing non-metrologists how such an instrument could contribute to solutions to current manufacturing problems. This workshop was held on August 25 with approximately 20 industrial representatives being given briefings and demonstrations of the capability of the Model 654 CMM.

This CRADA was originally scheduled to end on October 31. Due to the long delays in getting the Coordinate Measuring Machine installed and stabilized, many of the tasks were behind schedule. On August 15 a formal request was made by V.J. Tennery to extend the CRADA through December 31. Approvals were obtained from Martin Marietta Energy Systems and Brown and Sharpe in approximate one month from the original request date. To this date, this extension has not been approved by the local DOE office, however the DOE operating funds for this CRADA have been allowed to be available past October 31, so that the work could essentially be completed. The task charts for this CRADA are shown in Fig. 1.

The return of the CMM to the partner, Brown and Sharpe Co. is planned for January or February when special crating is obtained from Germany. Costs for this return are being covered by other funds, as the remaining CRADA funds are no longer available.

FIGURE 1
TASK CHARTS FOR CRADA 92-0090

**DIMENSIONAL CHARACTERIZATION OF AN ALUMINUM V-6 ENGINE BLOCK
WITH A LEITZ MODEL 654 COORDINATE MEASURING MACHINE**

**PHASE II, TASK 3
CRADA 92-0090**

**WITH
BROWN AND SHARPE CO.**

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DECEMBER 29, 1994**

1. SUMMARY

The Leitz Model 654 Coordinate Measuring Machine (CMM) was used to measure 30 dimensional variables for a Ford Motor Co. 2.5L aluminum engine block in which the iron cylinder liners are cast in place in the block. This engine represents the latest engine block technology for Ford Motor Co. The purpose of this work was to demonstrate the ability of the CMM to measure several critical dimensions and angles in the engine block and to determine the consistency of these dimensions. For example, the orientation of the cylinder central axes for the six cylinders relative to the three axes of two reference coordinate systems was determined and compared to the ideal values. In addition, the diameter and form relative to an ideal cylinder surface computed based upon the measured cylinder diameter was determined for each cylinder. All of these measurements were made within the framework of a full factorial design employing replication of each set of the three independent variables, which included two bases for the coordinate axes systems, two CMM probe sizes having diameters of either 5 or 8 mm., and two CMM scanning protocols. These two protocols included the highly accurate point to point method and a defined path scanning method based upon a beta software version provided by Brown and Sharpe Co.

The standard deviation for all of the angles made by the cylinder bore axis with the defined coordinate systems varied from 0.000858 to 0.038636. The alpha and beta angles varied from a high of 90.1780 to a minimum of 89.97100 degrees, where the theoretical value is 90.0000 degrees. The gamma angles varied from a high of 0.05880 to a minimum of 0.00730 degrees, where the theoretical value is 0.0000 degrees. The cylinder diameters varied from a high of 82.41800 to a minimum of 82.41110 mm. where the nominal value for this engine is 82.415 mm. Finally, the cylindrical form (maximum or minimum deviation from the ideal cylindrical surface in mm.) varied from a maximum of 0.00480 to a minimum of 0.00080 mm.

Analysis of variance (ANOVA) evaluations were conducted for all 30 dependent variables for each set of independent variables. These results are summarized as follows. For the cylinder axis angles, generally the largest source of error was associated with the coordinate systems. However in some cases, such as for the angle beta 2 (cylinder 2) the probe and scan variables contributed about equally to the error and the coordinate system variable contribution was very small. No physical explanation was determined for these variations. For the diameter determinations, the major source of errors was the scanning mode with the rapid scanning protocol providing less accurate values than did the point to point protocol. However, it should again be stressed that the errors in these measurements are extremely small compared to the expected values. The sources of error for the form determinations generally included two of the three independent variables. For example, for the form determination for cylinder no. 4, the reference axes and probe variables were the major error contributors and about equal in this regard. For the case of the form value for cylinder no. 5, the reference axes and scan variables were the major sources of error.

2. INTRODUCTION

The purpose of this work was to measure 30 dimensional variables for the six cylinders in a new Ford Motor Co. 2.5 L aluminum engine block containing cast in place liners using a Leitz Coordinate Measuring Machine. A full factorial design was used including three independent variables. For each of the six cylinders, three angles defining the relationship of the central bore axis were computed relative to two coordinate axis systems were measured (six dependent variables), plus the diameter and form of the cylinder were computed. The coordinate systems were defined from the engine head surface and one defined from the crankshaft axis plus the CMM working table surface. Two CMM probe tip sizes, 5 and 8 mm in diameter were employed, with two scanning modes, one the standard point-to-point protocol and the second being the much more rapid defined path scanning protocol.

For this full factorial experimental design with two replications, a total of 16 cases were run with two levels for the variable REF, the coordinate axes definitions; PROBE, the CMM probe size; and SCAN, the CMM scanning protocol. The measurements were all made in a random fashion as defined by the experimental plan. Analysis of the results were performed using the STATISTICA statistics package marketed by StatSoft, Tulsa, OK.

3. EXPERIMENTAL DETAIL

3.1 CALIBRATION OF THE CMM

A 25.0008 mm zirconia sphere was used for the initial CMM calibration. The probe configuration consisted of the following dimensions: two 8 mm tips x 90 mm shank length one position at -60 degrees elevation and 90 degrees azimuth the other at -60 degrees elevation and -90 degrees azimuth, two 5 mm tips x 82.5 mm shank length these probes had the same position as the 8 mm probes and two 5 mm tip x 50.8 mm shank length with one position at 0 degrees azimuth and -90 degrees elevation the other at 180 degrees azimuth and -90 elevation mounted on a 15 mm cube extending 220 mm from the probe head. The three axis deflection mode was used in order to obtain measurement values of quality possible with this system. One probe was selected (5mm tip x 50.8 at 0 degrees azimuth -90 degrees elevation) for the reference probe. A standard 25 mm. diameter calibration sphere was used to calibrate the instrument. The probe was brought into contact with the sphere and assigns this point as a sphere pole. This step was followed by an automatic calibration routine for all six probes used in this work. After these measurements were completed a calibration check was performed, this procedure consisting of measuring a 15 point sphere using the six probes. A evaluation of the form, diameter, and X Y Z positions was computed.

3.2 MANUAL SET UP

The engine block was placed on the working table of the coordinate measuring machine with the bottom of the engine block surface on the table with the crankshaft bore parallel to the machines X axis and number one cylinder (this is the firing order number) is positioned toward the machines plus (+) Y direction. As the operator faces the CMM, the machine plus (+) Y direction is oriented to the right. Four points were measured on the back surface of the engine block. This measurement was used to the zero position for the X axis. Four points were measured on back side of the crankshaft bore (67.945 mm dia.). Four points were measured on a 22.225 mm diameter hole 202.406 mm from bottom surface on back side. An axis was built using the crank bore and the 22.225 dia hole. This group of measurements defined the reference system for the + Z axis and its positive direction. The spatial alignment included the four points measured on the back side of engine block and this was used for defining the location in space of the zero value for the X axis. The four points measured on the crank bore were used for defining Y and Z zero.

3.3 AUTOMATIC SET UP

The crankshaft bore was measured starting at the back side by measuring 20 points then moving to the front side of the engine block and measuring another 20 points. These measurements defined the X axis and was used for spatial alignment in the reference system. A 25.4 mm gage block was used to build the Y axis. The gage block was placed at a point on -Y axis and measured, then the block was moved to a comparable point on the +Y axis measured. This procedure was used for defining the planar direction in the BORE reference system. The four points measured on the back side of the engine block were used for defining the position of $X=0$. The points were used to measure the crankshaft bore, i.e. zero Y and Z. These results were used to construct the BORE reference system, referred to in the experimental plan as BORE. Sixteen points were measured on the head surface on - Y side of the block, then a 36 point circle 10.0000 mm down from head surface was measured in cylinder No. 5. The same procedure was done on the + Y side of the block using cylinder No. 2 for a 36 point circle. The 16 points measured on the + Y and -Y sides of the block were used to generate two planes. These two surfaces intersect and this defines the X axis in the reference system called HEAD. These results were used for spatial alignment and defining the $Y=0$. The center points of the two 36 point circles were used to create a symmetry point. This point was used to define the location in space of $Z=0$. The symmetry point and the X axis that was created earlier was used to build a perpendicular. This perpendicular was used in the reference system to define the positive direction for Z. The four points measured on the back side of the block were used to define $X=0$. These steps were used to create the HEAD reference system.

3.4 PROCEDURE FOR TEST RUNS

Starting with cylinder No. 1 and progress to cylinder No.6 a reference system, probe size, and scanning path were selected and used as dictated by the full factorial experimental design. For each cylinder, two circumferences were probed along the height of the cylinder by making 36 measurements along each circumference at the two elevations in the cylinder. These measurements were used to define the cylindrical axis of each bore. These measurements were followed by measuring the circumference at a point in each cylinder exactly between the two circumferences scanned using the 36 point measurements previously made using the point to point protocol. Two scanning protocols were used for this central circumference measurement, point to point and defined path scanning, as dictated by the experimental plan. For the point to point mode, 72 points were measured. These results were then used to compute the angles ALPHA, BETA, and GAMMA which define the orientation of each cylinder's central axis relative to the two coordinate systems, plus diameters and form (the maximum deviation of the cylindrical surface from the circle computed from the diameter measurement). The orientation and definition of some of the objects in this work are shown in Fig. 1, a diagram for the block itself. Figure 2 shows the definition of the three angles for the central axis for a cylinder along with the location of the three circumferential scans used for defining the cylindrical surface in space.

4. RESULTS

The independent variables were selected at two levels each with one replication for each independent variable set. These are shown in Table 1.

TABLE 1
INDEPENDENT VARIABLES
FOR FULL FACTORIAL DESIGN

CASE	REF	PROBE	SCAN
1	HEAD	LARGE	PTP
2	BORE	SMALL	DPS
3	HEAD	SMALL	PTP
4	HEAD	LARGE	PTP
5	BORE	SMALL	PTP
6	HEAD	LARGE	DPS
7	BORE	LARGE	PTP
8	BORE	LARGE	DPS
9	HEAD	SMALL	DPS
10	HEAD	SMALL	DPS
11	BORE	LARGE	DPS
12	BORE	SMALL	DPS
13	HEAD	SMALL	PTP
14	HEAD	LARGE	DPS
15	BORE	LARGE	PTP
16	BORE	SMALL	PTP

The following definitions apply to Table 1. Each CASE includes a set of independent variables and the design requires a total of 16 CASES, including a replication of each case. Therefore, a total of 8 independent sets of independent variables were tested. The variable REF includes two coordinate axis systems used to define the angles for the cylinder bores and all other measurements. The variable PROBE had two values, either 5 mm. or 8 mm. for the size of the physical CMM probe used to contact the surfaces. The variable SCAN included two protocols, one being the conventional point to point method (expected to provide the highest accuracy) and a rapid scanning method identified as DPS (Defined Path Scanning) provided by the Brown and Sharpe Company.

The results for all of the combinations of the variables given in Table 1 are shown in Table 2 for the 18 angles defining the spatial direction of the cylindrical axis for the six block cylinders. The small value of the gamma angle is a measure of the angle between the central axis of each cylinder and the z axis of the coordinate system for that particular engine head. The alpha and beta angles would equal 90.0000 degrees if the axial alignment of the cylinder were perfect with the head surface. The data in Table 2 shows that the cylinder angles are extremely close to the

TABLE 2
RESULTS FOR DEPENDENT VARIABLES FOR 16 CASES
IN FULL FACTORIAL DESIGN
ANGLES FOR SIX CYLINDERS RELATIVE TO REFERENCE AXIS SYSTEMS

CASE	ALPHA1	BETA1	GAMMA1	ALPHA2	BETA2	GAMMA2	ALPHA3	BETA3	GAMMA3	ALPHA4	BETA4	GAMMA4	ALPHA5	BETA5	GAMMA5	ALPHA6	BETA6	GAMMA6
1	90.01650	90.04220	.045400	90.02240	90.03700	.04330	90.01380	90.05570	.057400	89.98000	90.00390	.020400	89.99880	89.99140	.008800	90.00220	89.98720	.013000
2	90.01100	90.02270	.025200	90.01700	90.17800	.02480	90.00840	90.03650	.037500	89.98780	89.98460	.019600	90.00850	89.97220	.028600	90.01010	89.98790	.033600
3	90.01680	90.04360	.046800	90.02250	90.03850	.04450	90.01400	90.05700	.058700	89.98000	90.00520	.020700	89.99880	89.99280	.007400	90.00230	89.98870	.011600
4	90.01680	90.04360	.046700	90.02280	90.03850	.04470	90.01420	90.05710	.058800	89.98010	90.00540	.020600	89.99880	89.99280	.007300	90.00240	89.98870	.011500
5	90.01110	90.02350	.028000	90.01700	90.01850	.02520	90.00840	90.03740	.038300	89.98800	89.98550	.018900	90.00870	89.97280	.027900	90.01040	89.98870	.032900
6	90.01680	90.04360	.046700	90.02270	90.03850	.04480	90.01430	90.05710	.058800	89.98010	90.00540	.020600	89.99880	89.99280	.007300	90.00250	89.98870	.011800
7	90.01140	90.02370	.026200	90.01730	90.01860	.02540	90.00870	90.03720	.038200	89.98810	89.98550	.018700	90.00880	89.97290	.027900	90.01040	89.98880	.032900
8	90.01130	90.02370	.026200	90.01740	90.01870	.02550	90.00880	90.03730	.038300	89.98810	89.98550	.018700	90.00890	89.97300	.027900	90.01050	89.98880	.032900
9	90.01680	90.04350	.046700	90.02270	90.03850	.04470	90.01420	90.05710	.058800	89.97990	90.00530	.020800	89.99880	89.99280	.007400	90.00230	89.98870	.011500
10	90.01690	90.04350	.046700	90.02280	90.03850	.04470	90.01420	90.05700	.058800	89.98000	90.00530	.020700	89.99880	89.99270	.007400	90.00220	89.98870	.011500
11	90.01140	90.02370	.026200	90.01730	90.01870	.02550	90.00880	90.03730	.038300	89.98810	89.98550	.018800	90.00880	89.97290	.027900	90.01050	89.98880	.032900
12	90.01120	90.02360	.026100	90.01720	90.01880	.02530	90.00870	90.03720	.038200	89.98790	89.98550	.018900	90.00870	89.97300	.027800	90.01030	89.98870	.032900
13	90.01650	90.04340	.046400	90.02230	90.03820	.04430	90.01390	90.05680	.058400	89.97990	90.00510	.020700	89.99850	89.99280	.007500	90.00210	89.98840	.011800
14	90.01870	90.04340	.046500	90.02250	90.03840	.04450	90.01400	90.05690	.058600	89.98000	90.00520	.020600	89.99870	89.99280	.007500	90.00220	89.98850	.011800
15	90.01100	90.02170	.024400	90.01710	90.01670	.02390	90.00860	90.03530	.036300	89.98800	89.98380	.020400	90.00870	89.97100	.029600	90.01030	89.98880	.034800
16	90.01090	90.02160	.024200	90.01690	90.01660	.02370	90.00830	90.03520	.036200	89.98790	89.98350	.020400	90.00860	89.97100	.029600	90.01020	89.98880	.034700

nominal values. Table 3 shows the values for the remaining 12 dependent variables measured for each cylinder. These include the diameter (DIAM) and form (FORM), measured in mm. The diameter was computed from the central circumference measurement for each cylinder, as discussed earlier, while the form was determined as the maximum or minimum difference in mm. from the computed cylinder based upon the diameter measurement. Again, these dependent variables showed very little variation from the nominal value. The diameters, as shown in Table 3, had extremely small variations regardless of the case number. Also, the cylinders were very close to being true circles, as illustrated by the values for the FORM variable.

4.1 STATISTICAL RESULTS

The results for each cylinder were analyzed using one way analysis of variance in addition to testing for adherence of the results to a normal distribution function. Selected results from these analyses will now be discussed. Table 4 shows the means, maximum and minimum values, and standard deviations for the 30 dependent variables in this study. The table shows that the angles ALPHA and BETA are all very close to 90 degrees. It also shows that the GAMMA angles are very close to zero, as expected. The range from the maximum to minimum values are also very small for these variables. In addition, the standard deviations are also very small, which shows two things, first the engine block has very high accuracy in cylinder alignment in the block and that the CMM is capable of measuring the very small deviations from the nominal values. The results for the variables DIAM and FORM also show that these dimensional parameters and their variations are very close to nominal or very small. The nominal bore diameter for this design is 82.415 mm. The analysis results for the BETA angles were very similar to those for the ALPHA angles. The probability analyses results for the GAMMA angle showed that this variable fit the normal distribution much better than was the case for the ALPHA or BETA angles.

ANOVA analyses and normal probability analyses were determined for each of the 30 dependent variables as functions of the three independent variables. Examples of these results will now be given and discussed.

The BETA 1 results were very typical of those for both the ALPHA and BETA results. This behavior is illustrated in Table 5 given below:

TABLE 5
ANOVA RESULTS FOR ANGLE BETA 1
2**(3-0) design of resolution R = FULL
BETA 1; Mean = 90.0332 Sigma = .0105192

		SS	df	MS	F	p
1	REF	.001652	1	.001652	2838	.000000
2	PROBE	.000000	1	.000000	.004	.949186
3	SCAN	.000001	1	.000001	2.078	.183287
12		.000000	1	.000000	.726	.416382
13		.000000	1	.000000	.429	.528680
23		.000000	1	.000000	.429	.528680
	Residual	.000005	9	.000001		

TABLE 3
RESULTS FOR DEPENDENT VARIABLES
FOR 16 CASES
IN FULL FACTORIAL DESIGN
DIAMETERS AND FORM

CASE	DIAM1	DIAM2	DIAM3	DIAM4	DIAM5	DIAM6	FORM1	FORM2	FORM3	FORM4	FORM5	FORM6
1	82.41430	82.41550	82.41270	82.41670	82.41380	82.41320	.001800	.001200	.001000	.001800	.001300	.001100
2	82.41520	82.41640	82.41370	82.41800	82.41530	82.41470	.002700	.001500	.002700	.004800	.001800	.002600
3	82.41410	82.41520	82.41220	82.41660	82.41390	82.41330	.001600	.001300	.003100	.004500	.001500	.001300
4	82.41110	82.41560	82.41280	82.41650	82.41370	82.41300	.001500	.001000	.001400	.002200	.001500	.001100
5	82.41400	82.41510	82.41220	82.41640	82.41370	82.41300	.001700	.001100	.001300	.002200	.001400	.002100
6	82.41460	82.41580	82.41310	82.41730	82.41460	82.41400	.001900	.001600	.001400	.002400	.002000	.002000
7	82.41430	82.41550	82.41280	82.41640	82.41370	82.41300	.001600	.001000	.001400	.001600	.000800	.001300
8	82.41450	82.41570	82.41300	82.41740	82.41460	82.41400	.002000	.001300	.001600	.002400	.001600	.002100
9	82.41500	82.41620	82.41360	82.41790	82.41520	82.41450	.002600	.001800	.002200	.002900	.001900	.002300
10	82.41510	82.41620	82.41350	82.41790	82.41500	82.41450	.002400	.001300	.002200	.002900	.001900	.002200
11	82.41460	82.41580	82.41310	82.41730	82.41460	82.41400	.001900	.001800	.001500	.002500	.001500	.001700
12	82.41490	82.41620	82.41360	82.41790	82.41510	82.41450	.002800	.001700	.002300	.002800	.001700	.002100
13	82.41410	82.41530	82.41260	82.41670	82.41380	82.41330	.001400	.001700	.001700	.002200	.002000	.001300
14	82.41510	82.41630	82.41370	82.41780	82.41500	82.41440	.002100	.001700	.001500	.002700	.002100	.002400
15	82.41450	82.41570	82.41300	82.41670	82.41390	82.41320	.001600	.001200	.001400	.002000	.001100	.001100
16	82.41420	82.41540	82.41260	82.41650	82.41380	82.41320	.001500	.001500	.001700	.002200	.001100	.001200

TABLE 4
MEANS, MINIMUMS, MAXIMUMS, AND STANDARD DEVIATIONS
FOR FIVE DIMENSIONS FOR SIX ENGINE CYLINDERS

VAR.	N	Mean	Minimum	Maximum	Std.Dev.
ALPHA1	16	90.01393	90.01090	90.01690	.002864
BETA1	16	90.03319	90.02160	90.04360	.010519
GAMMA1	16	.03601	.02420	.04670	.010813
ALPHA2	16	90.01987	90.01690	90.02280	.002813
BETA2	16	90.03816	90.01660	90.17800	.038636
GAMMA2	16	.03466	.02370	.04480	.010113
ALPHA3	16	90.01133	90.00830	90.01430	.002839
BETA3	16	90.04676	90.03520	90.05710	.010436
GAMMA3	16	.04810	.03620	.05880	.010803
ALPHA4	16	89.98399	89.97990	89.98810	.004126
BETA4	16	89.99500	89.98350	90.00540	.010454
GAMMA4	16	.01997	.01870	.02080	.000858
ALPHA5	16	90.00268	89.99850	90.00690	.004165
BETA5	16	89.98246	89.97100	89.99280	.010454
GAMMA5	16	.01801	.00730	.02980	.010802
ALPHA6	16	90.00631	90.00210	90.01050	.004165
BETA6	16	89.97831	89.96680	89.98870	.010500
GAMMA6	16	.02262	.01150	.03480	.011206
DIAM1	16	82.41435	82.41110	82.41520	.000951
DIAM2	16	82.41574	82.41510	82.41640	.000411
DIAM3	16	82.41301	82.41220	82.41370	.000499
DIAM4	16	82.41713	82.41640	82.41800	.000622
DIAM5	16	82.41436	82.41370	82.41530	.000622
DIAM6	16	82.41374	82.41300	82.41470	.000643
FORM1	16	.00194	.00140	.00280	.000455
FORM2	16	.00142	.00100	.00180	.000279
FORM3	16	.00178	.00100	.00310	.000567
FORM4	16	.00263	.00160	.00480	.000872
FORM5	16	.00158	.00080	.00210	.000373
FORM6	16	.00174	.00110	.00260	.000533

Table 5 shows that the largest source of error for angle BETA 1 is derived from the coordinate reference systems. The probability analysis results for angle BETA 1 is shown in Fig. 3. This result is typical for nearly all of the angular measurements, i.e. neither the main effects interaction effects fit the gaussian distribution function very well. This result contrasts with that for angle BETA 2, for example where the ANOVA table given in TABLE 6 shows that the largest sources of error are about equally derived from the PROBE and SCAN variables. The physical reason for these differences could not be identified. The probability analysis results for angle BETA 2 is shown in Fig. 4, where the fit to a gaussian distribution for all of the effects is relatively good.

TABLE 6
ANOVA RESULTS FOR ANGLE BETA 2
2**(3-0) design of resolution R = FULL
BETA 2; Mean = 90.0382 Sigma = .0386365

		SS	df	MS	F	p
1	REF	.000000	1	.000000	.000114	.991731
2	PROBE	.001606	1	.001606	1.009433	.341285
3	SCAN	.001708	1	.001708	1.073387	.327216
12		.001554	1	.001554	.976953	.348779
13		.001638	1	.001638	1.029684	.336734
23		.001566	1	.001566	.984401	.347039
	Residual	.014319	9	.001591		

Table 6 shows that major sources of error in the measurement of the angle BETA 2 are about equally derived from the variables PROBE and SCAN. The main effect interactions also shown in these tables are not discussed in this report, as their physical interpretation is not possible based upon the current results. Figure 3 shows the probability analysis

Analysis of the diameter data showed generally that the variable SCAN tended to be the major source of error, and in some cases the variable PROBE was also important. Table 7 shows the results for DIAM 1. In this case, the SCAN variable contributed the most to the errors for this dependent variable. It should be stressed here that the errors in these diameter measurements are extremely small. The probability analysis results for the diameter in cylinder 1 (DIAM 1) is shown in Fig. 5, which shows that most of the effects fit the gaussian distribution quite well.

TABLE 7
ANOVA RESULTS FOR DIAMETER 1
2**(3-0) design of resolution R = FULL
DIAM 1; Mean = 82.4144 Sigma = .0009515

		SS	df	MS	F	p
1	REF	.000000	1	.000000	.695584	.425853
2	PROBE	.000001	1	.000001	1.149842	.311492
3	SCAN	.000004	1	.000004	6.260252	.033748
12		.000000	1	.000000	.695584	.425853
13		.000001	1	.000001	1.419558	.263947
23		.000000	1	.000000	.056782	.816993
	Residual	.000006	9	.000001		

Results for other diameters were similar to those shown in Table 7. For example, the ANOVA table for diameter 3 is shown in Table 8. This table shows that for this diameter, the scanning

TABLE 8
ANOVA RESULTS FOR DIAMETER 3
2**(3-0) design of resolution R = FULL
DIAM 3; Mean = 82.4130 Sigma = .0004992

		SS	df	MS	F	p
1	REF	.00000000	1	.00000000	.047872	.8316889
2	PROBE	.00000000	1	.00000000	.047872	.8316889
3	SCAN	.00000256	1	.00000256	49.021280	.0000631
12		.00000002	1	.00000000	.430851	.5279954
13		.00000004	1	.00000000	.765957	.4042217
23		.00000064	1	.00000006	12.255320	.0067155
	Residual	.00000047	9	.00000001		

mode used provided the major sources of error in the diameter measurement, although these errors were very small.

Analysis of the form measurements showed that reference coordinate system (REF) and probe size (PROBE) variables introduced the majority of the error and their contributions were about equal as shown in Table 9. The scanning mode made a very small error contribution. Probability analyses for the FORM measurements showed that they fit the gaussian (normal) distribution function very well, as illustrated in Fig. 6 for FORM 4.

TABLE 9
ANOVA ANALYSIS FOR FORM 4
2**(3-0) design of resolution R = FULL
FORM 4; Mean = .002631 Sigma = .0008716

		SS	df	MS	F	p
1	REF	.000002	1	.000002	2.298585	.163798
2	PROBE	.000001	1	.000001	1.456122	.258308
3	SCAN	.000000	1	.000000	.023934	.880468
12		.000002	1	.000002	3.332518	.101213
13		.000001	1	.000001	.920008	.362530
23		.000000	1	.000000	.422189	.532078
	Residual	.000006	9	.000001		

Table 10 shows results of the ANOVA analysis for Form 5. Form 5 had a standard deviation which was about a factor of three smaller than that for Form 4, as shown in Table 4. The results in Table 10 show that for Form 5 the REF and SCAN variables contributed about equally to the errors, which were, of course, smaller than for the case of Form 4 which had a larger standard deviation.

TABLE 10
ANOVA ANALYSIS FOR FORM 5
2**(3-0) design of resolution R = FULL
FORM 5; Mean = .001575 Sigma = .0003733

		SS	df	MS	F	p
1	REF	.000001	1	.000001	19.86207	.001585
2	PROBE	.000000	1	.000000	3.80172	.082993
3	SCAN	.000001	1	.000001	28.00862	.000499
12		.000000	1	.000000	.69828	.424991
13		.000000	1	.000000	.69828	.424991
23		.000000	1	.000000	2.79310	.129005
	Residual	.000000	9	.000000		

The normal probability analysis results are shown in Fig. 7, which shows again, as in the case for Form 4 that these variables fit the normal very well in terms of both the main effects and the interactive effects.

x-y Plane defined by head surface

z axis is oriented perpendicular to head surface

**16 points measured
on each head surface
defines reference plane**

ENGINE BLOCK

Cylinders

**36 points measured
to define each
cylinder surface**

**V-6 Aluminum Engine Block
with Cast in Place Iron Liners**

Figure 1. V-6 Engine Block with Definitions.

Figure 3. Normal Probability Diagram for Angle Beta 1.

Figure 4. Normal Probability Diagram for Angle Beta 2.

Figure 5. Normal Probability Diagram for Diameter 1.

NORMAL PROBABILITY ANALYSIS
FORM 4; Mean = .002631 Sigma = .0008716

Figure 6. Normal Probability Diagram for Form 4.

Figure 7. Normal Probability Diagram for Form 5.