GBT MEMO 168

Measurements Of 201 Manufactured GBT Surface Retroreflector Assemblies.

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ABSTRACT

A sample of 201 pieces, selected from 1900 manufactured GBT main surface retroreflector assemblies, was characterized by means of 3D CMM measurements. Equations for the three cube corner faces and the optical entry face of the retroreflector prism were determined, for each prism-casting assembly, relative to the plane annular rim surface and linear edge of the casting. Coordinates of the prism's optical reference point, corner vertex point and normal projection point of the vertex onto the prism entry face were obtained from these equations. From the coordinates, the heights of the vertex and projection points from the casting rim plane and the altitude of the prism were computed. Those distances are needed in order to correct GBT rangefinder measurements from feed arm lasers to surface retroreflectors, to give ranges to the main reflector surface points.

Prism heights obtained by use of a coordinate measuring machine are compared to heights obtained by vee block measurements of the prisms.

The statistics of the measured heights are discussed in regard to the method of manufacturing the assemblies and the accuracy and precision thereby attainable.

1 INTRODUCTION

One of the assigned missions of the rangefinder metrology system on the Green Bank Telescope is to measure the telescope's main reflector surface. Ideally, distances of points on this surface, measured from reference scan-fiducial-points of feed arm rangefinders, together with other measured distances, are used to determine the shape and pointing of the main reflector surface. In practice, distance is not measured directly to the surface point but, instead, to the optical fiducial point of a retroreflector prism located at a surface panel corner. A zinc-aluminum alloy casting, to which a glass cube corner retroreflector prism is cemented, is mounted at one corner of each surface panel. The measured ranges from laser scan points to prism fiducial points must be converted (somehow) into a measured range between the laser scan point and an appropriate panel surface point.

The method of obtaining the range from a laser scan reference point to a main reflector surface point is discussed at length in GBT Memo 154 [Go-1]. One can associate a well-defined surface panel point with each prism-casting assembly. This surface panel point is the foot of the perpendicular from the optical fiducial point of the prism to the plane of the annular rim surface of the casting. The

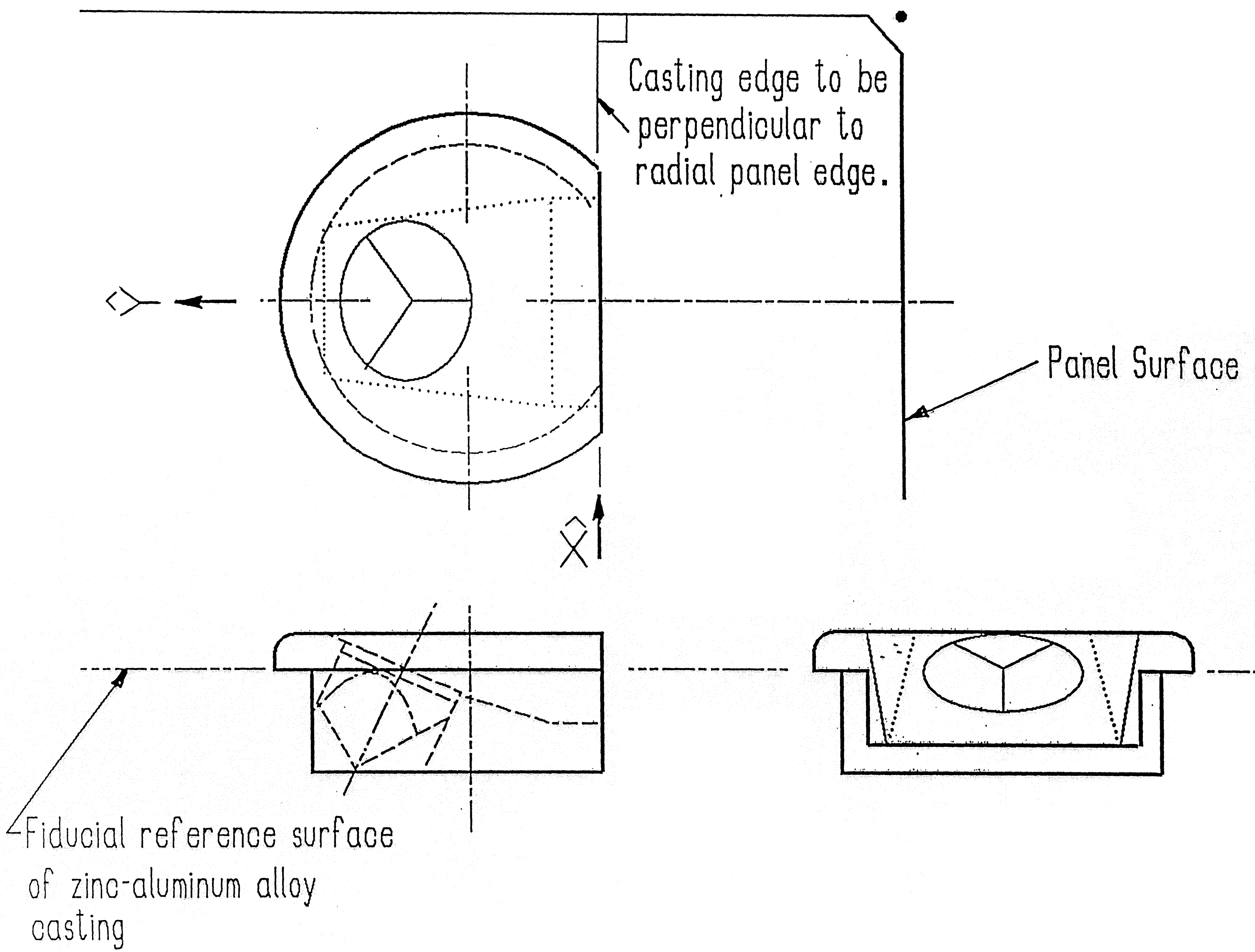
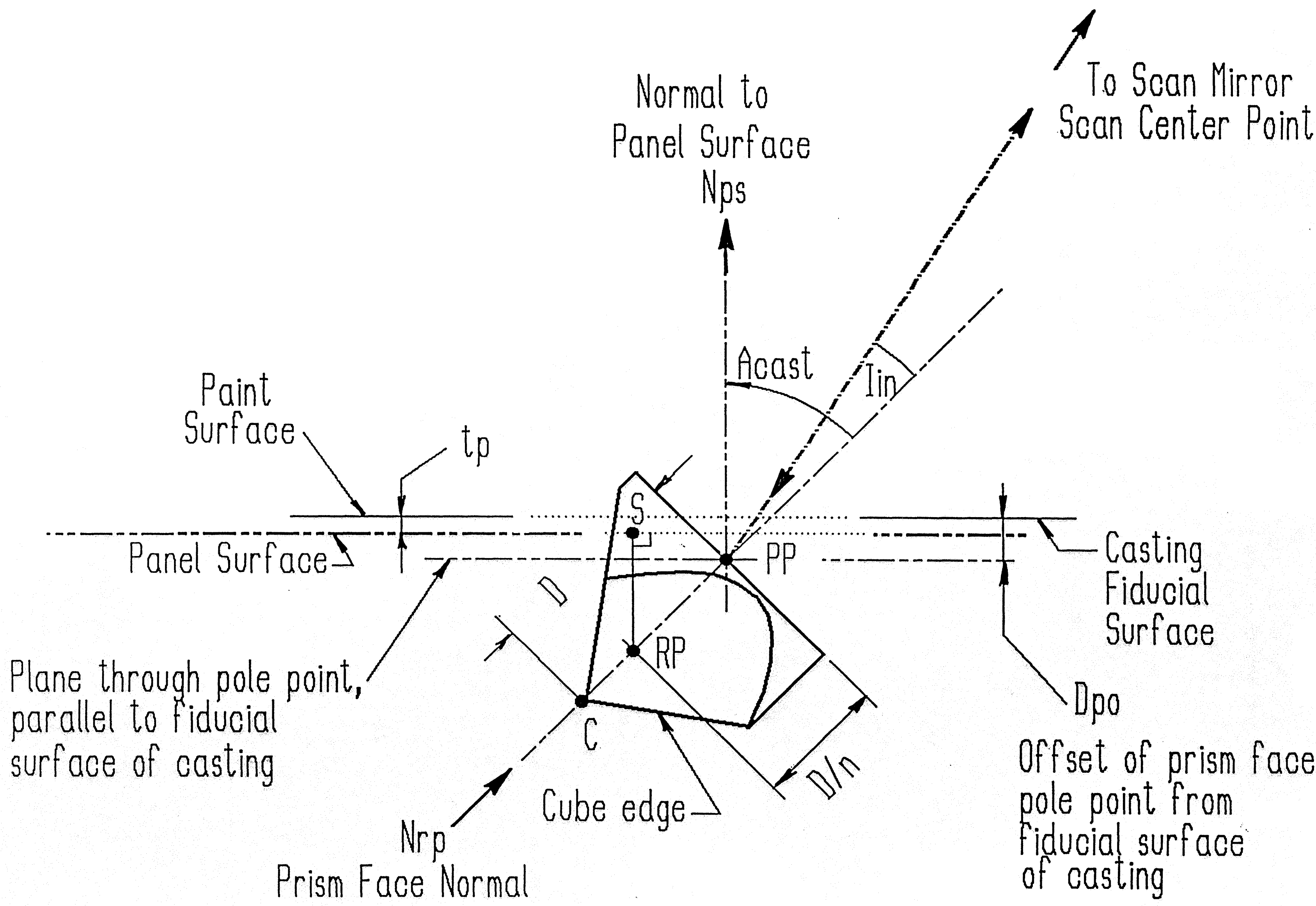


Figure 1. The Cube Retroprism Mount Casting



[n = Group Index of Glass/Group Index of Air]

Figure 2. Retroprism - Panel Surface Reflection Geometry.

plane of the casting rim coincides with the tangent plane to the panel surface locally where the casting is bolted to the panel. (Provided that the panel is locally unpainted in the area of contact between casting and panel. If the panel is painted, the casting rim plane is displaced parallel to the local panel tangent plane by the paint thickness.) There is then a surface footprint point of the optical reference point of the prism, whose coordinates and range can be found if the corresponding quantities for the prism reference point are known. Equations for these coordinates and ranges are given in Memo 154.

To describe the location of the telescope surface footprint point associated with a cube corner retroprism ,$\mathfrak{P}_i$, we define the following points and quantities associated with that prism, its casting, and the local panel surface (Fig. 1, Fig. 2):

C is the apex point of the prism, which is the intersection point of the cube faces.

S is the associated main reflector surface point, the surface footprint of the prism's optical reference point.

PP is the pole point (or pedal point), which is the foot of the perpendicular from the apex point C to the optical entry face of the prism.

D is the prism depth, which is the distance from C to PP.

n is the group refractive index of the prism glass relative to that of air, at the laser wavelength RP is a computed optical reference point for the prism. It lies on the line joining C to PP, at a distance D/n from PP.

A_{cast} is the angle between the prism entry face normal and the rim plane of the casting.

$Z\_PP \equiv D_{po}$ is the perpendicular distance from the pole point to the rim plane of the casting.

Z_RP is the perpendicular distance from the optical reference point to the rim plane of the casting.

If $\overrightarrow{N}_{ps}(\mathfrak{P}_i)$ is the unit normal vector- to the panel surface at prism $\mathfrak{P}_i$, and t_p is the paint thickness between the surface panel and the prism casting, then S is at a distance

(1.1) $D_{S,RP} = (D_{po} - t_p) + (D/n)\cos(A_{cast})$ from RP and the direction of displacement of S from RP is in the direction $\overrightarrow{N}_{ps}(\mathfrak{P}_i)$. The position of the associated surface point, expressed as a position vector, independent of any particular coordinate system, is:

(1.2) $$\overrightarrow{S} = \overrightarrow{RP} + (D_{S,RP})\overrightarrow{N}_{ps}(\mathfrak{P}_i) \; .$$

We also notice that

(1.3) $$D_{S,RP} = Z\_RP - t_p \; .$$

The quantities $\overrightarrow{N}_{ps}(\mathfrak{P}_i)$, t_p , A_{cast} , D and D_{po} determine the location of S with respect to RP The surface panel unit normal vector is known (to the accuracy needed for these corrections) from the nominal elevation and azimuth coordinates of the telescope tipping structure and the geometric model of the telescope. The local panel paint thickness will either be measured, or the surface paint layer will be masked and will not extend under the casting. The remaining three quantities are determined by the manufacture for each prism-casting assembly. When they have been determined one can relate measurements to the prism retroreflectors to points on the main reflector surface panels.

At present, approximately 1900 of the 2200 retroreflector-casting assemblies for the GBT main reflector surface have been fabricated. The assemblies are of three types, with $A_{cast} = 25°, 35°, 45°$ respectively. The fabrication of the remaining assemblies awaits a decision on the distribution among the types to be produced, based on a final choice of laser locations on the telescope feed arm.

The fixtured design values of D_{po} for the three casting shapes, calculated to be compatible with the castings' design drawings were:

$$
(1.4) \qquad \begin{array}{ll} D_{po} = +0.1250" , & A_{cast} = 25° , \\ D_{po} = +0.2000" , & A_{cast} = 35° , \\ D_{po} = +0.0400" , & A_{cast} = 45° . \end{array}
$$

The castings are specified in GBT design drawings D35420M083, M086, M087; prisms are specified in drawing D35420M063. The prism is cemented into the zinc-aluminum die casting, which is screw-fastened onto a surface panel of the telescope dish. The casting possesses a plane annular rim surface which rests on the painted surface of the panel. This rim surface is the primary locating reference surface for the panel. The fixturing and cementing procedures for manufacture of the assemblies are described in detail in [Go-2]. From the fixture design tolerances, and the clearances between the prisms and the prism hole wall of the castings, it was estimated *a-priori* that the expected standard error of D_{po} would be $\pm 0.0025"$.

During the initial production, for the 45° assemblies, it was found that a locating nose piece of the 45° assembly fixture was not tightened fully, and had slippage. This condition was rectified in subsequent assembly fabrication. The range of variation of D_{po} for those initial assemblies is larger than the expected standard error of 2.5 milli-inches. About half of the 45° samples measured by coordinate measuring machine were from this initial lot, and the rest were from a later lot that did not have slippage.

As part of the assembly manufacturing process, the prism depth D was measured. The measurement uses a surface plate, sine plate, gage blocks, vee block, and an indicator height gage. The vee block rests on the sine plate so that the vee edge is inclined at an angle $\cos^{-1}(\sqrt{\frac{2}{3}})$ to the surface plate. An end plate is bolted to the vee block, so that a retroprism may be placed in fixed position on the block. One of the prism's cube faces will then be parallel to the surface plate. The height of that face is measured. The prism is rotated by multiples of 120° to place each cube face in turn parallel to the surface plate, and the average face height above the plate is computed. A ball bearing of known diameter is substituted for the prism to establish a calibration constant. The prism depth can then be computed, independent of any direct measurement to its corner point. The method,due to D. Parker, is specified in GBT drawing D35420M153. An accuracy better than 0.2 milli-inches is expected for these measurements. The measured cube corner prism depth determined by this method, for an early run sample of 162 prisms, was $0.7414" \pm 0.0018"$.

After 1900 assemblies had been manufactured, it was decided that an independent outside measurement of the prism depth D , the distance $D_{po} (= Z\_PP)$ from the pole point to the casting rim plane, and the distance Z_PP from the optical reference point to the rim plane, for a statistically significant production sample, would provide valuable information for the rangefinder metrology program. A sample of about 60 to 70 prisms of each type would be sufficient to characterize the manufacturing variability of the prism assemblies and would also provide enough sample to relate range information to sufficiently many main reflector surface points to allow a useful fit or check measurement of main reflector surface geometry. The statistical results of these measurements provide a basis for a decision whether to measure the remaining assemblies by coordinate measurement machine, by a substitution laser ranging method, or (to save time and money) to use the measured assembly sample's mean values as estimators of the three distance variables for the remaining assemblies.

2 3-D COORDINATE MEASUREMENTS

A sample of 75 25°-assemblies, 67 35°-assemblies, 59 45°-assemblies was measured on a 3D coordinate measuring machine by Direct Dimensions, Inc., 1450 South Rolling Road, Baltimore MD. The machine was a counter-balanced, temperature compensated, six degree of freedom measurement arm containing optical encoders at each joint, manufactured by Faro Technologies, Inc., Lake Mary FL.

The prism-casting assemblies were bolted to a rectangular fixture block with accurately plane parallel faces and a cylindrical access hole and threaded screw holes to mount the casting rim flush with the block surface. The casting linear edge was set parallel to a perpendicular face of the fixture block.

An X,Y,Z coordinate system was established with respect to the fixture block plane face coincident with the casting's plane annular rim surface, the linear edge of the casting, and the midpoint of the fixture's cylindrical hole. The rim plane was defined to be the plane $Z = 0$. The linear casting edge direction was defined to be the X-axis. The Y-axis was defined to lie in the plane Z=0 and be perpendicular to the X-axis, so that the X,Y,Z axes in that order defined a right handed triple.

Using a ball end stylus at the end of the measurement arm, coordinates of points on the fixture block surface coincident with the casting rim were measured to define the casting rim plane. Coordinates of points on the four plane glass surfaces of the prism cemented into the fixtured casting were then measured, to establish the four prism face planes. Analytical equations describing the four prism face planes were than fitted to the measured prism surface points. The coordinates of the vertex point C, the pole point P and the optical reference point RP were then computed from the face plane equations. Length $D_{po} = Z\_PP$ is then equal to the Z-coordinate of pole point P, that is $Z(P) = D_{po} = Z\_PP$. Inb the same manner, $Z(RP) = Z\_RP$. The prism depth, D , was computed as the distance from C to P, using the measured coordinates of C and P. The coordinate measuring machine measurements give the following results.

For the 25-degree prisms (75 units):

Measured Quantity (inches)	D_{po} (Z_PP)	Z_RP	Prism Depth, D (Distance C-PP)
Average Value	0.12485	0.56613	0.73979
Sample Standard Deviation	0.00222	0.00246	0.00269
Maximum Value	0.12997	0.57188	0.74398
Minimum Value	0.11365	0.55597	0.73210
Maximum-Minimum	0.01632	0.01591	0.01188

For the 35-degree prisms (67 units):

Measured Quantity (inches)	D_{po} (Z_PP)	Z_RP	Prism Depth, D (Distance C-PP)
Average Value	0.20379	0.60693	0.73918
Sample Standard Deviation	0.00182	0.00223	0.00213
Maximum Value	0.20712	0.61164	0.74183
Minimum Value	0.19791	0.60097	0.73198
Maximum-Minimum	0.00921	0.01067	0.00985

For the 45-degree prisms (59 units):

Measured Quantity (inches)	D_{po} (Z_PP)	Z_RP	Prism Depth, D (Distance C-PP)
Average Value	0.04426	0.39160	0.74005
Sample Standard Deviation	0.00386	0.00518	0.00258
Maximum Value	0.05456	0.40227	0.74509
Minimum Value	0.03009	0.37690	0.74323
Maximum-Minimum	0.02447	0.02537	0.00186

For the sample of 201 prisms a comparison of the statistics of the vee block measurements of prism depth, D ,at NRAO, Green Bank versus those of prism depth re-measured for the prism-casting assembly, by the coordinate measurement machine, at Direct Dimensions, Inc., Baltimore, gives the following results:

Measured Quantity (inches)	D CMM Measurement	D Vee Block Measurement	Difference Vee Block minus CMM Measurement
Average Value	0.73966	0.74054	0.00087
Sample Standard Deviation	0.00251	0.00248	0.00047
Maximum Value	0.74509	0.7462	0.0026
Minimum Value	0.73198	0.7329	-0.00063
Maximum-Minimum	0.01311	0.0133	

Comparing the measured sample average values of D_{po} to the fixture design values (1.4) gives agreement to 0.2 milli-inch for the 25° assemblies, 3.8 milli-inch for the 35° assemblies, and 4.4 milli-inch for the 45° assemblies. Some of the difference is caused by the space between the prism and the casting. A difference in diameters is needed to insure that the cement film thickness is sufficient to prevent overstress of the cement during thermal cycling when the assemblies are on the telescope. Because of this, and because of the widths of the distributions of manufactured prism cylindrical surface and casting hole diameters, design of the assembly cementing fixturing to achieve precision centering of each prism in its casting hole was not practicable. Some freedom for the prism to move laterally on its locating nose piece was allowed in the fixture design. For the 45° assemblies, some of the difference was due to nose slippage. The difference of the fixture design and measured sample values of D_{po} reflect and are compatible with these considerations.

The range of measured values of D_{po} for each of the three assembly types is, clearly, too wide for one to employ the sample average as a correction value to relate the prism optical reference point to the associated surface panel point, if 100 μm surface range accuracy is to be achieved. Individual measurement values should be used for relating the prism's optical reference point to the associated panel surface point.

The question then arises, what is the accuracy of the measurements? To answer this question we have available a comparison of the individual measured values of the prism depth by the vee block method and by coordinate measuring machine We note that the depth measured by the coordinate measurement machine is determined by solving equations relating five planes, and is a more complex measurement than the simple vee block procedure. The statistics of the two types of measurement of D are given in the table above. The individual measurement differences are given in Fig. 3, versus assembly identification number.

The range of variation of prism depth is 13 milli-inches. Except for two outliers, the individual prism depth measured by the two methods tracks within 1.9 milli-inches. But there is a systematic difference between the two measurements. Vee block measurements are consistently larger than coordinate machine measurements. The average offset between the two measurements is 0.87 milli-inches; this magnitude of offset is surprisingly large. Also significant is the observation that the prism depth measured by coordinate machine is larger than the depth measured by vee block method for only four of the two hundred and one prisms. This suggests that there is a systematic offset error in at least one of the measurement procedures, in addition to the statistical errors of measurement. The sample standard deviations for the two methods of prism depth measurement are nearly the same: 2.51 milli-inches for coordinate machine measurements, and 2.48 milli-inches for vee block measurements. The standard deviation of the difference of depth measured by the two methods is 0.47 milli-inches. The calibration constant for the vee block procedure was remeasured subsequently, and agreed with the earlier measured value within 0.2 milli-inches.

The measurement results suggest that there is a systematic offset error in the coordinate machine measurement of prism depth of approximately 0.87 milli-inches and a random statistical standard error component of approximately 0.47 milli-inches. Apart from a very few outliers, whose identity numbers are known, the measurements of prism depth are known to two milli-inch accuracy. The accuracy of the pole point distance measurements should also be within two milli-inches, limited by the accuracy of the prism face plane determinations.

At the end of this note, the statistics of the coordinate machine measurements and vee block measurements-are presented versus the prism-assembly identification number, as a guide to investigating whether there are any significant variations in production quality dependent on casting type, assembly date or batch. No major dependence was observed except for some early-run 45 degree assembly outliers, where slippage of the fixturing nose was known to occur.

Measurement results for the individual assemblies are listed in Appendix A and Appendix B. A typical coordinate measurement machine output data listing sheet is included in Appendix C.

3 DISCUSSION

We now discuss the implications of the coordinate measurements with respect to the laser rangefinder program for the GBT main reflector surface. The measurement results for the 201 assembly sample lead to the following conclusions:

The distances of the optical reference point and prism pole point from the casting rim face have ranges of variation, depending on casting type, which are large (10 to 24 milli-inches) compared to the accuracy to which they are measured (about 2 milli-inches). About half of the variation is due to the range of prism manufactured depth and the rest due to the freedom of motion of the prism in its casting when cemented. One would like to determine the telescope panel surface points to accuracy of a few milli-inches. This means that one wants to know the individual prism assembly distances to a few milli-inches and one should then measure every one of the assemblies. Use of mean sample pole point distance and prism depth as parameters to specify the prism-to-surface corrections for the remaining (unmeasured) assemblies does not give the desired accuracy for surface point correction. If the prisms are individually measured, one will have the prism-to-surface correction to about two milli-inches, which is acceptable for the surface metrology. We strongly recommend that the remaining prism assemblies be measured individually.

It may be possible to measure the remaining assemblies by a substitutution method, instead of by coordinate measuring machine. A good measured prism would be fixtured in the laboratory, and ranged by laser rangefinder. The assembly to be measured would be substituted in the fixture, for the already-measured unit. The prism depth has been measured by the vee block method for all manufactured assemblies, and the relative differential range contribution components due to pole point distance and prism depth can be separated, and an appropriate prism-to-surface correction can be computed. This differential range method of obtaining the prism-to surface correction is not more accurate than the coordinate measurement machine method, because it includes an error component from the prism assembly chosen as the comparison reference standard.

If one considers the labor availability, labor cost, measurement time, software setup and evaluation time, and time involved in making measurements by the substitution method, it is not clear that the substitution method is superior to the coordinate measurement machine. Fixturing, software and automatic data recording are aready available for the coordinate measuring machine determinations. From a cost-benefit point of view, the latter would be preferable. Also, a comparison of prism depth measurements by coordinate machine and by vee block would be available as an independent accuracy check. For these reasons it is recommended that the remaining assemblies also be measured by coordinate measuring machine, if the price is not outrageous.

The present assembly measurements reveal some prism assemblies to be outliers, in the sense that they show larger discrepacies between vee block and CMM measurement of prism depth, and also lie far from the center of the distributions in prism depth and pole height distance from the rim. These assemblies show larger than average uncertainty in prism-to-surface correction. It is possible to use these assemblies in less critical locations on the telescope main reflector dish, that is, near the rim of the dish rather than near the center.

We also make the following final observation. If the error in the prism reference point to surface point correction is composed of a constant offset error of about one milli-inch compounded with a random measurement error component of about one half milli-inch, the offset contribution to the surface point range measurement will contribute to an error of one milli-inch in surface position, but not to an error in determination of surface shape.

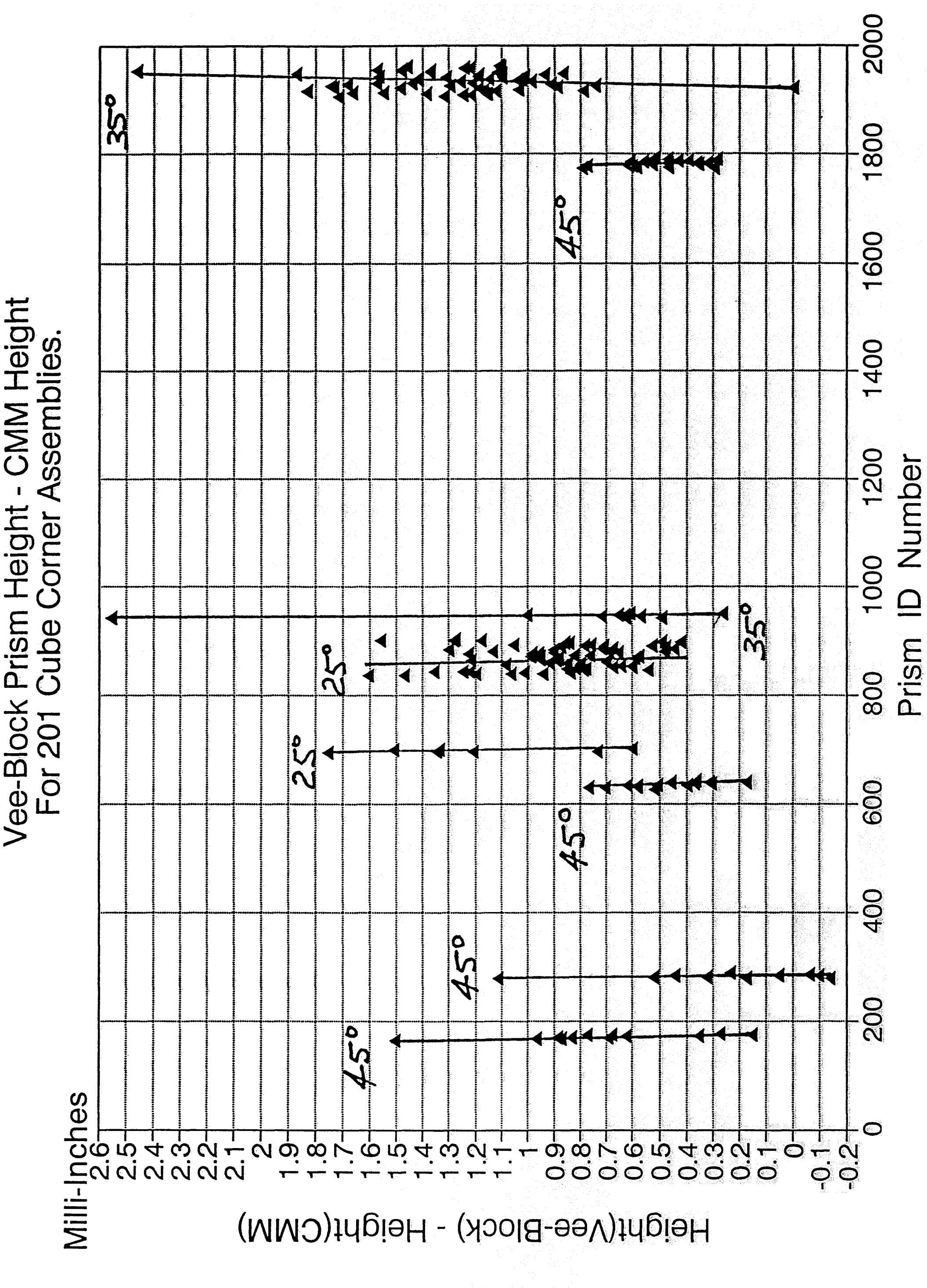

Vee-Block Prism Height - CMM Height
For 201 Cube Corner Assemblies.
Milli-Inches
Height(Vee-Block) - Height(CMM)
Prism ID Number
2.6
2.5
2.4
2.3
2.2
2.1
2
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
0
200
400
600
800
1000
1200
1400
1600
1800
2000
45°
45°
45°
25°
25°
35°
45°
35°

FIGURE 3.

BIBLIOGRAPHY:

[Go-1] M.A. Goldman, *GBT Dish Laser Range Measurement Corrections,* GBT Technical Report 154, June 25, 1996.

[Go-2] M.A. Goldman, *Notes On The Cementing Of Cube Corner Retroreflectors Into Their Castings,* GBT Archive Series Report L0105, August 2, 1996.

APPENDIX A.

File: ASSYSTAT.ASC May 5, 1997

Prism-casting assembly 3D CMM coordinate measurement results.

ID is the prism casting assembly identification number.

Z_PP is the normal distance from the prism entry face's pole point (foot of the perpendicular from the prism's vertex point to the entry face plane) to the plane of the casting's rim.

Z_RP is the normal distance of the prism's computed optical reference point to the plane of the casting's rim.

Dist C-PP is the CMM-measured distance from the prism's vertex point to the prism's pole point.

Distances are given in inches.
Results have not been rounded.

<----------45 Degree Prisms---------->
59 units

ID	Z_PP	Z_RP	Dist C-PP
165	0.040959	0.387894	0.742705
166	0.042769	0.387574	0.741597
167	0.046399	0.392160	0.741726
168	0.042025	0.388965	0.743130
169	0.039926	0.385841	0.744302
170	0.053745	0.396837	0.739109
171	0.054555	0.400155	0.736166
172	0.047158	0.395266	0.741747
173	0.042566	0.389198	0.742275
174	0.052826	0.396668	0.742319
175	0.045419	0.388906	0.742046
176	0.042646	0.387889	0.741624
177	0.053002	0.398153	0.743224
278	0.043517	0.387501	0.742337
279	0.044038	0.390356	0.745089
280	0.038525	0.384588	0.740725
281	0.044493	0.386040	0.739177
282	0.039537	0.382801	0.738274
283	0.040613	0.386304	0.743294
284	0.042455	0.387737	0.742443
285	0.030089	0.376904	0.742459
286	0.043100	0.389515	0.743418
287	0.040609	0.385177	0.739257

288	0.03946	0.384864	0.740067
627	0.044231	0.386335	0.734284
628	0.044061	0.388439	0.739231
629	0.045871	0.39084	0.740992
630	0.044147	0.386474	0.734227
631	0.045392	0.391074	0.741911
632	0.04175	0.386895	0.73912
633	0.042802	0.386542	0.73778
634	0.045449	0.389407	0.738502
635	0.046685	0.390426	0.736493
636	0.042414	0.385075	0.735496
637	0.047798	0.392577	0.740231
638	0.045708	0.390551	0.739943
639	0.047781	0.390154	0.735286
640	0.046335	0.391078	0.739323
641	0.044563	0.391633	0.744738
1773	0.043458	0.397760	0.740007
1774	0.043356	0.396615	0.740107
1775	0.043418	0.39554	0.736115
1776	0.04755	0.400051	0.739931
1777	0.042161	0.396019	0.740984
1778	0.046523	0.399098	0.740099
1779	0.048255	0.402269	0.740322
1780	0.043654	0.395595	0.740847
1781	0.049366	0.398147	0.734474
1782	0.044219	0.396	0.740831
1783	0.042943	0.391485	0.737538
1784	0.045565	0.396743	0.736078
1785	0.043271	0.396167	0.740588
1786	0.043045	0.397176	0.740339
1787	0.043785	0.397615	0.737966
1788	0.041982	0.395051	0.740169
1789	0.043808	0.395555	0.740508
1790	0.046373	0.396595	0.738328
1791	0.038974	0.390099	0.741214
1792	0.043959	0.396219	0.740381

<----------25 Degree Prisms---------->

75 units

ID	Z_PP	Z_RP	Dist C-PP
694	0.126573	0.563665	0.735047
695	0.125625	0.564211	0.737491
696	0.12679	0.568062	0.741562
697	0.124982	0.564448	0.737652
698	0.122249	0.562545	0.738088
699	0.126722	0.565652	0.737764
700	0.124686	0.564873	0.738498
837	0.129968	0.571457	0.741996
838	0.125472	0.567226	0.740127
839	0.128432	0.568364	0.741137

840	0.125170	0.566350	0.741202
841	0.124153	0.566976	0.742958
842	0.127312	0.569482	0.743088
843	0.125302	0.564088	0.736061
844	0.127408	0.566250	0.737846
845	0.127545	0.567605	0.740078
846	0.124235	0.565597	0.740455
847	0.125444	0.566787	0.741757
848	0.125211	0.566905	0.741411
849	0.121793	0.564627	0.741844
850	0.126857	0.568776	0.741621
851	0.122745	0.565575	0.741081
852	0.126218	0.566892	0.740826
853	0.123829	0.566206	0.741800
854	0.123756	0.560458	0.732101
855	0.128471	0.568474	0.737956
856	0.126676	0.563973	0.734495
857	0.120506	0.561817	0.739093
858	0.124908	0.566868	0.741217
859	0.123301	0.565647	0.740879
860	0.124519	0.566138	0.740698
861	0.123521	0.566464	0.741848
862	0.125580	0.567306	0.740882
863	0.123221	0.562004	0.734698
864	0.124559	0.562898	0.735404
865	0.128477	0.569671	0.740182
866	0.127601	0.569314	0.739797
867	0.124705	0.565370	0.739145
868	0.122980	0.565657	0.741614
869	0.125353	0.567198	0.741508
870	0.125073	0.567737	0.742708
871	0.12522	0.566401	0.740725
872	0.125037	0.568303	0.742609
873	0.123994	0.566402	0.741547
874	0.126760	0.566406	0.737635
875	0.124179	0.56536	0.738773
876	0.127753	0.568492	0.738640
877	0.123160	0.567305	0.738815
878	0.123358	0.566946	0.742675
879	0.122892	0.565182	0.740595
880	0.123417	0.569602	0.741543
881	0.120925	0.564937	0.74281
882	0.125689	0.568784	0.742467
883	0.123811	0.564877	0.738419
884	0.113645	0.555965	0.733097
885	0.126425	0.566624	0.737596
886	0.124834	0.567378	0.740781
887	0.125565	0.568171	0.741324
888	0.125535	0.567852	0.741451
889	0.124223	0.567387	0.741720
890	0.123214	0.56652	0.742723
891	0.12268	0.565664	0.742089
892	0.127758	0.571877	0.743975
893	0.123784	0.562340	0.734815
894	0.125782	0.562591	0.732845
895	0.124343	0.564740	0.738338
896	0.124385	0.565080	0.739155

897	0.123861	0.563242	0.735908
898	0.126689	0.569436	0.742540
899	0.123451	0.566368	0.742779
900	0.124351	0.566542	0.741408
901	0.124414	0.566360	0.741042
902	0.123665	0.563377	0.736420
903	0.124070	0.566440	0.741918
904	0.126617	0.567263	0.739722

<---------35 Degree Prisms---------->

ID	Z_PP	Z_RP	Dist C-PP
943	0.203053	0.604322	0.741408
944	0.20507	0.605239	0.739775
945	0.202031	0.602803	0.740748
946	0.20508	0.606259	0.741828
947	0.203062	0.604521	0.741577
948	0.202072	0.602986	0.741097
949	0.202757	0.604246	0.741546
950	0.203108	0.604804	0.741568
951	0.202954	0.601075	0.735587
952	0.202979	0.604566	0.741638
1907	0.200818	0.605141	0.738788
1908	0.202509	0.60596	0.736085
1909	0.197907	0.600968	0.734755
1910	0.203979	0.608735	0.740185
1911	0.20409	0.606694	0.739146
1912	0.203435	0.608241	0.738942
1913	0.201811	0.605203	0.738912
1914	0.202807	0.606143	0.740234
1915	0.205038	0.609784	0.740451
1916	0.200563	0.604026	0.738765
1917	0.202158	0.606831	0.739608
1918	0.203157	0.606733	0.740075
1919	0.204512	0.608927	0.740833
1920	0.206209	0.609728	0.739166
1921	0.205307	0.608396	0.740017
1922	0.202259	0.606113	0.738013
1923	0.205112	0.611533	0.7416
1924	0.202556	0.607067	0.739912
1925	0.204631	0.607932	0.739166
1926	0.203112	0.605196	0.737205
1927	0.207072	0.608308	0.733954
1928	0.2063	0.607846	0.733654
1929	0.205363	0.611642	0.740584
1930	0.206204	0.60874	0.735518
1931	0.204501	0.608076	0.739059
1932	0.204434	0.607557	0.739788
1933	0.206929	0.609156	0.739323
1934	0.206126	0.610177	0.740441
1935	0.203492	0.607134	0.740412

1936	0.207120	0.609530	0.740362
1937	0.204547	0.606556	0.739474
1938	0.205248	0.609437	0.740578
1939	0.204074	0.606667	0.739850
1940	0.203355	0.602686	0.731984
1941	0.204266	0.607775	0.740103
1942	0.204808	0.608305	0.739290
1943	0.206342	0.609179	0.739734
1944	0.20362	0.609595	0.740688
1945	0.206906	0.609601	0.739507
1946	0.202175	0.606986	0.739763
1947	0.201572	0.606769	0.740110
1948	0.202428	0.606214	0.737000
1949	0.206184	0.607207	0.734332
1950	0.206831	0.608270	0.734826
1951	0.203921	0.607784	0.739229
1952	0.205277	0.608944	0.739984
1953	0.199989	0.604902	0.740529
1954	0.203587	0.607838	0.739019
1955	0.202636	0.608181	0.740735
1956	0.202337	0.606559	0.739624
1957	0.20243	0.606701	0.740121
1958	0.201796	0.605761	0.738799
1959	0.203379	0.605953	0.739379
1960	0.203151	0.604535	0.737460
1961	0.202658	0.607815	0.741096
1962	0.205467	0.609564	0.740638
1963	0.203097	0.606149	0.739290

APPENDIX B

A comparison of prism depth measured by vee block and by coordinate measuring machine.

Assembly Identity Number (ID)	Prism Depth Measured By CMM D(CMM) Inches	Prism Depth Measured In Vee Block D(VBM) Inches	Difference D(VBM)-D(CMM) Milli-inches
165	0.74271	0.7425	-0.21
166	0.74160	0.7431	1.50
167	0.74173	0.7426	0.87
168	0.74313	0.7441	0.97
169	0.74430	0.7450	0.70
170	0.73911	0.7400	0.89
171	0.73617	0.7370	0.83
172	0.74175	0.7421	0.35
173	0.74228	0.7429	0.63
174	0.74232	0.7430	0.68
175	0.74205	0.7422	0.15
176	0.74162	0.7424	0.78
177	0.74322	0.7435	0.28
278	0.74234	0.7422	-0.14
279	0.74509	0.7462	1.11
280	0.74073	0.7409	0.18
281	0.73918	0.7397	0.52
282	0.73827	0.7386	0.33
283	0.74329	0.7432	-0.09
284	0.74244	0.7425	0.06
285	0.74246	0.7429	0.44
286	0.74342	0.7431	-0.32
287	0.73926	0.7392	-0.06
288	0.74007	0.7403	0.23
627	0.73428	0.7348	0.52
628	0.73923	0.7400	0.77
629	0.74099	0.7417	0.71
630	0.73423	0.7336	-0.63
631	0.74191	0.7425	0.59
632	0.73912	0.7397	0.58
633	0.73778	0.7384	0.62
634	0.73850	0.7389	0.40
635	0.73649	0.7370	0.51
636	0.73550	0.7358	0.30
637	0.74023	0.7406	0.37
638	0.73994	0.7404	0.46
639	0.73529	0.7356	0.31
640	0.73932	0.7395	0.18
641	0.74474	0.7451	0.36
694	0.73505	0.7368	1.75

695	0.73749	0.7387	1.21
696	0.74156	0.7423	0.74
697	0.73765	0.7390	1.35
698	0.73809	0.7396	1.51
699	0.73776	0.7391	1.34
700	0.73850	0.7391	0.60
837	0.74200	0.7436	1.60
838	0.74013	0.7416	1.47
839	0.74114	0.7422	1.06
840	0.74120	0.7424	1.20
841	0.74296	0.7439	0.94
842	0.74309	0.7441	1.01
843	0.73606	0.7369	0.84
844	0.73785	0.7392	1.35
845	0.74008	0.7413	1.22
846	0.74046	0.7417	1.25
847	0.74176	0.7423	0.54
848	0.74141	0.7422	0.79
849	0.74184	0.7427	0.86
850	0.74162	0.7424	0.78
851	0.74108	0.7419	0.82
852	0.74083	0.7415	0.67
853	0.74180	0.7424	0.60
854	0.73210	0.7329	0.80
855	0.73796	0.7386	0.64
856	0.73450	0.7351	0.61
857	0.73909	0.7399	0.81
858	0.74122	0.7423	1.08
859	0.74088	0.7418	0.92
860	0.74070	0.7415	0.80
861	0.74185	0.7427	0.85
862	0.74088	0.7418	0.92
863	0.73470	0.7354	0.70
864	0.73540	0.7363	0.90
865	0.74018	0.7414	1.22
866	0.73980	0.7405	0.70
867	0.73915	0.7401	0.96
868	0.74161	0.7425	0.89
869	0.74151	0.7424	0.89
870	0.74271	0.7433	0.59
871	0.74073	0.7413	0.58
872	0.74261	0.7436	0.99
873	0.74155	0.7425	0.95
874	0.73764	0.7384	0.77
875	0.73877	0.7396	0.83
876	0.7386	0.7396	0.96
877	0.73882	0.7398	0.99
878	0.74268	0.7439	1.23
879	0.74060	0.7415	0.91
880	0.74154	0.7422	0.657
881	0.74281	0.7435	0.69
882	0.74247	0.7436	1.13

883	0.73842	0.7389	0.48
884	0.73310	0.7344	1.30
885	0.73760	0.7385	0.90
886	0.74078	0.7415	0.72
887	0.74132	0.7420	0.68
888	0.74145	0.7419	0.45
889	0.74172	0.7422	0.48
890	0.74272	0.7436	0.88
891	0.74209	0.7428	0.71
892	0.74398	0.7445	0.53
893	0.73482	0.7356	0.79
894	0.73285	0.7339	1.06
895	0.73834	0.7391	0.76
896	0.73916	0.7400	0.85
897	0.73591	0.7357	-0.21
898	0.74254	0.7434	0.86
899	0.74278	0.7432	0.42
900	0.74141	0.7419	0.49
901	0.74104	0.7426	1.56
902	0.73642	0.7376	1.18
903	0.74192	0.7432	1.28
904	0.73972	0.7410	1.28
943	0.74141	0.7419	0.49
944	0.73978	0.7404	0.63
945	0.74075	0.7433	2.55
946	0.74183	0.7424	0.57
947	0.74158	0.7423	0.72
948	0.74110	0.7421	1.00
949	0.74155	0.7422	0.65
950	0.74157	0.7422	0.63
951	0.73559	0.7362	0.61
952	0.74164	0.7419	0.26
1773	0.74001	0.7408	0.79
1774	0.74011	0.7404	0.29
1775	0.73612	0.7367	0.59
1776	0.73993	0.7404	0.47
1777	0.74098	0.7416	0.62
1778	0.74010	0.7407	0.60
1779	0.74032	0.7411	0.78
1780	0.74085	0.7412	0.35
1781	0.73447	0.7350	0.53
1782	0.74083	0.7413	0.47
1783	0.73754	0.7379	0.36
1784	0.73608	0.7364	0.32
1785	0.74059	0.7412	0.61
1786	0.74034	0.7409	0.56
1787	0.73797	0.7384	0.43
1788	0.74017	0.7407	0.53
1789	0.74051	0.7409	0.39
1790	0.73833	0.7388	0.47

1791	0.74121	0.7415	0.29
1792	0.74038	0.7409	0.52
1907	0.73879	0.7405	1.71
1908	0.73609	0.7374	1.32
1909	0.73476	0.7360	1.25
1910	0.74019	0.7414	1.22
1911	0.73915	0.7403	1.15
1912	0.73894	0.7401	1.16
1913	0.73891	0.7403	1.39
1914	0.74023	0.7419	1.67
1915	0.74045	0.7420	1.55
1916	0.73877	0.7406	1.84
1917	0.73961	0.7404	0.79
1918	0.74008	0.7412	1.13
1919	0.74083	0.7420	1.17
1920	0.73917	0.7402	1.03
1921	0.74002	0.7415	1.48
1922	0.73801	0.7392	1.19
1923	0.74160	0.7416	0.00
1924	0.73991	0.7408	0.89
1925	0.73917	0.7409	1.73
1926	0.73721	0.7385	1.30
1927	0.73395	0.7347	0.75
1928	0.73365	0.7354	1.75
1929	0.74058	0.7415	0.92
1930	0.73552	0.7372	1.68
1931	0.73906	0.7405	1.44
1932	0.73979	0.7410	1.21
1933	0.73932	0.7409	1.58
1934	0.74044	0.7417	1.26
1935	0.74041	0.7414	0.99
1936	0.74036	0.7414	1.04
1937	0.73947	0.7405	1.03
1938	0.74058	0.7420	1.42
1939	0.73985	0.7410	1.15
1940	0.73198	0.7334	1.42
1941	0.74010	0.7412	1.10
1942	0.73929	0.7406	1.31
1943	0.73973	0.7413	1.57
1944	0.74069	0.7417	1.01
1945	0.73951	0.7407	1.19
1946	0.73976	0.7407	0.94
1947	0.74011	0.7413	1.19
1948	0.73700	0.7381	1.10
1949	0.73433	0.7352	0.88
1950	0.73483	0.7367	1.87
1951	0.73923	0.7406	1.37
1952	0.73998	0.7411	1.12
1953	0.74053	0.7419	1.37
1954	0.73903	0.7405	1.48
1955	0.74074	0.7432	2.47
1956	0.73962	0.7412	1.58
1957	0.74012	0.7416	1.48
1958	0.73880	0.7399	1.10
1959	0.73938	0.7406	1.22
1960	0.73746	0.7387	1.24
1961	0.74110	0.7422	1.10
1962	0.74064	0.7421	1.46
1963	0.73929	0.7404	1.11

APPENDIX C.

Coordinate Measurement Results For NRAO Green Bank

Cube Corner Prism-Casting Assemblies

April 1997

Notation:

CF1, CF2, CF3 are cube face planes of the prism.

EF is the optical entry face plane of the prism.

The equation of a plane is $aX + bY + cZ = d$

The equation of the casting's rim reference plane is: $Z = 0$

The rectangular coordinates of a point are X,Y,Z. Coordinate Z is perpendicular to the casting's rim plane.

The casting's edge is parallel to the X-axis.

C is the apex point, which is the intersection point of the cube faces.

PP is the pedal point, which is the foot of the perpendicular from the apex point C to the optical entry face of the prism.

RP is a computed fiducial reference point for the prism. The coordinates of RP are defined by the following equations:

$$X(RP) = (0.657562)*X(C) + (0.342438)*X(PP)$$

$$Y(RP) = (0.657562)*Y(C) + (0.342438)*Y(PP)$$

$$Z(RP) = (0.657562)*Z(C) + (0.342438)*Z(PP)$$

where $1.0/.657562 = 1.527077$, which is the group index of the BK7 prism glass relative to that of air.

CUBE PRISM ID:
0165 (Degree Prism)

	a	b	c	d
EF	-0.703807	-0.002507	0.710387	0.176461
CF1	0.983402	0.044861	0.175807	-0.619945
CF2	-0.085474	-0.682805	0.725584	0.474214
CF3	-0.149917	0.728660	0.668266	0.490677

	X	Y	X (Inches)
Apex Point (C)	-0.732114	0.001327	0.568567
Pedal Point (PP)	-0.209393	0.003189	0.040959
Computed RP	-0.553115	0.001965	0.387894

EF Plane Normal	Theta X	Theta Y	Theta Z (Degrees)
Angle to Axis	134.733261	90.143654	44.733627
Distance (inches) from (C) to (PP):		0.742705	

CUBE PRISM ID:
0166 (Degree Prism)

	a	b	c	d
EF	-0.707132	-0.000567	0.707081	0.179039
CF1	0.985868	-0.003162	0.167492	-0.629463
CF2	-0.120720	-0.707715	0.696108	0.482210
CF3	-0.116613	0.706326	0.698216	0.482962

	X	Y	X (Inches)
Apex Point (C)	-0.734833	0.001820	0.567138
Pedal Point (PP)	-0.210426	0.002241	0.042769
Computed RP	-0.555256	0.001964	0.387574

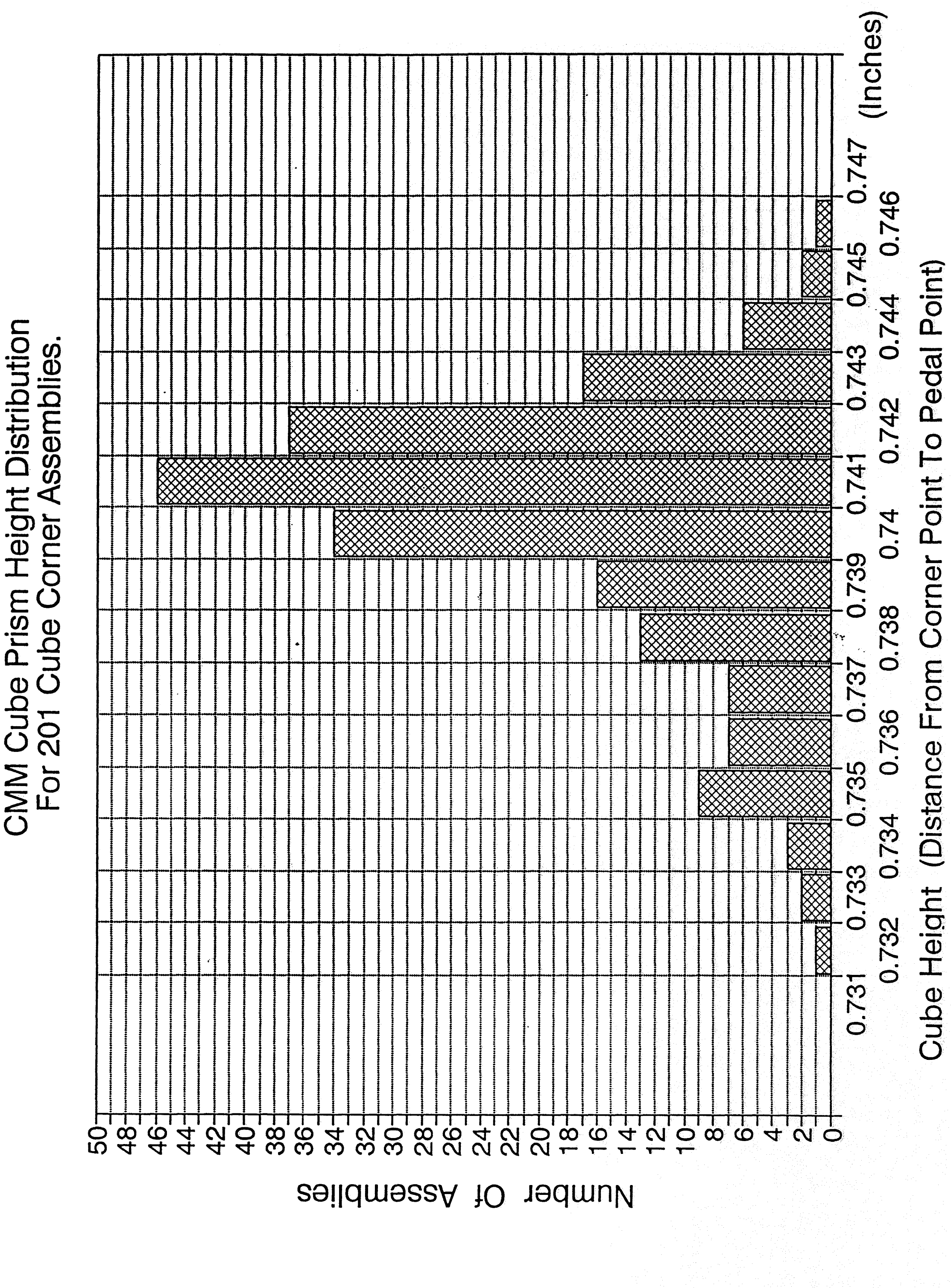
EF Plane Normal	Theta X	Theta Y	Theta Z (Degrees)
Angle to Axis	135.002045	90.032501	45.002056
Distance (inches) from (C) to (PP):		0.741597	

CUBE PRISM ID:
0167 (Degree Prism)

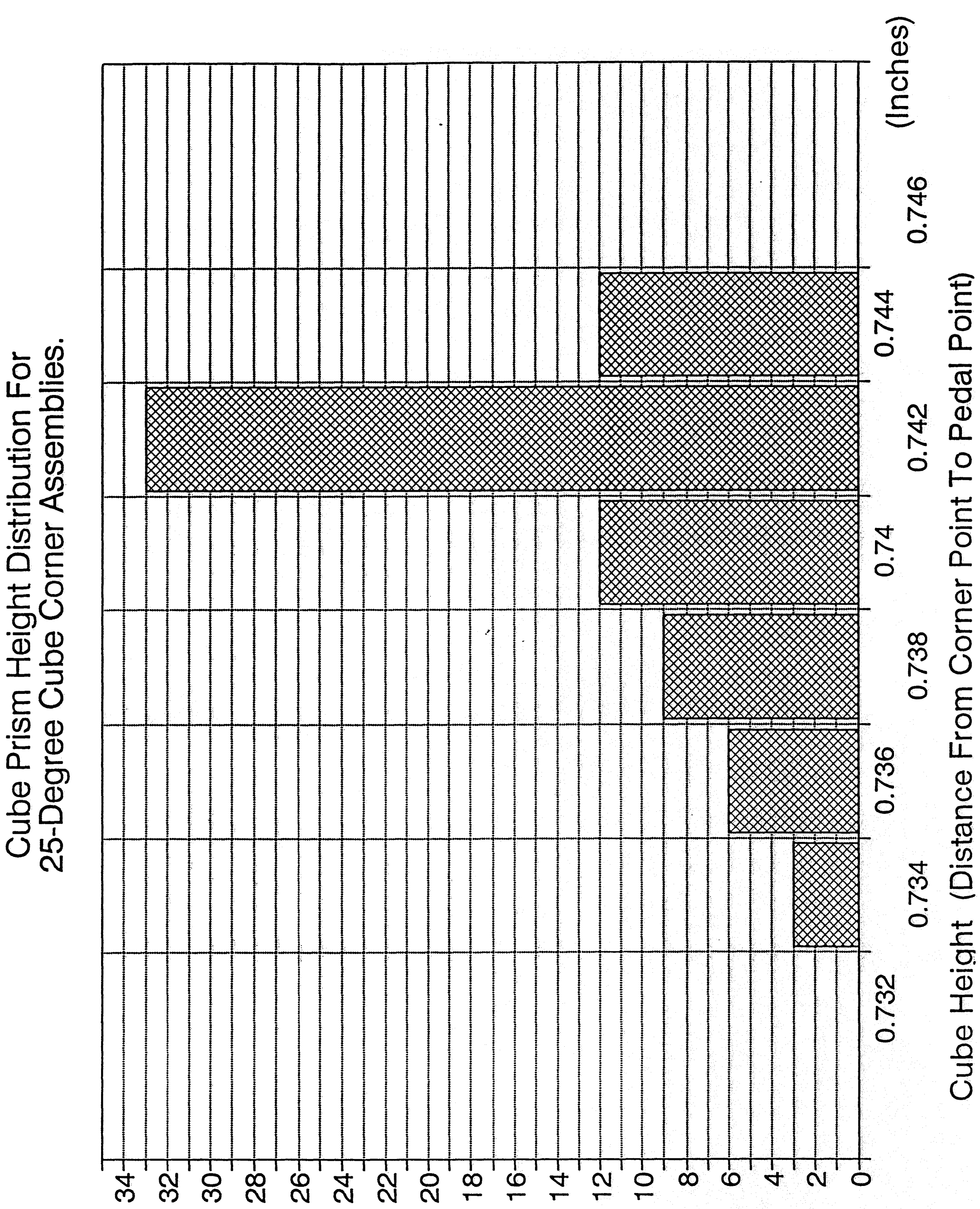
	a	b	c	d
EF	-0.705291	0.000400	0.708918	0.185093
CF1	0.985800	-0.005389	0.167838	-0.632424
CF2	-0.121935	-0.710296	0.693262	0.482789
CF3	-0.115419	0.704314	0.700443	0.490072

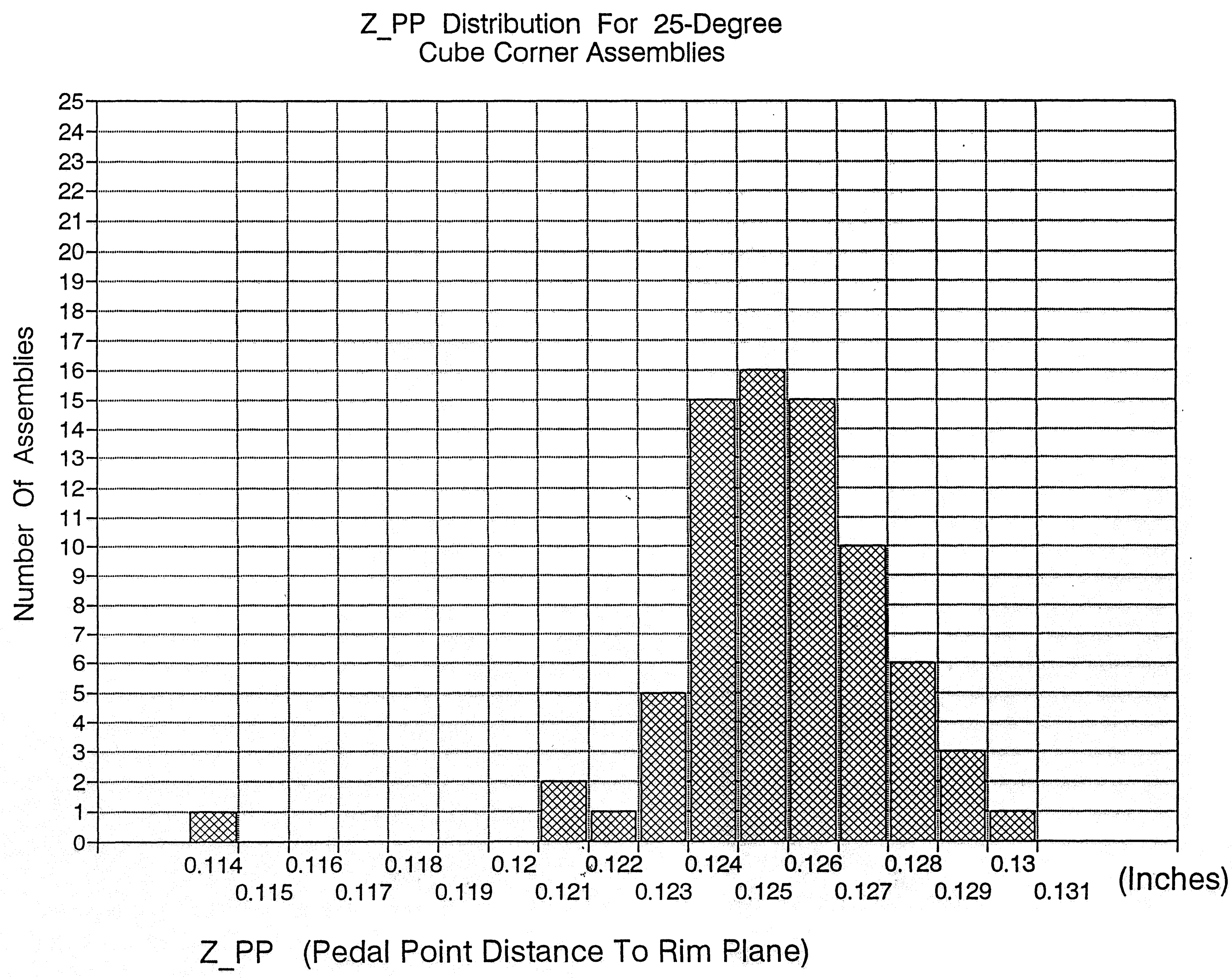
	X	Y	X (Inches)
Apex Point (C)	-0.738927	0.005647	0.572222
Pedal Point (PP)	-0.215794	0.005351	0.046399
Computed RP	-0.559786	0.005546	0.392160

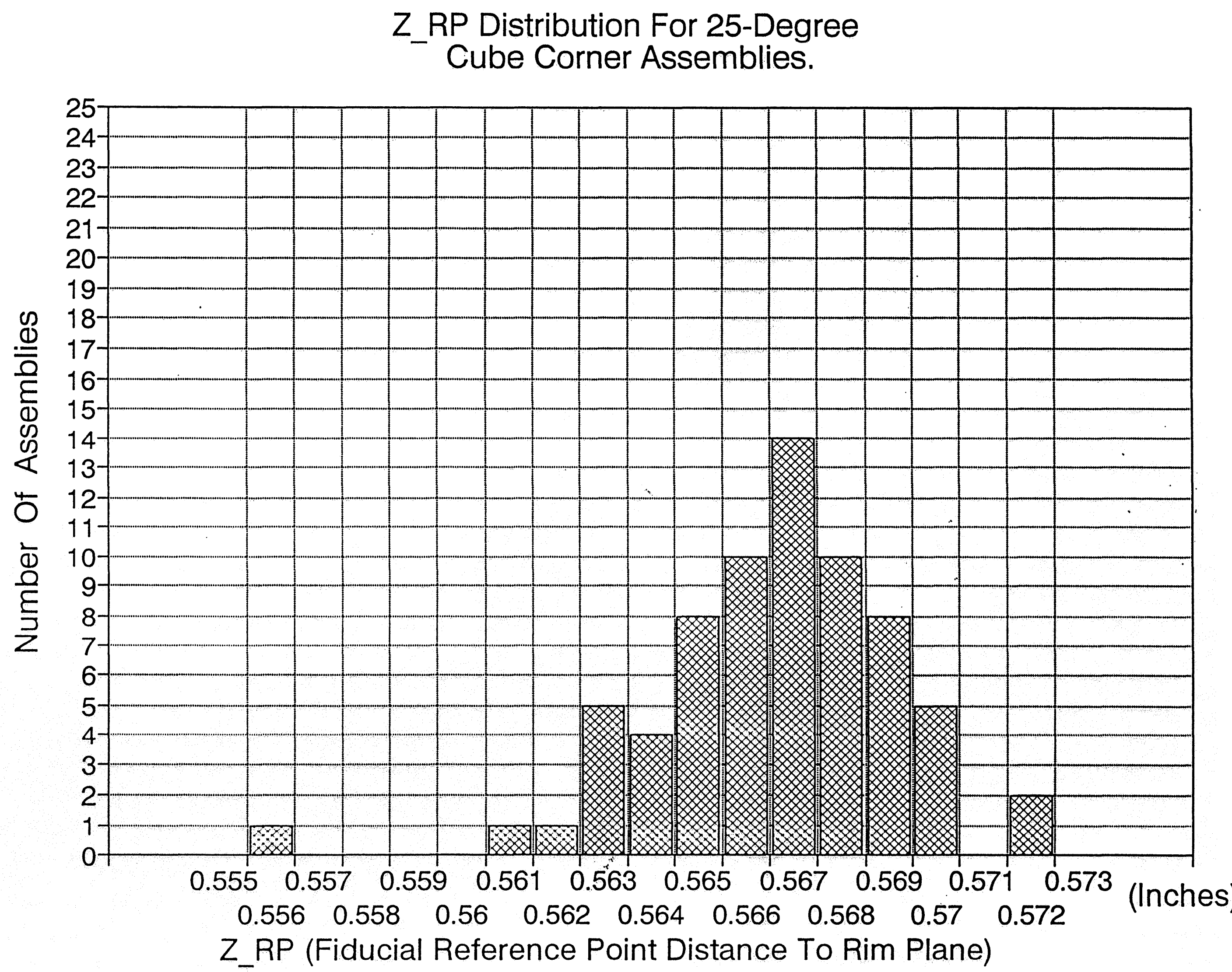
EF Plane Normal	Theta X	Theta Y	Theta Z (Degrees)
Angle to Axis	134.853073	89.977104	44.853077
Distance (inches) from (C) to (PP):		0.741726	



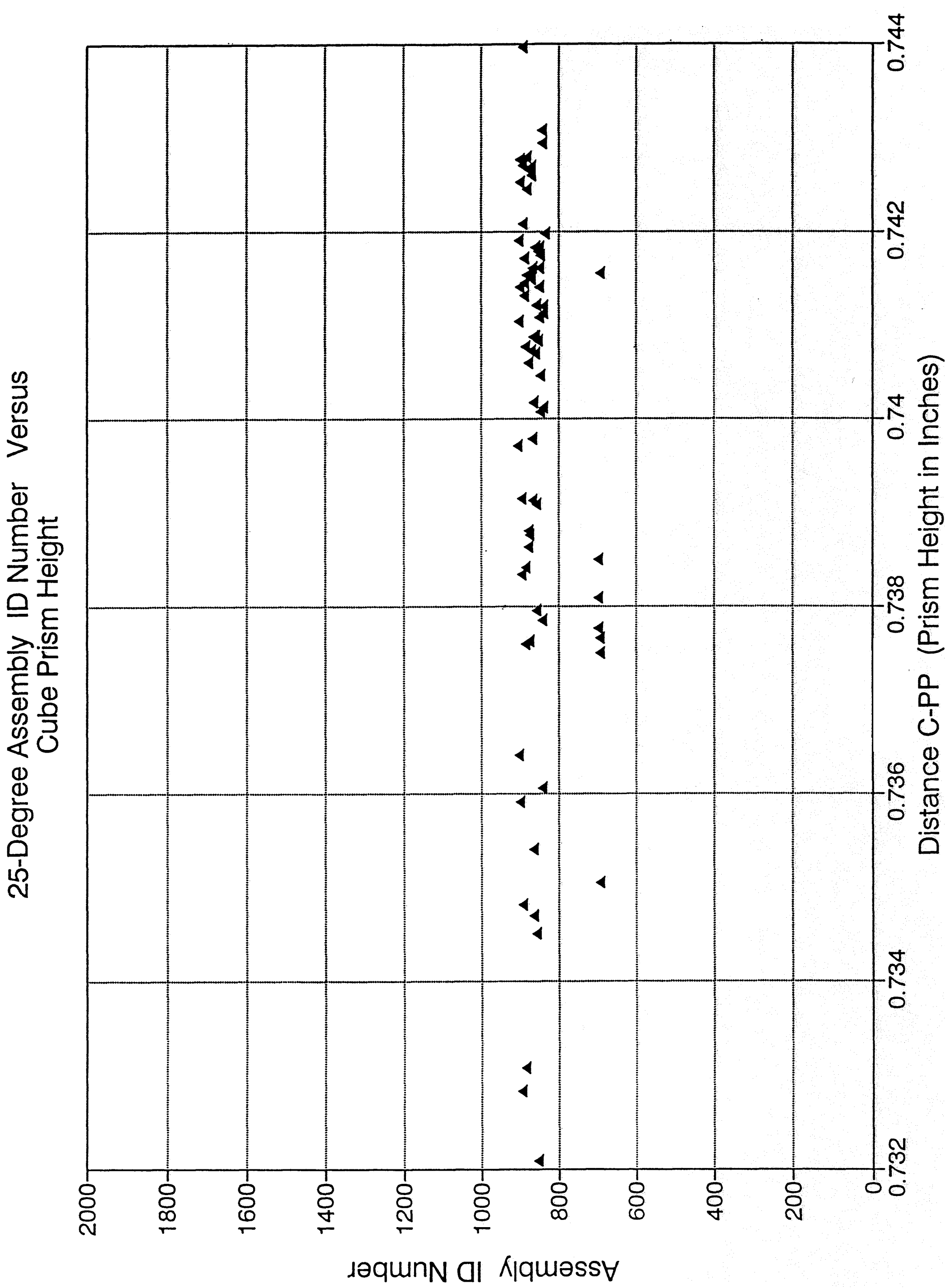
CMM Cube Prism Height Distribution
For 201 Cube Corner Assemblies.
Number Of Assemblies
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40
42
44
46
48
50
0.731
0.732
0.733
0.734
0.735
0.736
0.737
0.738
0.739
0.74
0.741
0.742
0.743
0.744
0.745
0.746
0.747
(Inches)
Cube Height (Distance From Corner Point To Pedal Point)


Cube Prism Height Distribution For
25-Degree Cube Corner Assemblies.
Number Of Assemblies
34
32
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
0.732
0.734
0.736
0.738
0.74
0.742
0.744
0.746
(Inches)
Cube Height (Distance From Corner Point To Pedal Point)

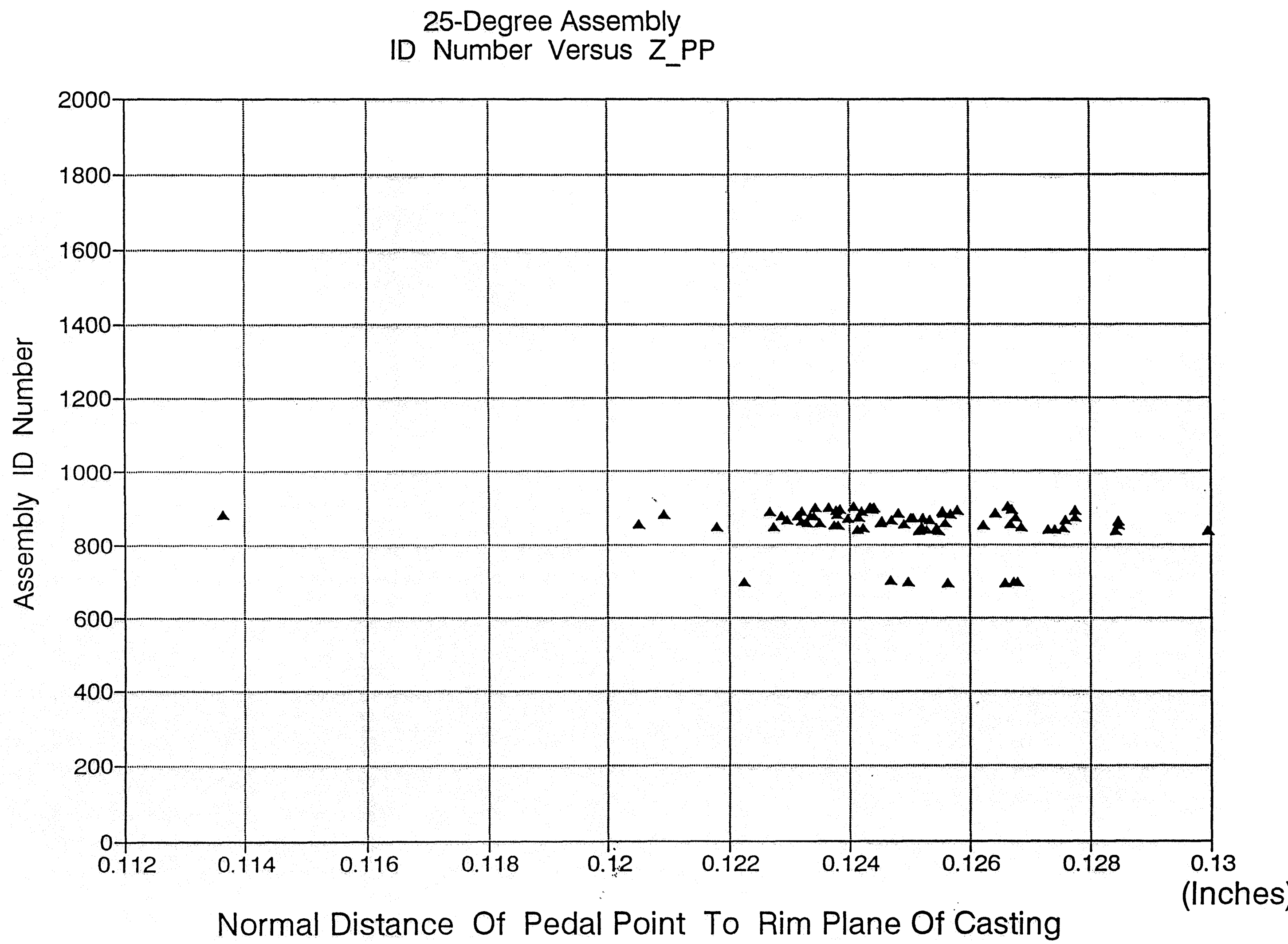

Z_PP Distribution For 25-Degree
Cube Corner Assemblies
Number Of Assemblies
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
0.114
0.115
0.116
0.117
0.118
0.119
0.12
0.121
0.122
0.123
0.124
0.125
0.126
0.127
0.128
0.129
0.13
0.131
(Inches)
Z_PP (Pedal Point Distance To Rim Plane)



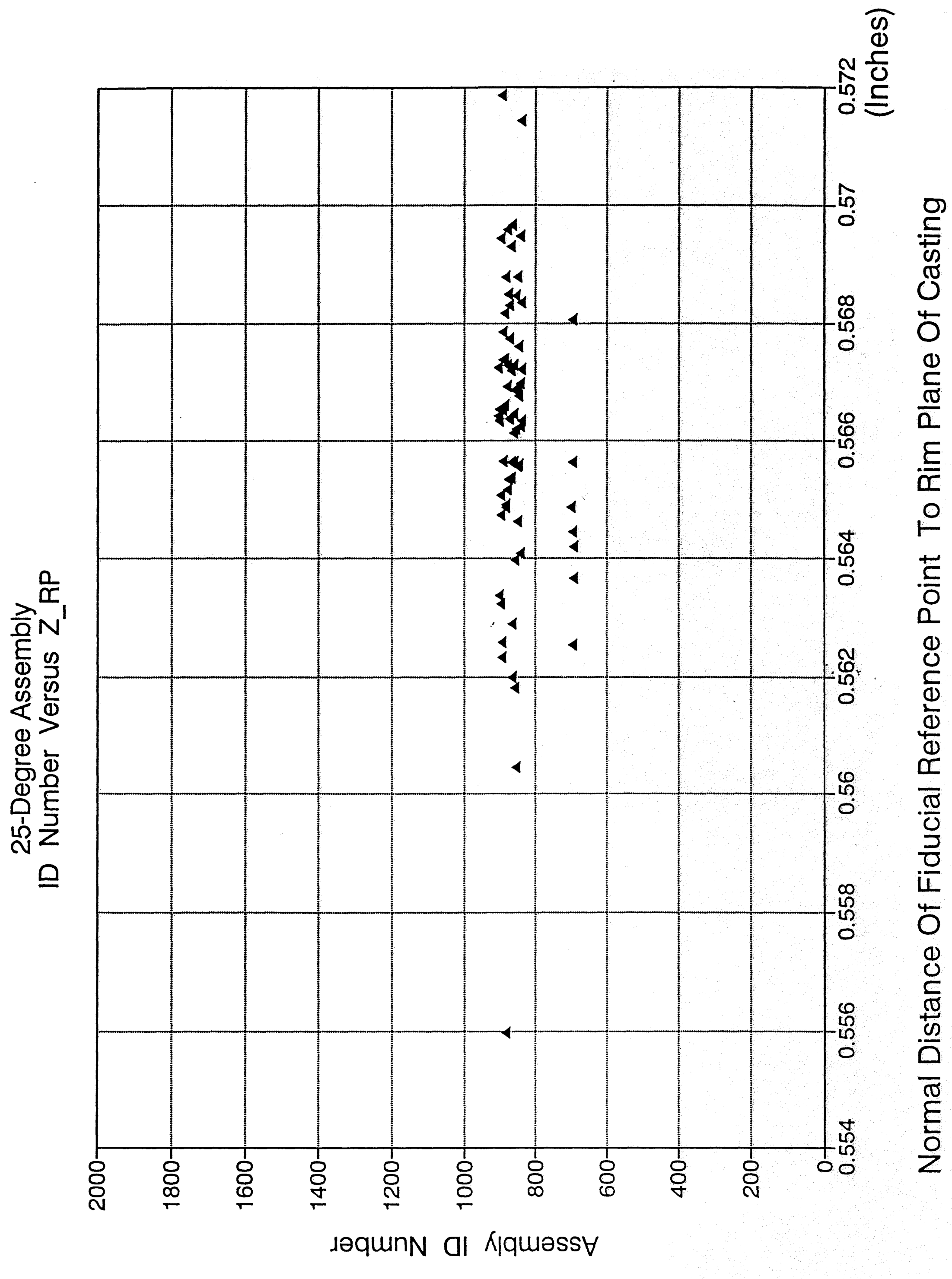
Z_RP Distribution For 25-Degree
Cube Corner Assemblies.
Number Of Assemblies
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
0.555
0.556
0.557
0.558
0.559
0.56
0.561
0.562
0.563
0.564
0.565
0.566
0.567
0.568
0.569
0.57
0.571
0.572
0.573
(Inches)
Z_RP (Fiducial Reference Point Distance To Rim Plane)

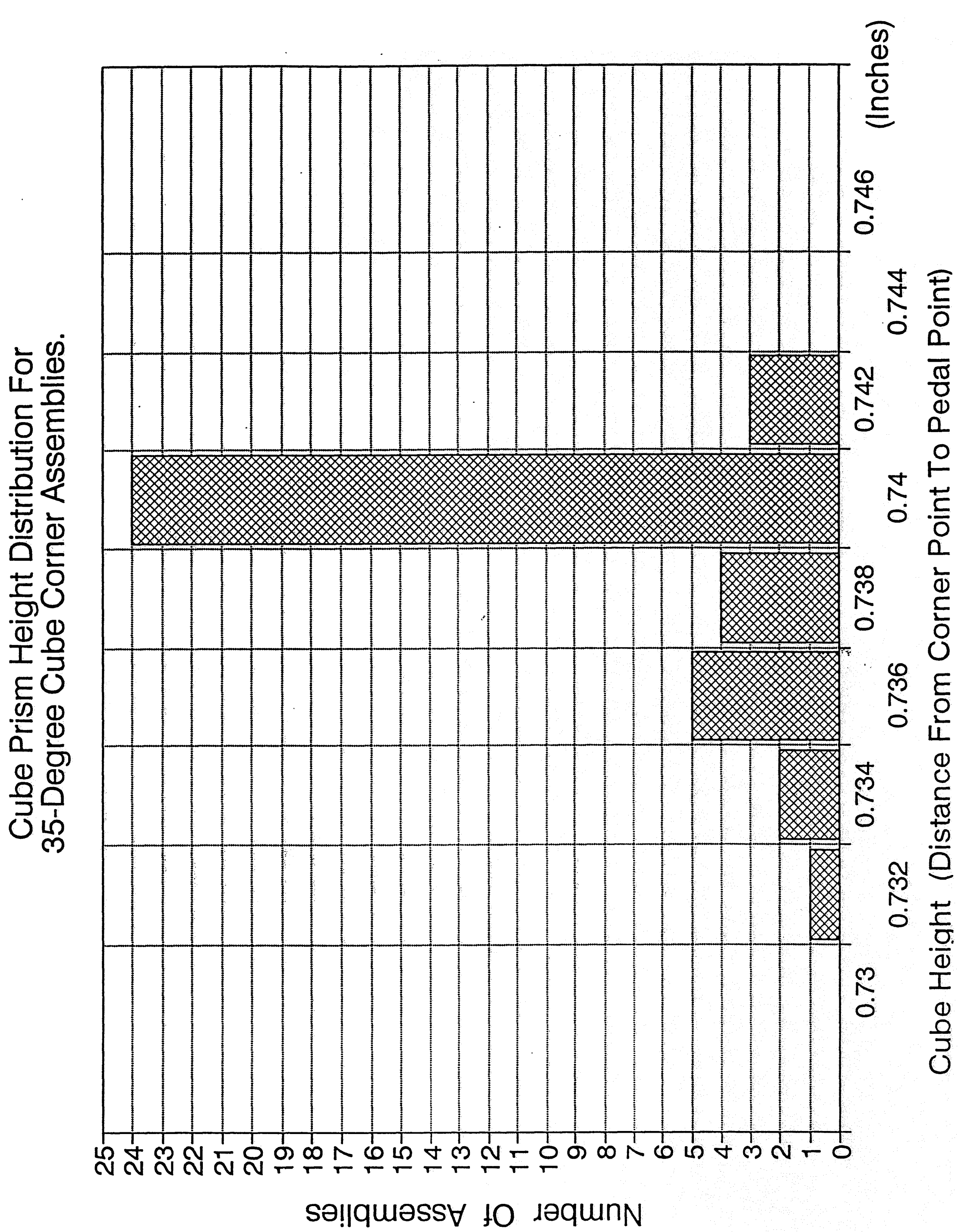


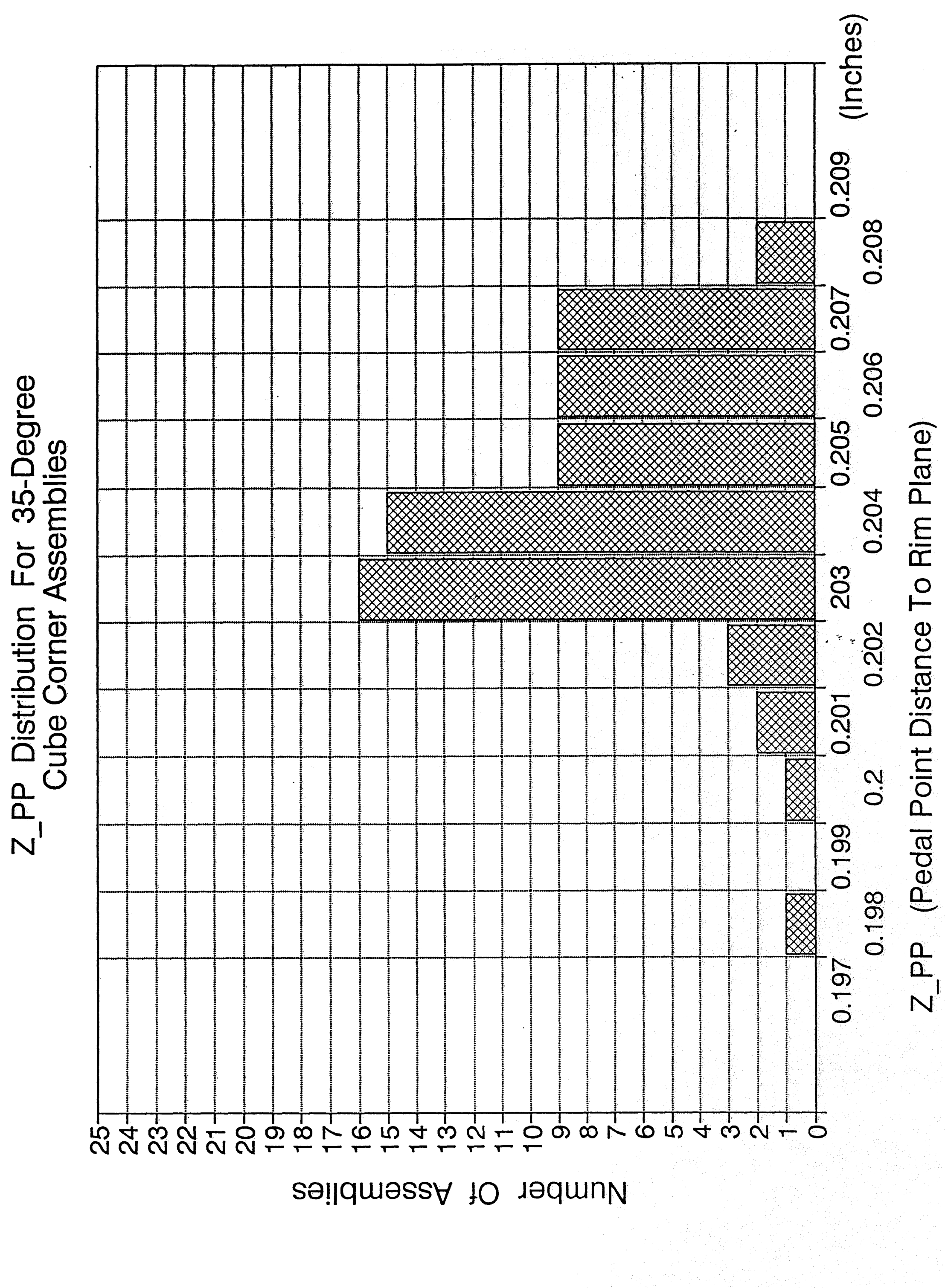
25-Degree Assembly ID Number Versus
Cube Prism Height
Assembly ID Number
Distance C-PP (Prism Height in Inches)
0
200
400
600
800
1000
1200
1400
1600
1800
2000
0.732
0.734
0.736
0.738
0.74
0.742
0.744



25-Degree Assembly
ID Number Versus Z_PP
Assembly ID Number
2000
1800
1600
1400
1200
1000
800
600
400
200
0
0.112
0.114
0.116
0.118
0.12
0.122
0.124
0.126
0.128
0.13
(Inches)
Normal Distance Of Pedal Point To Rim Plane Of Casting

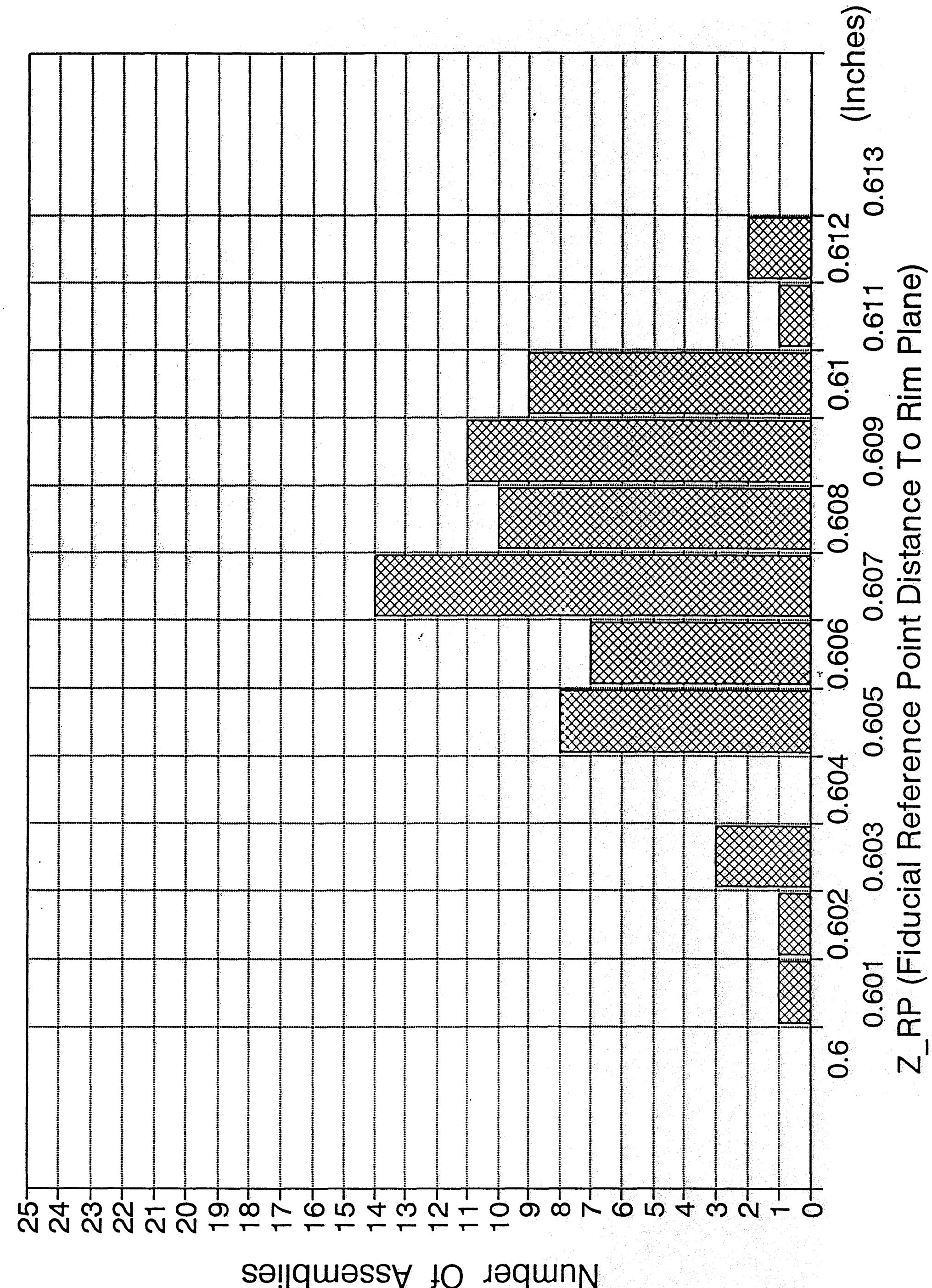

25-Degree Assembly
ID Number Versus Z_RP
Assembly ID Number
2000
1800
1600
1400
1200
1000
800
600
400
200
0
0.554
0.556
0.558
0.56
0.562
0.564
0.566
0.568
0.57
0.572
(Inches)
Normal Distance Of Fiducial Reference Point To Rim Plane Of Casting


Cube Prism Height Distribution For
35-Degree Cube Corner Assemblies.
Number Of Assemblies
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
0.73
0.732
0.734
0.736
0.738
0.74
0.742
0.744
0.746
(Inches)
Cube Height (Distance From Corner Point To Pedal Point)

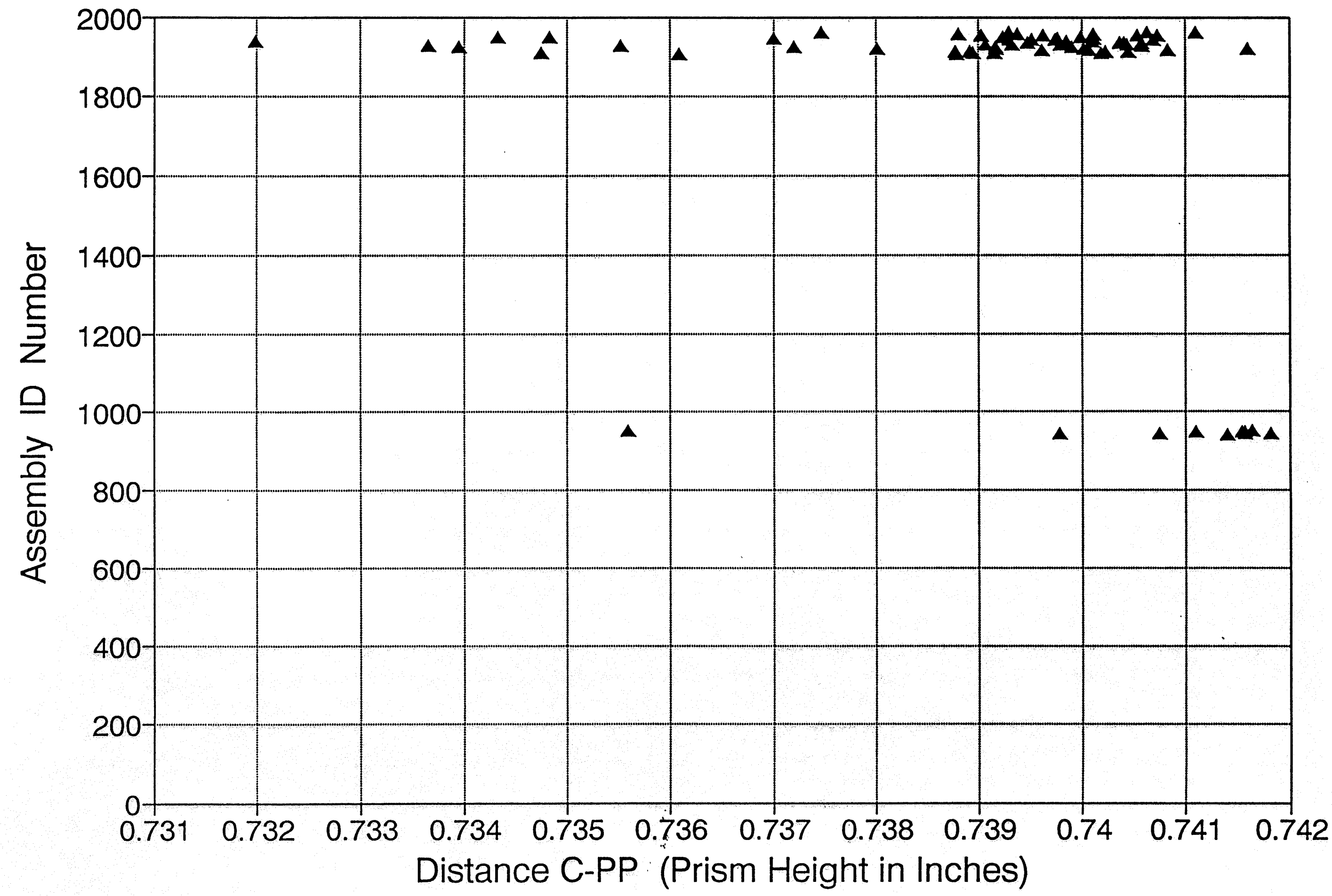


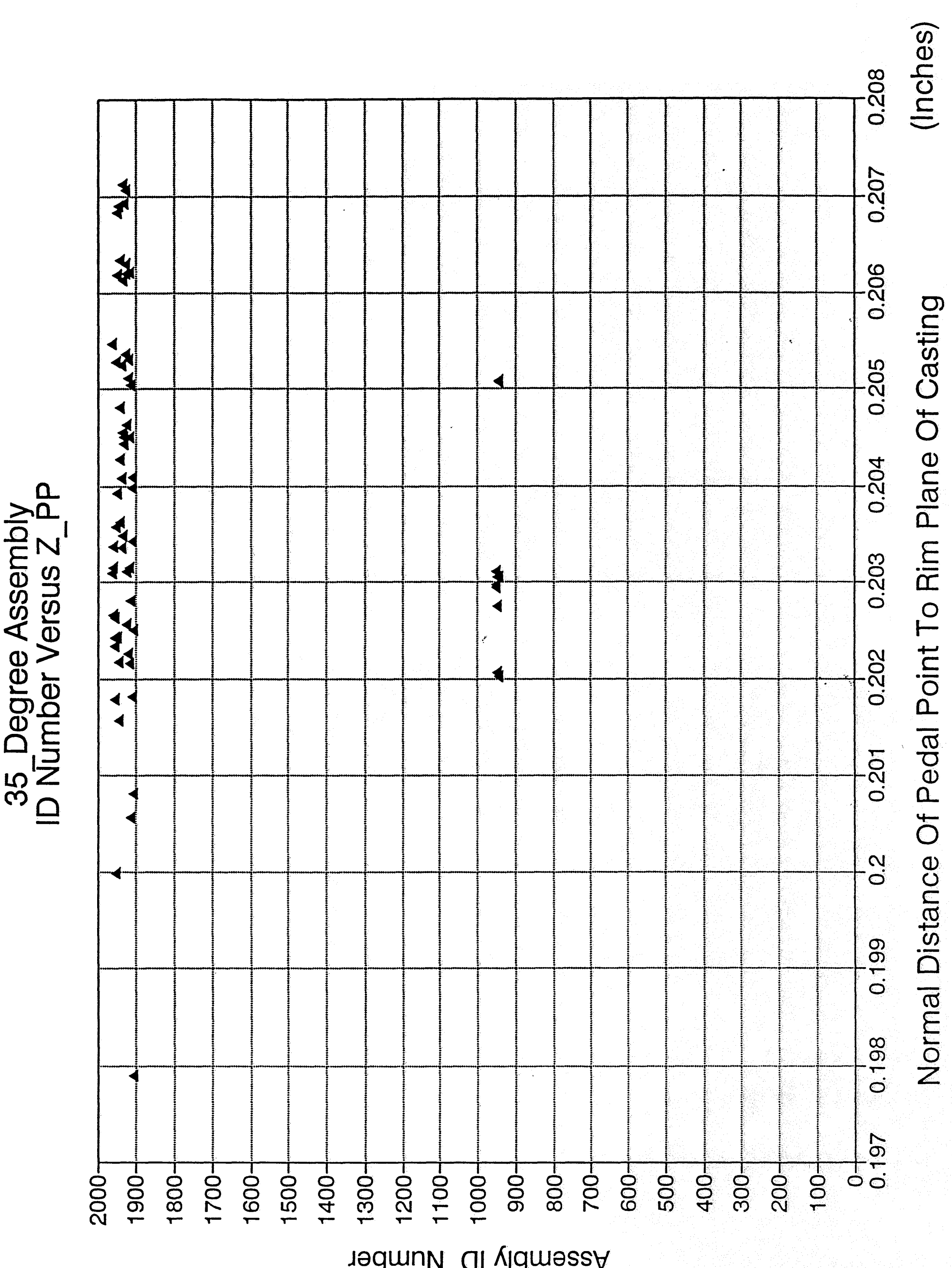
Z_PP Distribution For 35-Degree
Cube Corner Assemblies
Number Of Assemblies
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
0.197
0.198
0.199
0.2
0.201
0.202
203
0.204
0.205
0.206
0.207
0.208
0.209
(Inches)
Z_PP (Pedal Point Distance To Rim Plane)

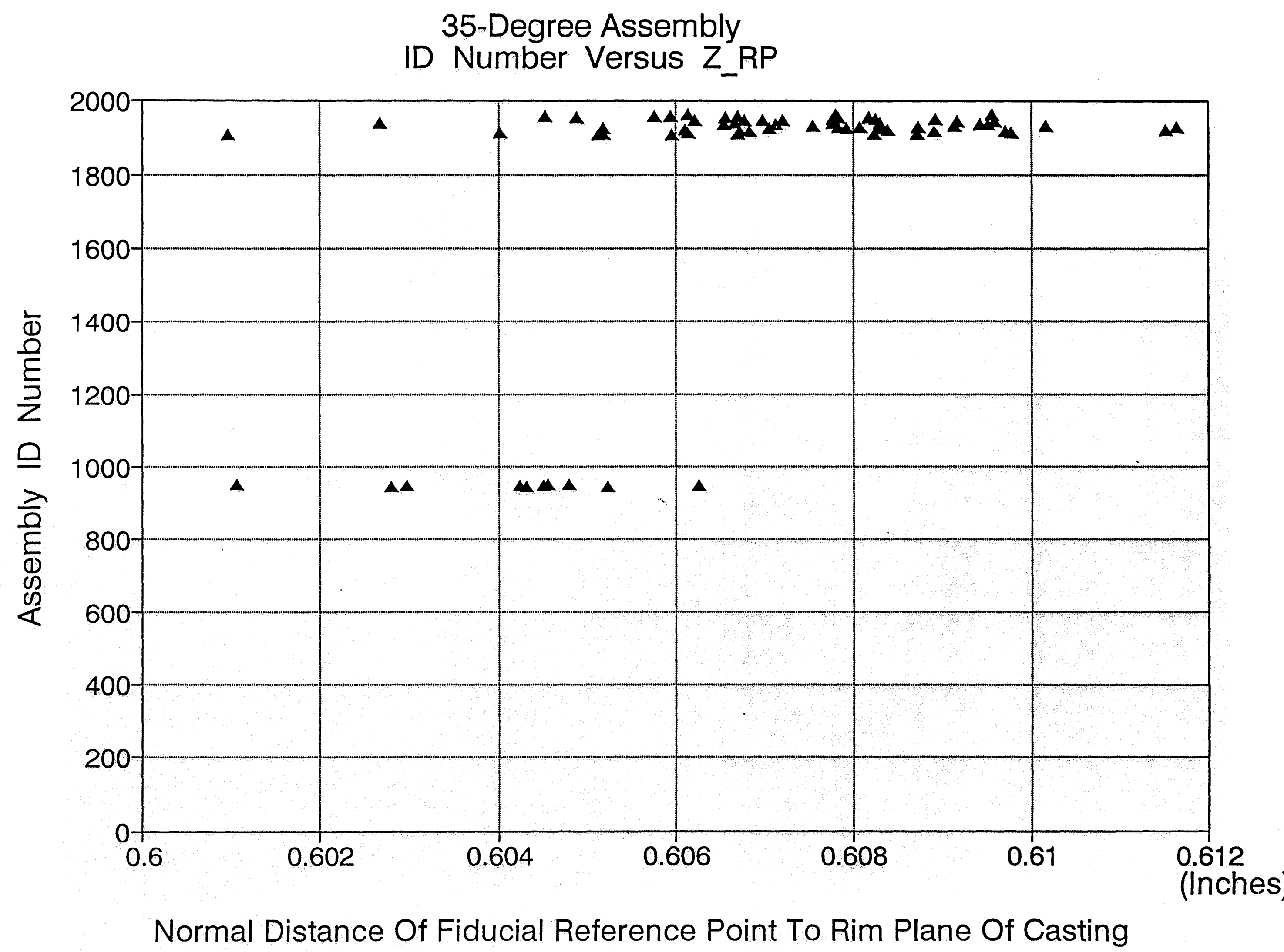
Z_RP Distribution For 35-Degree Cube Corner Assemblies.

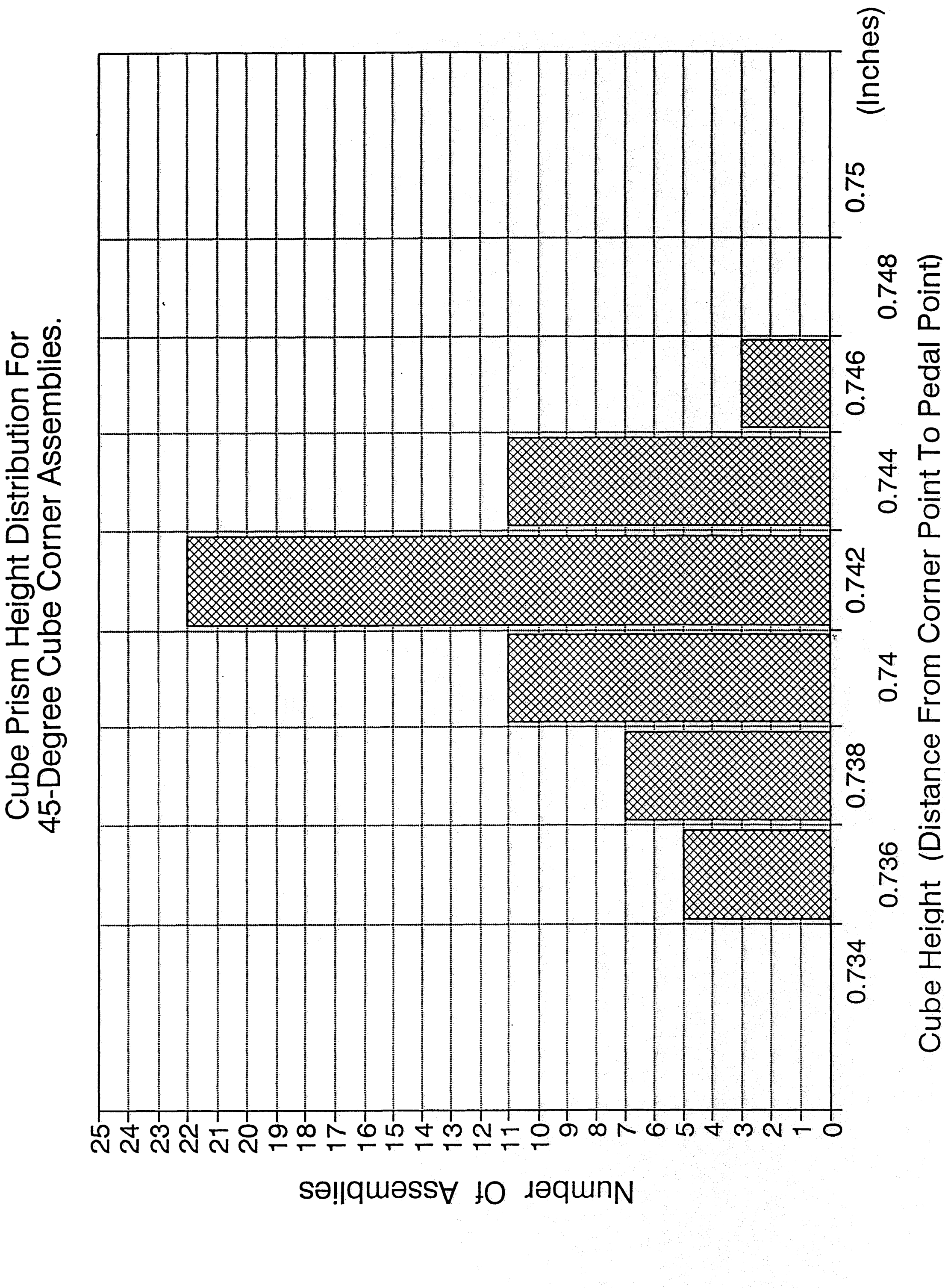


35-Degree Assembly ID Number Versus
Cube Prism Height

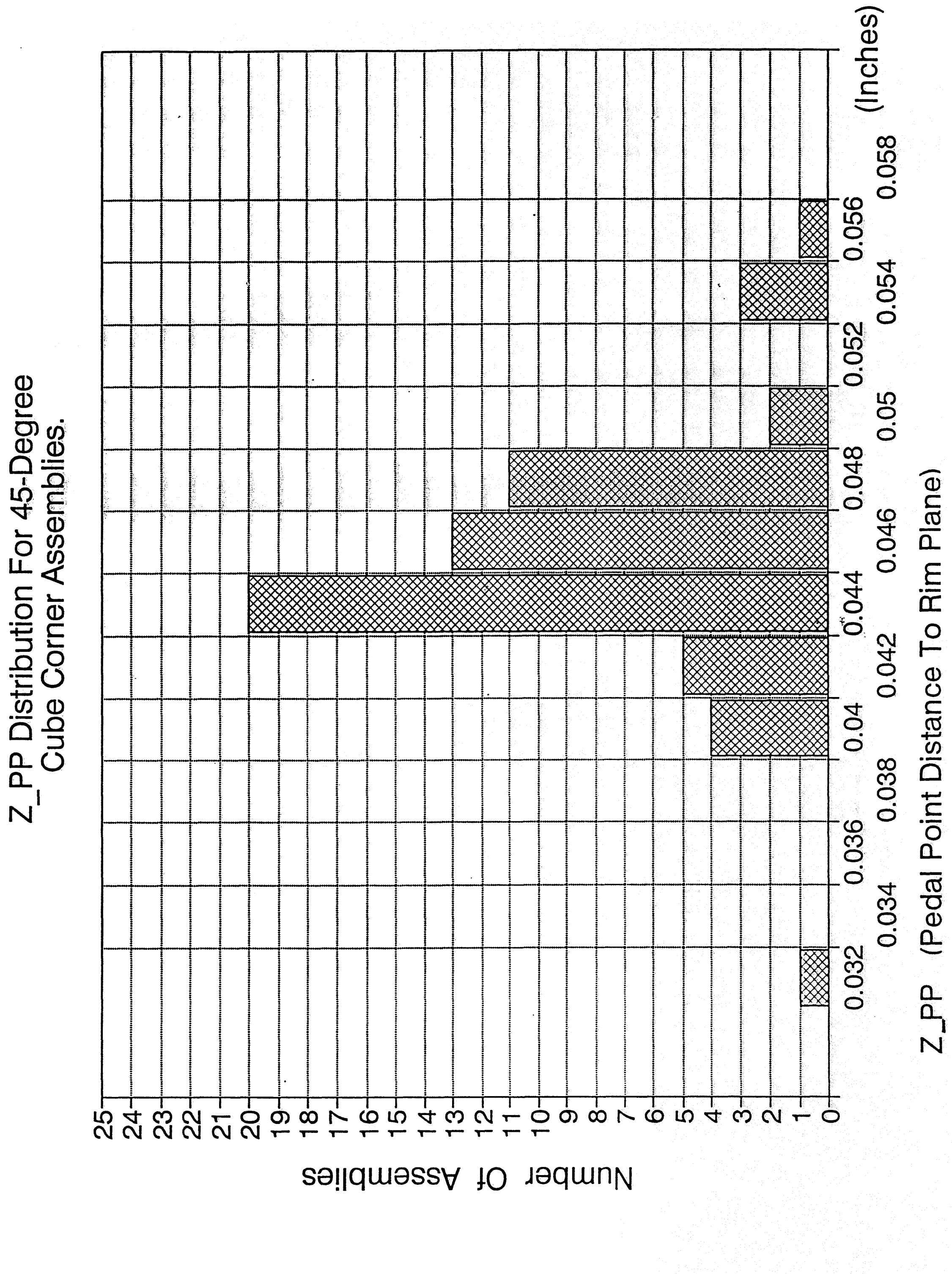



35_Degree Assembly
ID Number Versus Z_PP
Normal Distance Of Pedal Point To Rim Plane Of Casting
(Inches)
Assembly ID Number
0.197
0.198
0.199
0.2
0.201
0.202
0.203
0.204
0.205
0.206
0.207
0.208
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000


35-Degree Assembly
ID Number Versus Z_RP
Assembly ID Number
2000
1800
1600
1400
1200
1000
800
600
400
200
0
0.6
0.602
0.604
0.606
0.608
0.61
0.612
(Inches)
Normal Distance Of Fiducial Reference Point To Rim Plane Of Casting

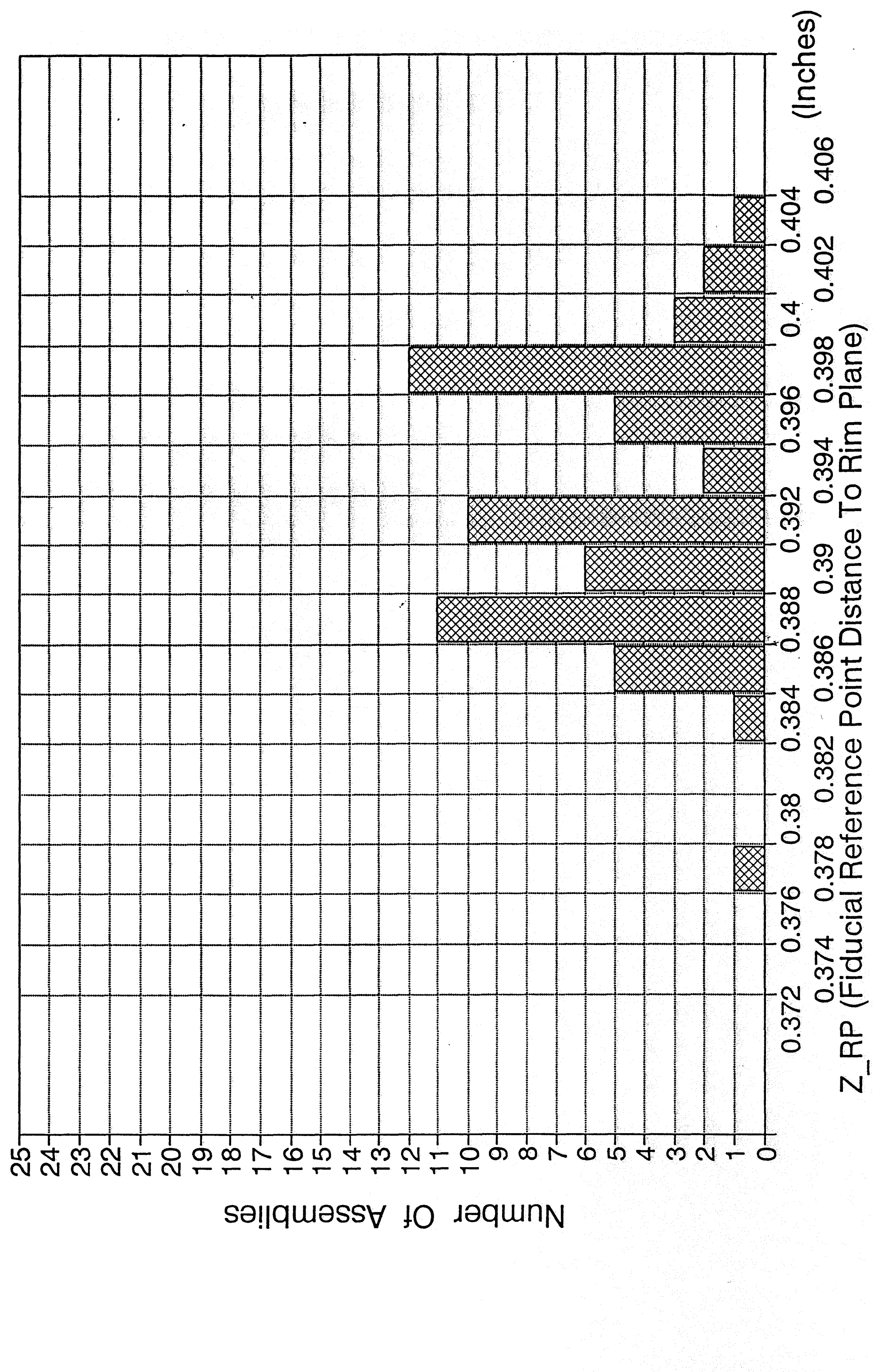


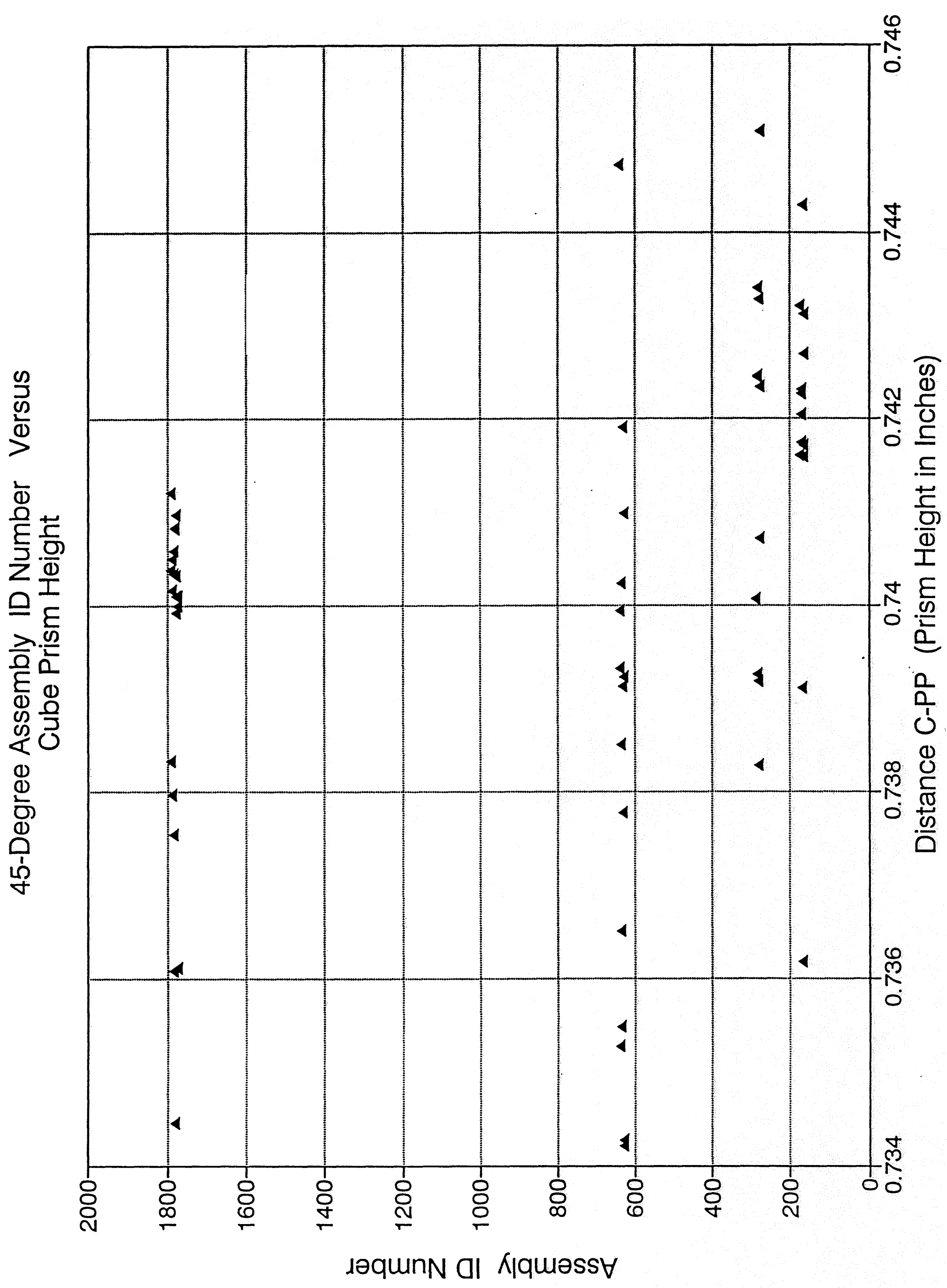
Cube Prism Height Distribution For
45-Degree Cube Corner Assemblies.
Number Of Assemblies
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
0.734
0.736
0.738
0.74
0.742
0.744
0.746
0.748
0.75
(Inches)
Cube Height (Distance From Corner Point To Pedal Point)

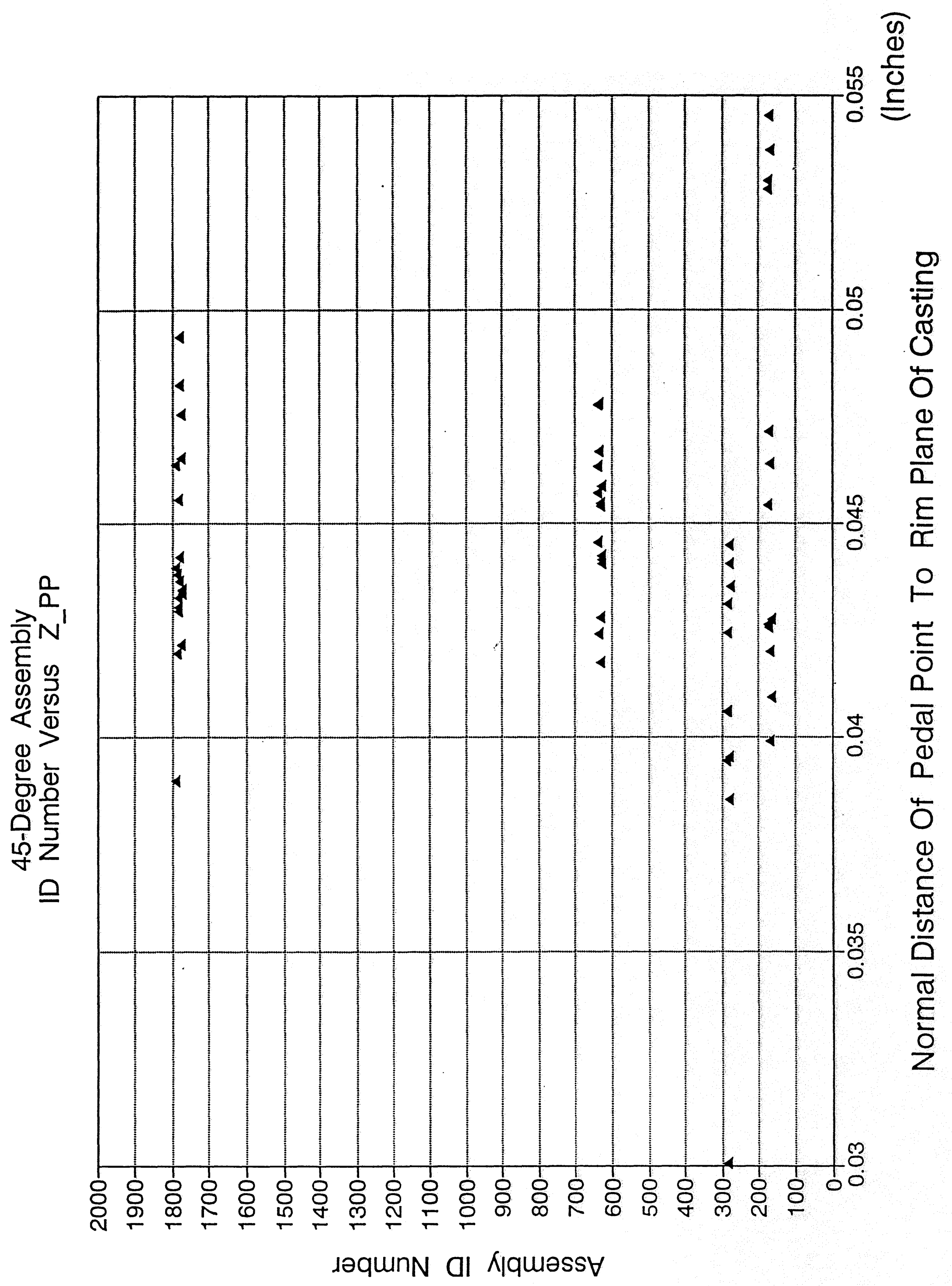


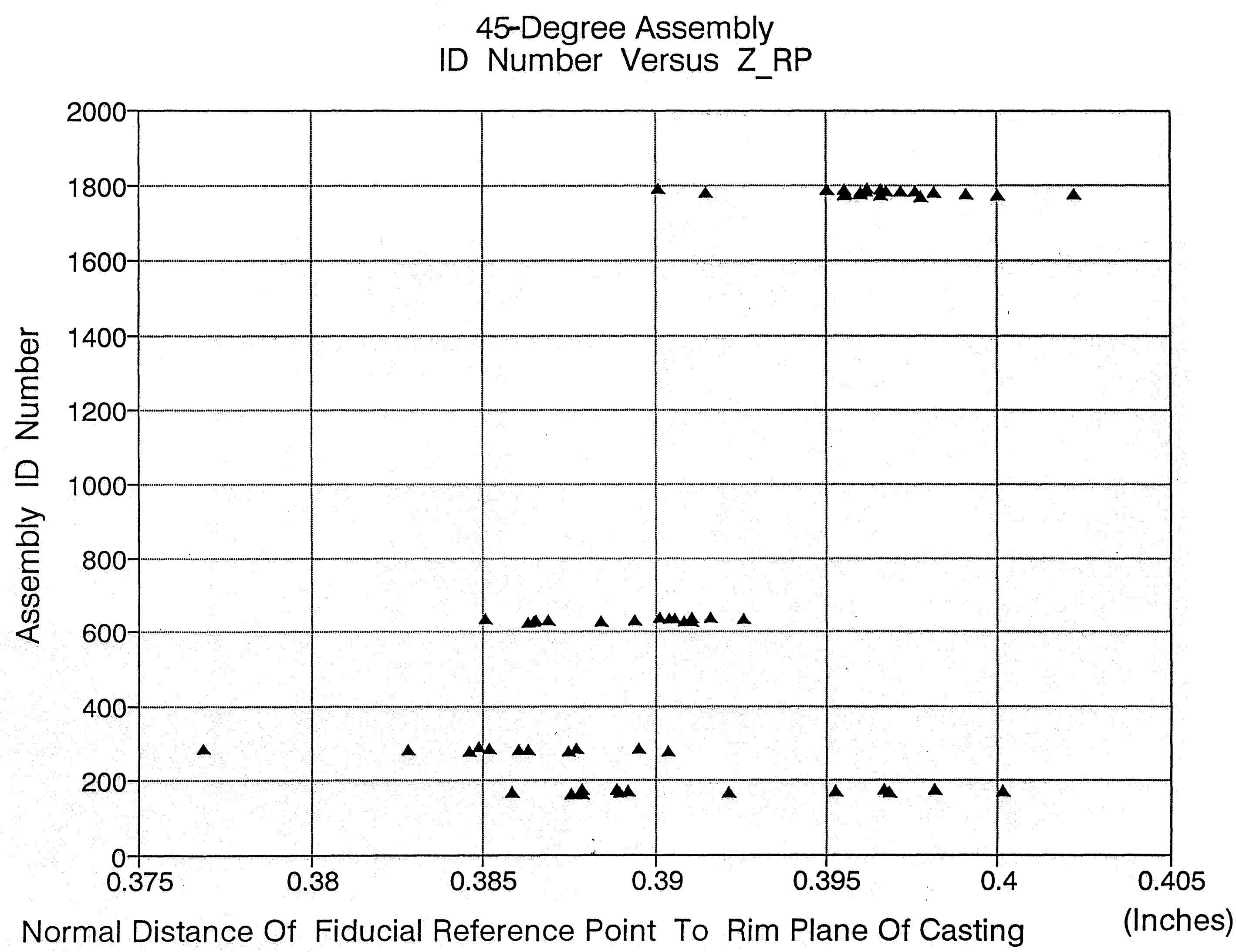
Z_PP Distribution For 45-Degree
Cube Corner Assemblies.
Number Of Assemblies
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
0.032
0.034
0.036
0.038
0.04
0.042
0.044
0.046
0.048
0.05
0.052
0.054
0.056
0.058
(Inches)
Z_PP (Pedal Point Distance To Rim Plane)

Z_RP Distribution For 45-Degree
Cube Corner Assemblies.




45-Degree Assembly ID Number Versus
Cube Prism Height
Assembly ID Number
2000
1800
1600
1400
1200
1000
800
600
400
200
0
0.734
0.736
0.738
0.74
0.742
0.744
0.746
Distance C-PP (Prism Height in Inches)


45-Degree Assembly
ID Number Versus Z_PP
Assembly ID Number
2000
1900
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
0.03
0.035
0.04
0.045
0.05
0.055
Normal Distance Of Pedal Point To Rim Plane Of Casting
(Inches)


45-Degree Assembly
ID Number Versus Z_RP
Assembly ID Number
2000
1800
1600
1400
1200
1000
800
600
400
200
0
0.375
0.38
0.385
0.39
0.395
0.4
0.405
Normal Distance Of Fiducial Reference Point To Rim Plane Of Casting
(Inches)