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Performance of an 18 path Acoustic Flowmeter at Robert Moses Niagara Power Plant Unit 13

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Abstract

This paper discusses the integration uncertainty of multiple path acoustic flowrate measurement. When 8 path flowmeter systems (4 chordal paths in 2 planes) are installed in a long straight section of penstocks the velocity distribution typically approaches a 1/n exponential or logarithmic shape. The Gauss-Chebyshev integration technique, using 8 acoustic paths, can integrate these profiles very accurately (on the order of 0.1%). Under the conditions prevalent below a bend, the momentum of the flow alters the velocity distribution so that it may not resemble an exponential or logarithmic shape. The uncertainty of the 8 path technique appears greater when these distorted velocity distributions are integrated. This suggests, that more paths are needed to define and integrate a distorted velocity distribution to achieve a high degree of accuracy. A brief discussion of the numerical analysis places bounds on the 8 path integration uncertainty of approximately 1%. To achieve a higher level of discharge measurement accuracy, the first 18 path flowmeter installed at Robert Moses is described. The test data show an average difference between the 8 and 18 path flowrate measurement in this application of 0.9%. The reasons for the differences are discussed.

Flowrate Measurement Background

Since 1967 multiple path acoustic flowmeters have been used in the water transport and hydroelectric market for a reliable and accurate measure of discharge. In the past decade, the acoustic flowmeter has been used as a primary method of discharge measurement for contractual performance testing of hydroelectric turbines.

Typically, multiple chordal acoustic paths are installed in a penstock in accordance with the Gauss-Chebyshev integration technique. For applications such as performance testing, two planes each having 4 acoustic paths are installed at 4 unique elevations in the penstock.

Ultrasonic flowmeters measure flowrate by transmitting and receiving acoustic signals diagonally across moving water. The propagation time of acoustic pulses sent downstream will be shorter than a pulse sent upstream. Knowing the acoustic path length (l_p) and angle that is made with respect to the penstock centerline (Θ) and measuring the acoustic pulse travel times in both upstream and downstream directions, a spatially averaged axial velocity of the fluid can be determined[1] (see figure 1). Flowrate is determined by integrating the velocity distribution across the penstock. Since the exact velocity distribution cannot be determined from a discrete number of samples, a numerical integration technique is used to determine volumetric flowrate.

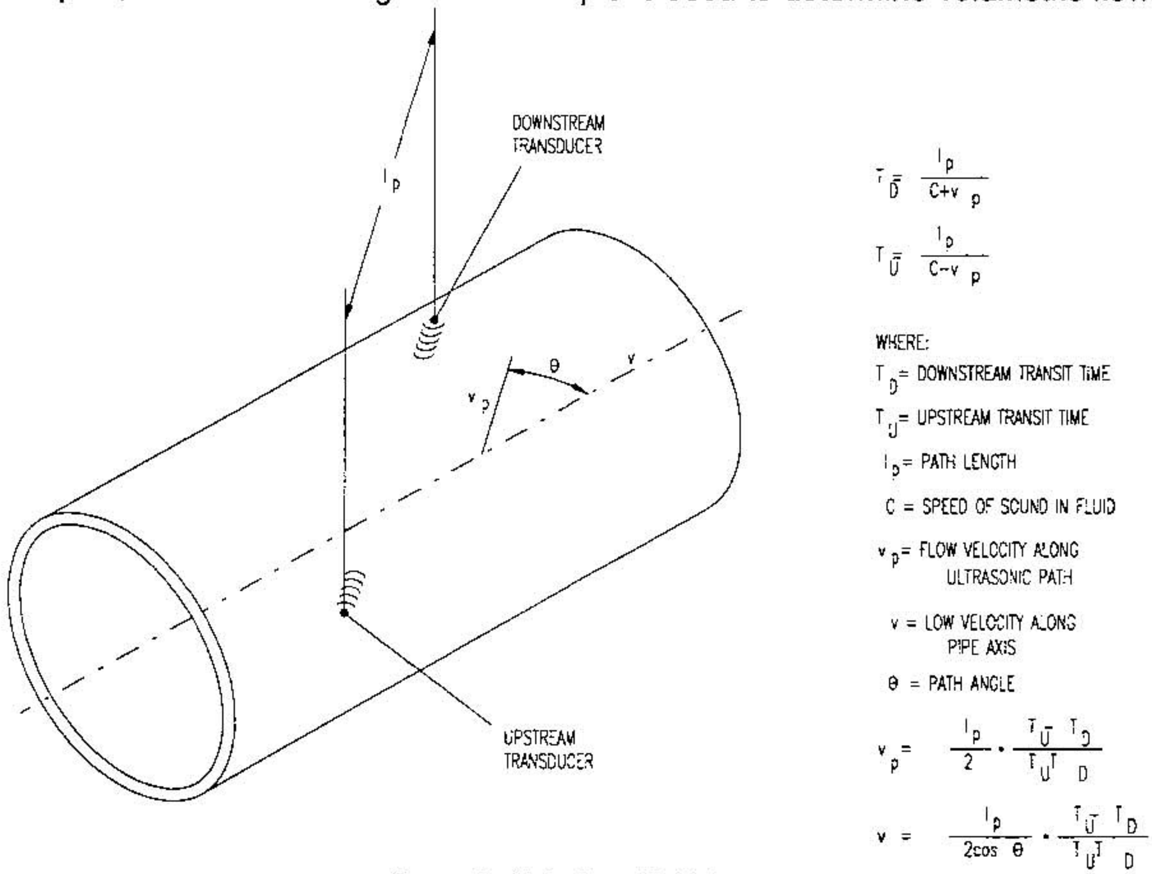


Figure 1 - Velocity of fluid determination

[1] Lowell, F.C. JR and Hirschfeld,F. 'Acoustic flowmeters for pipeline flowrate' *International Water Power & Dam Construction*, June 1979.

Measurement section location

At the Robert Moses Niagara Power Project, units 3 and 4 are fitted with standard 8 path measurement sections. These meters were installed in the late 1980s. In unit 13, a 9 chord path per plane 18 path system was installed in April of 1994. The end view arrangement of the 18 path system is shown in Figure 3. All meter sections (e.g. transducer locations) are installed 2 diameters downstream from the elbow (as shown in figure 4). The 18 path meter section has additional paths located on the diameter, and in between the standard path locations and is described below (see figure 3).

On units 3 and 4, two intersecting planes each having 4 horizontal acoustic paths are positioned in the penstock such that a nominal acoustic path angle of 65 degrees is

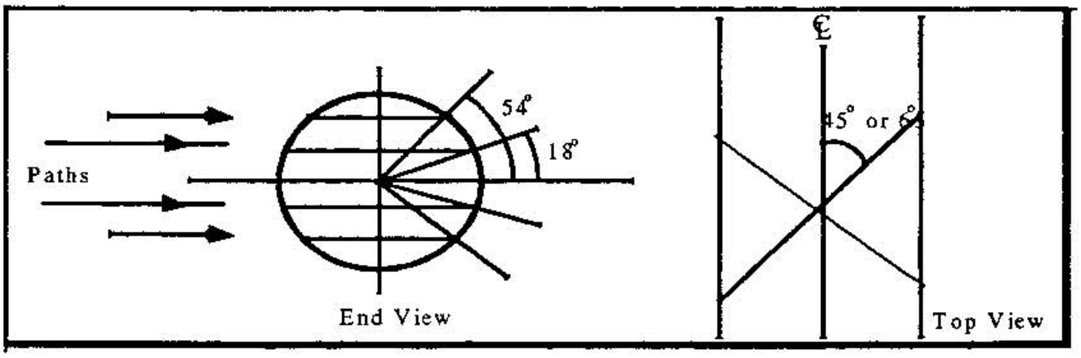


Figure 2 - Standard 8 path installation

made with respect to the penstock centerline. The acoustic paths in each plane are positioned at 4 chords in the penstock at locations corresponding to normalized elevations of +/- 0.309 * R and +/- 0.809 * R (where R is the penstock radius). This can also be described as angles of +/-18 and 54 degrees with respect to the centerline elevation of the penstock (see figure 2). The elevations and weights of the acoustic paths are determined by the Gauss Chebyshev numerical integration technique. This flowrate measurement technique is in the international and American codes for turbine performance testing that specifies the path elevations and weighting (IEC Publication 41-1991 and ASME PTC -18 - 1992).

In unit 13, the elevation of the 9 paths was determined by the same integration technique (see equation 4). Nine paths were chosen since 4 of the 9 elevations corresponded to the standard 4 path elevations as shown in figure 2. This is due to the sinusoidal function for path spacing. This arrangement allows direct comparison of the 4 path measurement with the 9 path measurement.

Figure 3 - End view of 18 path meter section showing chord elevations

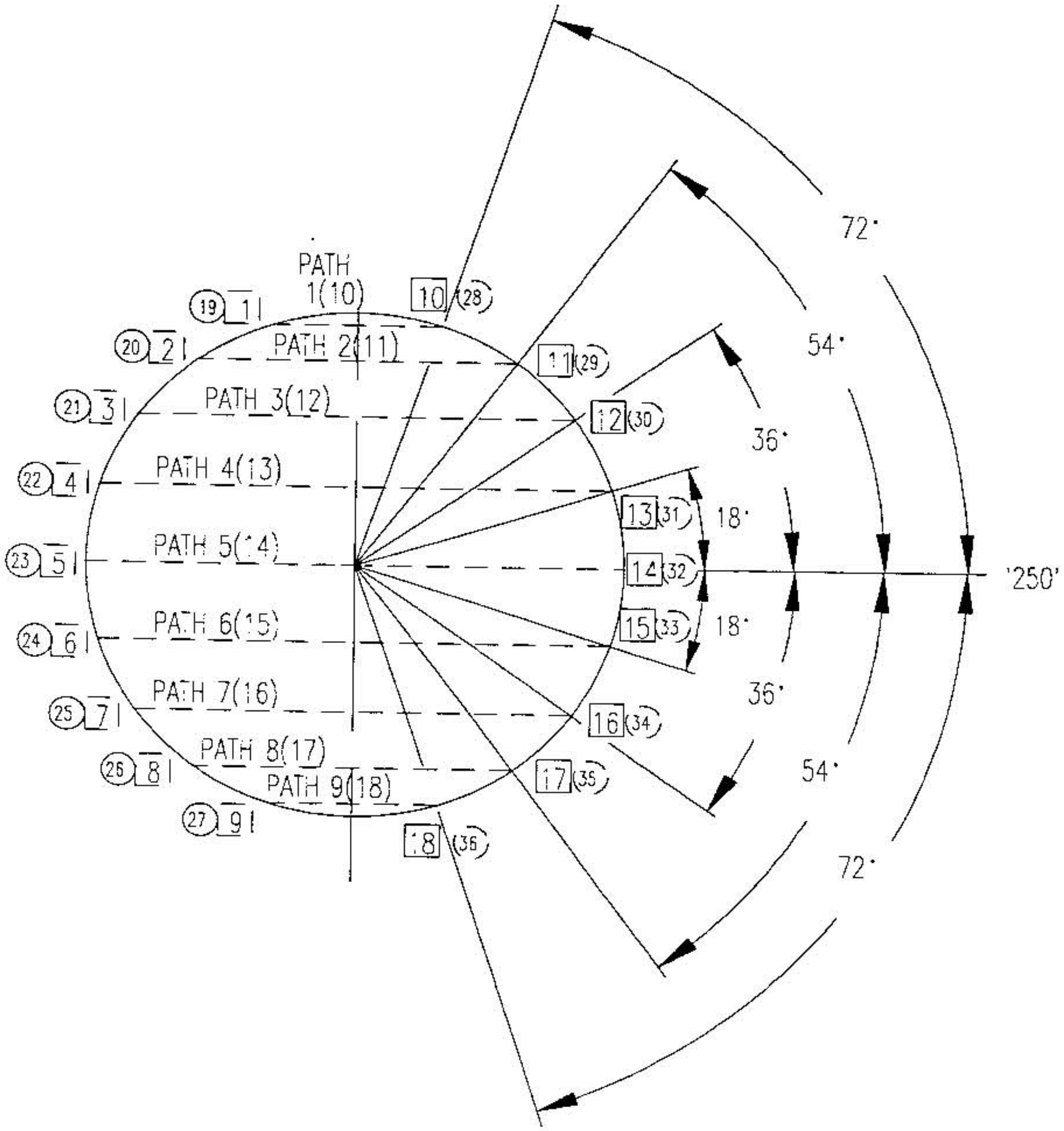
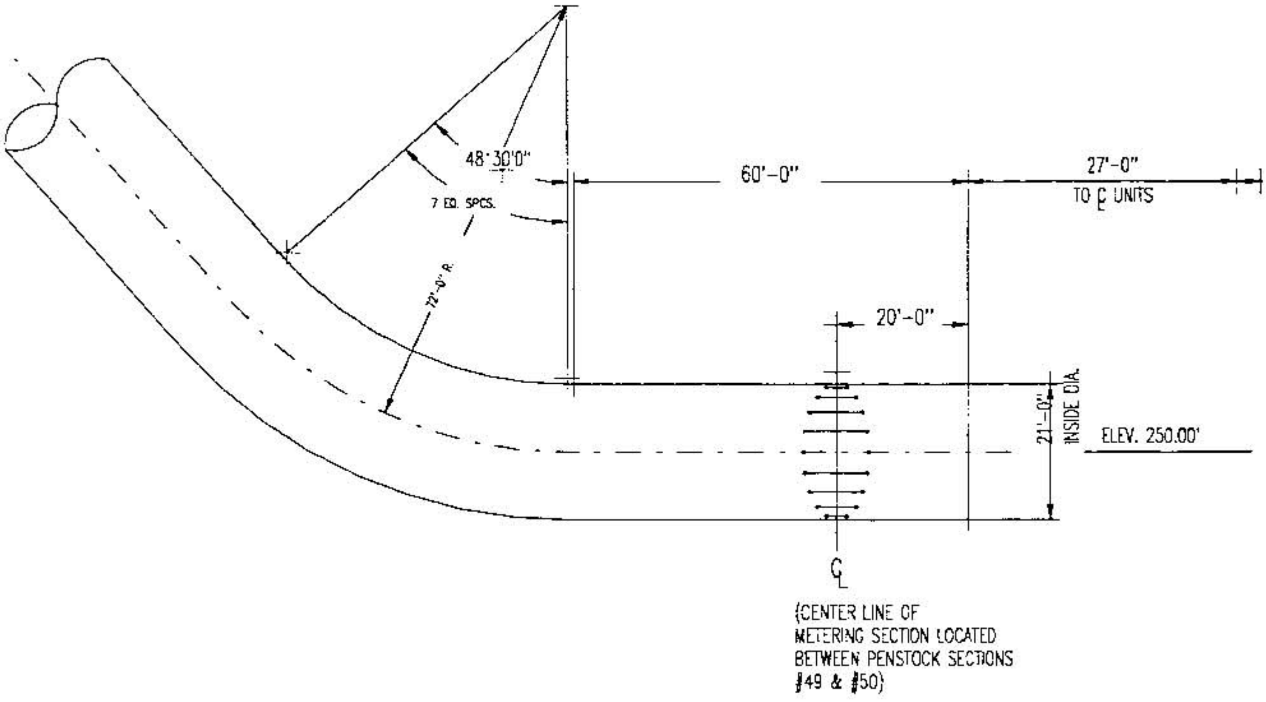


Figure 4 - Meter section location



The tests were run concurrently with a turbine performance acceptance test. Three Accusonic model 7410 flowmeters were used to measure flowrate, and two data acquisition systems were used throughout the test. One data acquisition system obtained the power, pressure, and flow velocities for the standard set of acoustic paths. The second data acquisition system collected the velocities from the three flowmeters to calculate 18 path based discharge. These velocities were combined and weighted off line using a spreadsheet to calculate flowrate.

Uncertainty

In any field measurement test there are always two categories of uncertainty. The bias, which influences the absolute results of the test can usually have uncertainties assigned. There are also random uncertainties, which arise from repeating the same measurement numerous times, which do not and are not expected to agree.

Bias errors resulting from the installation of transducers and their effects on accuracy in flowrate measurements have been quantified by others[2] and generally are in the 0.3 to 0.4 % range. Since the transducers comprising the eight and eighteen path meters are installed in the same section of penstock the radius bias cancels in both discharge measurements. The differences in the weighted path uncertainties among the 8 and 18 path length and angle measurements are negligible. This is because the length and angle uncertainties are in the one part per thousand range. Therefore, the remaining uncertainties in flowrate measurement are random and integration uncertainties. The integration uncertainty has been the subject of debate among various flowmeter manufacturers, utilities and turbine suppliers. Prior to installing the eighteen path

[2] Ibid.

flowmeter, several discussions between Accusonic and NYPA were held to address the integration uncertainty when the velocity distribution was skewed downstream of a bend. Skewed velocity distributions that take on forms that may be other than logarithmic, similar to profiles observed at Robert Moses were analyzed. A bound on the uncertainly of the integration technique was placed on the 8 path flowmeter and is described below.

The axial flow field v(x,y) can be represented in the penstock along an acoustic path as:

$$\bar{v}(y) = \tfrac{1}{2b}\int_{-b}^{+b} v(x,y)\,dx \quad \textit{(equation 1)}$$

The flowrate is:

$$Q = \int_{-R}^{+R} 2b\,\bar{u}(y)\,dy \quad \textit{(equation 2)}$$

with $b = \sqrt{R^2-y^2}$
or

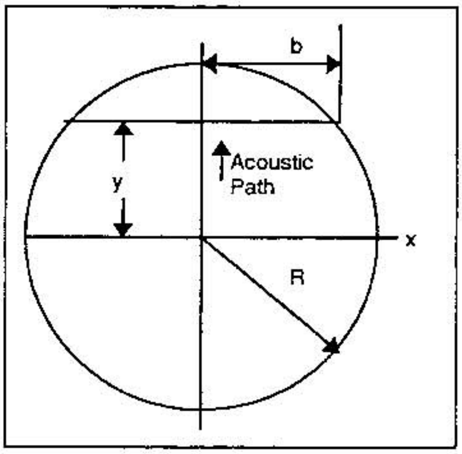


Figure 5

$$Q = 2R^2\int_{-1}^{+1}\sqrt{1-z^2} * \bar{u}(z)\,dz \quad \textit{(equation 3)}$$

where z = y/R

This takes the form of an established mathematical relationship[3] for the Gaussian integration method.

$$\int_{-1}^{+1} f(z) * \sqrt{1-z^2}\,dz \approx \sum_{i=1}^{N} w_i f(z_i) \quad \textit{(equation 4)}$$

Where the weights (w_i) are given at locations at abscissas x_i (+/- 0.309 +/- 0.809). The velocity profile measured by the flowmeter are f(z) that represent the spatially averaged velocity along the acoustic path. In the integrand, the velocity function f(z) times the radical ($\sqrt{1-z^2}$) makes erratic functions more "well behaved". Hence, the function actually being integrated (f(z) $*\sqrt{1-z^2}$) is smoother than the velocity profile f(z). This smoothing is significant because velocity profiles f(z) which may have several increases and or decreases along the penstock height are smoothed and rendered monatomic on the radii. In analysis performed by Ludewig[4], it has been shown that the integration uncertainty is bounded by about +-1 %. The Ludewig analysis was performed using several velocity distributions where no sharp corners occurred in f(z) and the shapes of the curves were similar to the field measured velocity distributions.

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[3] M Abramowitz and Stegun , ed.,Handbook of Mathematical Functions Applied Mathematics Series 55 (US government printing office 1963), Pg. 889

[4] Ludewig, Peter, September 4, 1992 Analysis of Gauss-Chebyshev Integration technique

These velocity distributions also included polynomial functions recognizing that this numerical technique is exact for certain classes of functions (that is polynomials of order 2n-1 or less where n is the number of paths on each plane). Considering this and NYPAs' business needs for high accuracy and needs in the industry, a test program was initiated to place 18 acoustic paths in Unit 13 at the Robert Moses Power Project in Niagara Falls New York.

At numerous power plants, the random error in flowrate has been observed by taking instantaneous measurements of flowrate and analyzing the distribution of the data. In all cases, the distributions of the instantaneous readings approach a normal distribution with a mean and a standard deviation. This is supported by Chi square evaluations on instantaneous flowrate distributions which result in a high degree of certainty (greater than 90 %) that the normal statistical distribution can be used[5].

In the experience of Accusonic, the majority of applications the standard deviation is typically 1 to 1 ½ % of the mean. This is usually influenced by how far the meter is situated from hydraulic structures such as elbows and "Y" branches. Generally, meter sections installed in straight long sections of penstocks have lower reading to reading jitter and therefore lower standard deviations. For high accuracy applications, hundreds of readings must be used to minimize the standard error of the mean. A plot of the standard error of the mean assuming a standard deviation of 1.25 % of flowrate is illustrated in figure 6.

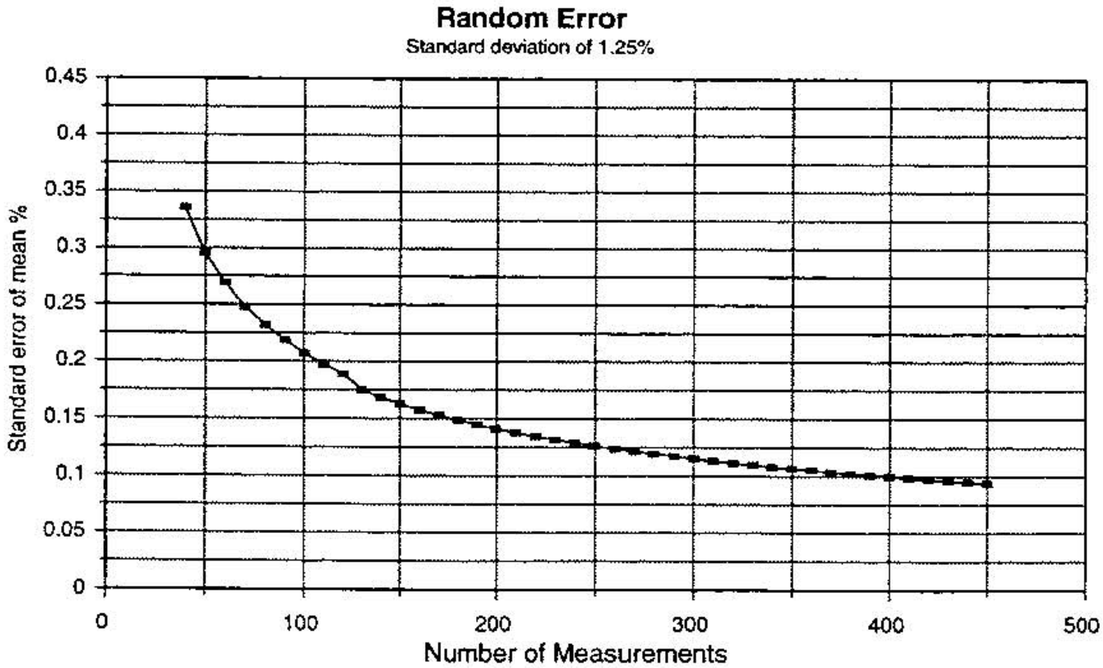


Figure 6 - Number of measurement influence on the standard error

At Robert Moses, each test was run over an interval of 15 minutes that yielded 450 readings. As shown in figure 6, the amount of readings minimizes the random

[5] Walsh, James T. 1991 &1995 Internal analysis of flowmeter variability

component of the flowrate measurement. For statistical significance the differences between the 8 and 18 path flowmeter must exceed 0.13 %.

Field Data

Presented in Table 1 is the data from the first 60 runs performed at Robert Moses Power Plant Unit 13. This data was collected concurrent with a contractual performance test. In the third column the flowrate based on 8 acoustic paths is tabulated by run. The fifth column is the 18 path data and the fourth column is difference between the 8 path and 18 path using the 8 path as the reference. Figure 7 shows the differences of the 18 and 8 path flowmeters as a function of flowrate indicating that there is no bias that is flowrate related. On average, the 18 path derived flowrate is 0.9% lower than the 8 path flowrate.

Analysis of Results

Typical velocity distributions are graphed for a full, low and best gate openings that illustrates a velocity deficit at the + 36 degree (path 3 and 12) elevation. In figure 9 a detail of the velocity deficit is expanded for the flowrate at 70 % wicket gate opening. A spline fit is used to predict the axial velocity in the absences of the 36 degree velocity data. If this data is used in place of the 36 degree path velocity data, the difference between the 8 and 18 path data reduces to 0.1%. This indicates that the majority of the discrepancy lies with the velocity deficit. This velocity deficit is prevalent in all velocity distributions obtained for all ranges of discharges measured at Robert Moses. Other analysis have been made to assure that the transducer protrusion and positioning accuracy at the correct path elevation could not have cause the discharge differences.

Results and Conclusions

It has been shown that there is a difference between the 18 and 8 path acoustic flowmeter 2 diameters downstream of the elbow is at Robert Moses. This 0.9 % difference is chiefly due to the velocity deficit as seen by the upper paths at the + 36 degree elevation (paths 3 and 12 on the 18 path flowmeter). The major portion of the difference between the 18 and 8 path flowmeter is due to the velocity deficit.

Acknowledgments

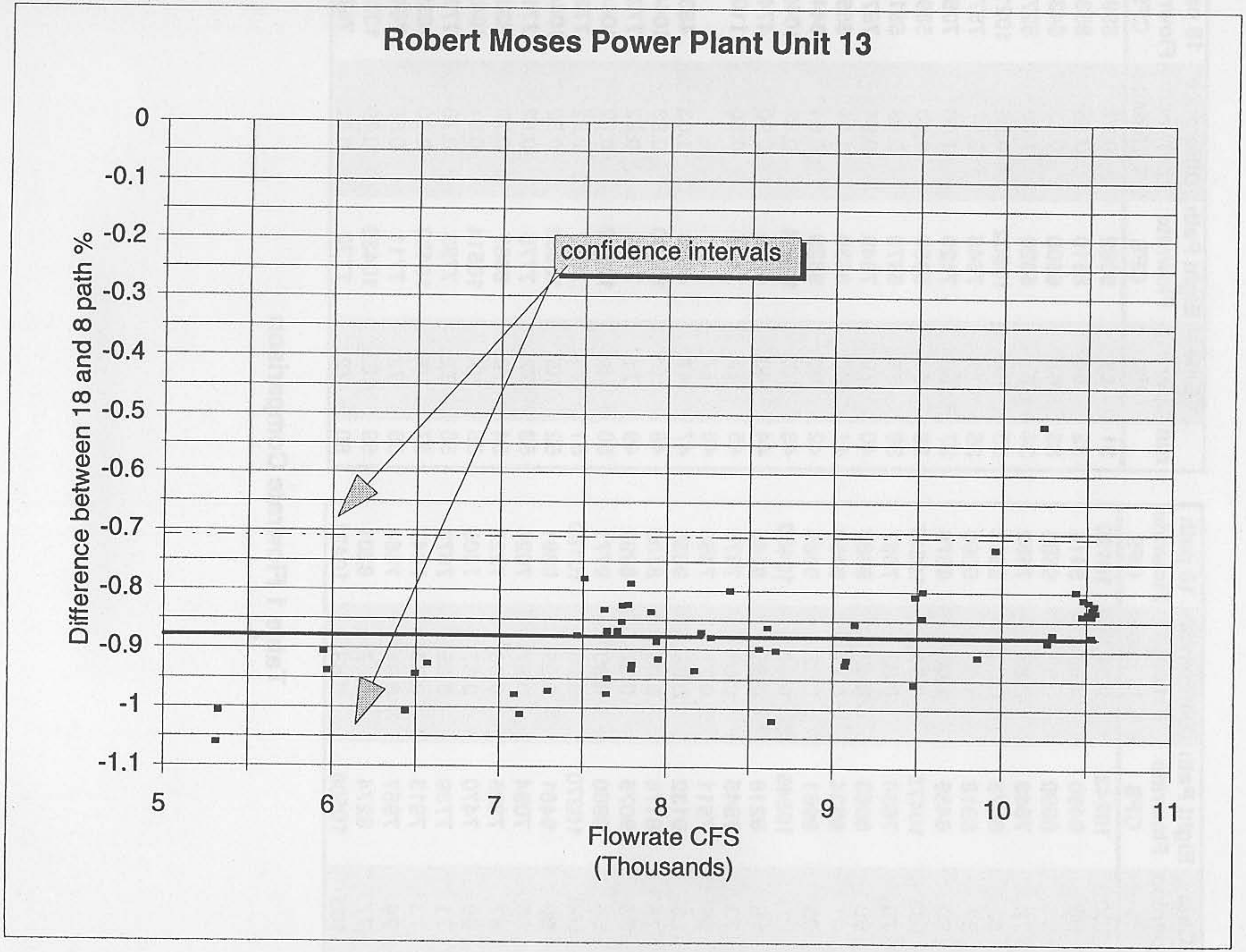
Development and testing of the 18-path flowmeter was done to increase the accuracy of available flow measurement methods. This work was sponsored by the New York Power Authority, with co-funding for the Empire State Electric Energy Research Corporation.

The authors also wish to thank the staff of the Niagara Power Project, Alden Research Laboratories and Ontario Hydro for their efforts during the various tests.

run	Gate Opening %	Eight Path Flowrate CFS	Difference between 8 & 18 paths	18 path Flowrate CFS
1	100	10243	0.51	10190
2	90	9490	0.80	9414
3	81	8660	0.89	8583
4	70	7648	0.86	7582
5	62	6573	0.92	6513
6	51	5316	1.05	5260
7	60	6439	1.00	6375
8	103	10475	0.83	10387
9	70	7630	0.83	7567
10	80	8563	0.89	8487
11	91	9534	0.79	9459
12	95	9961	0.72	9889
13	103	10546	0.81	10460
14	75	8216	0.86	8145
15	73	7945	0.88	7875
16	69	7511	0.77	7453
17	85	9132	0.85	9055
18	76	8176	0.93	8100
19	85	9075	0.92	8992
20	95	9860	0.90	9771
21	100	10270	0.88	10180
22	90	9481	0.95	9391
23	66	7094	0.97	7026
24	67	7295	0.96	7225
25	69	7470	0.87	7405
26	71	7739	0.85	7673
27	73	7913	0.83	7847
28	74	7957	0.91	7884
29	77	8274	0.87	8201
30	103	10508	0.83	10421

run	Gate Opening %	Eight Path Flowrate CFS	Difference between 8 & 18 paths	18 path Flowrat CFS
31	85	9082	0.91	8999
32	80	8610	0.85	8537
33	61	6500	0.93	6439
34	51	5329	1.00	5275
35	100	10302	0.86	10213
36	71	7645	0.97	7571
37	66	7129	1.00	7058
38	56	5950	0.90	5896
39	56	5974	0.93	5919
40	70	7649	0.94	7577
41	80	8639	1.01	8551
42	90	9529	0.84	9449
43	103	10554	0.83	10466
44	46	4789	0.90	4745
45	13	1107	0.66	1100
46	77			
47	47	4888	1.03	4837
48	103	10530	0.83	10442
49	71	7796	0.92	7724
50	103	10532	0.87	10441
51	71	7800	0.92	7729
52	103	10533	0.82	10446
53	72	7775	0.82	7712
54	78	8387	0.79	8320
55	103	10514	0.81	10429
56	72	7793	0.78	7732
57	103	10483	0.80	10398
58	72	7711	0.86	7645
59	103	10439	0.79	10356
60	72	7739	0.82	7676

Table 1 Flowrate Comparison



Robert Moses Power Plant Unit 13
confidence intervals
Difference between 18 and 8 path %
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
-0.9
-1
-1.1
5
6
7
8
9
10
11
Flowrate CFS
(Thousands)

Figure 7

Robert Mosess Unit 13

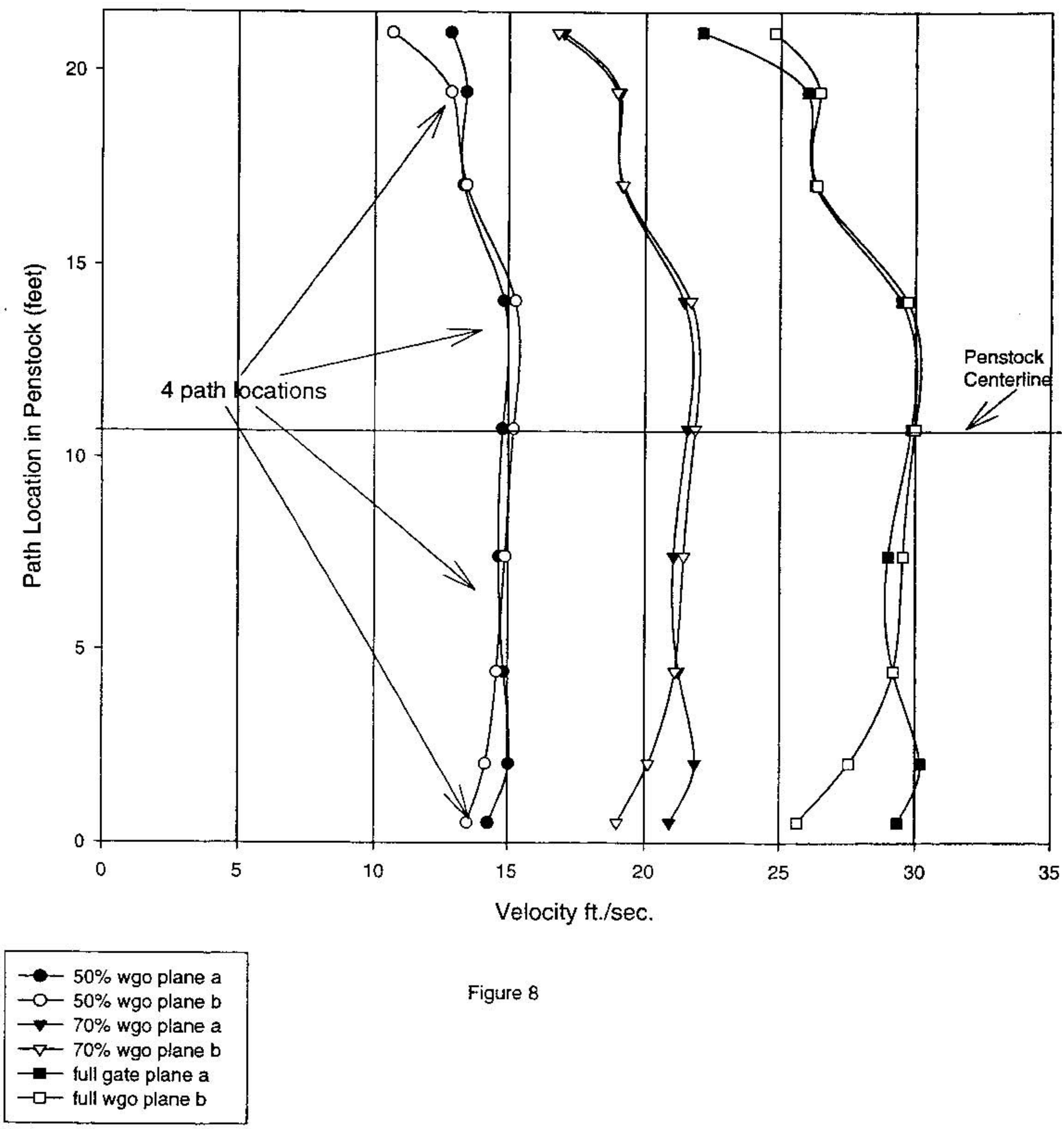


Figure 8

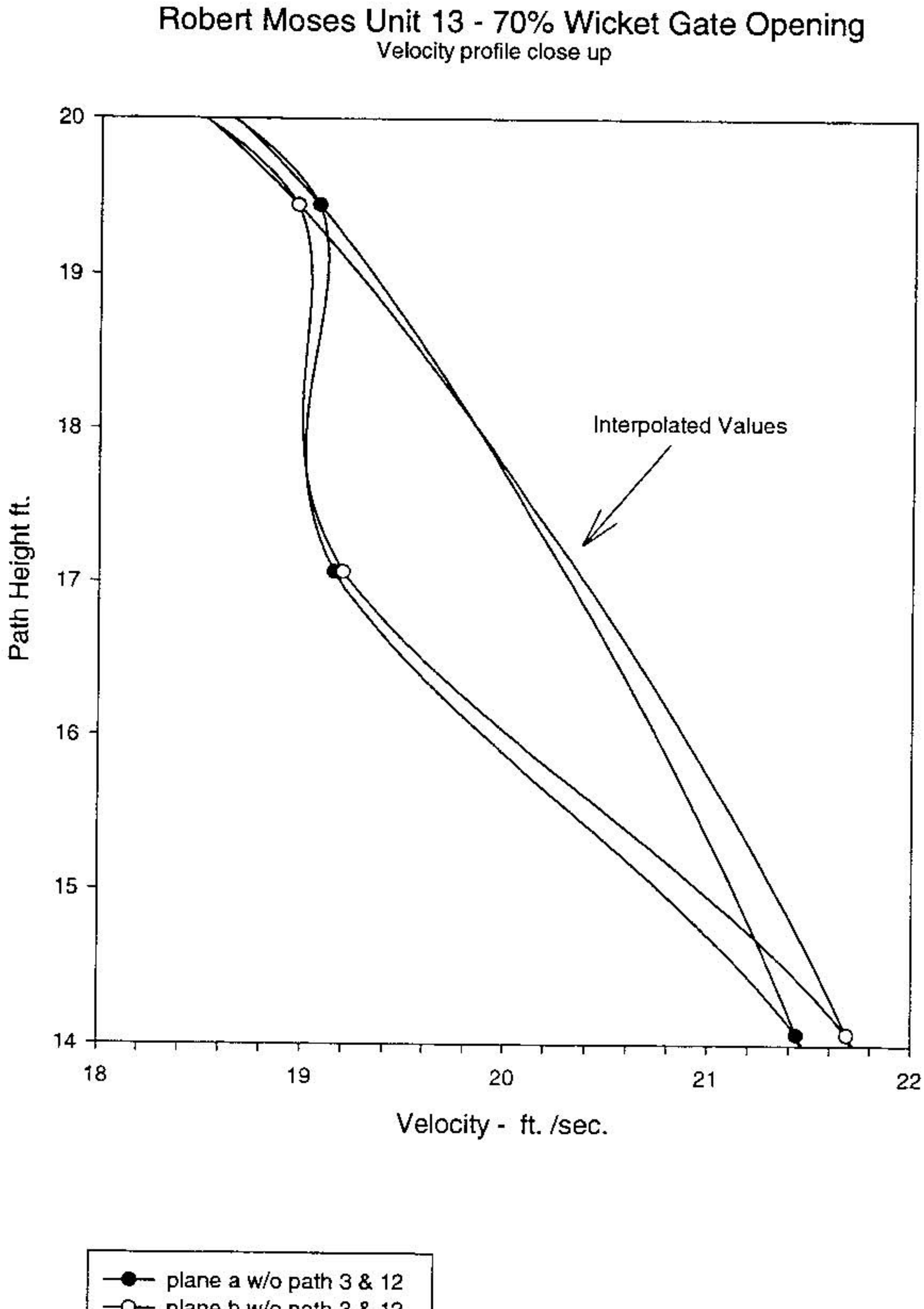

Robert Moses Unit 13 - 70% Wicket Gate Opening
Velocity profile close up
20
19
18
17
16
15
14
18
19
20
21
22
Path Height ft.
Velocity - ft. /sec.
Interpolated Values
plane a w/o path 3 & 12
plane b w/o path 3 & 12
Plane a
plane b

Figure 9