Appendix B: Turbine Performance Model Studies

Table of Contents

List of Figures

Appendix B: Turbine Performance Model Studies

B.1 McNary Performance Model

In 1993 a contract was awarded for investigations into fish screen effects and comparison of Froude and Reynolds similitude modeling techniques. This testing consisted of comparisons of field measurements to model measurements along with the development of the entire operating range of the turbine design. Only a summary comparing field test information to modeling is contained herein. The full data set of information is very extensive and specific information can be obtained from the Hydroelectric Design Center if the data is not proprietary.

The field index test was repeated in the model testing with and without fish screens installed. The index test was performed with measurement of relative flow and relative efficiency. The model testing was done with absolute efficiency. There is some uncertainty associated with the determination of prototype efficiency levels and associated power output. The following information is the best on cam information resulting from the testing.

B.1.1 Index Test Duplication – Without Screens

The comparison between Froude and Reynolds modeling techniques indicated a close correlation between them. However, the Froude technique better replicated the shape of the performance curve. The performance comparisons are shown in Figure B - 1. Figure B - 2 illustrates the significantly different on cam curves resulting from these performance comparisons, i.e., the Froude technique results in a different cam curve than the Reynolds technique. It is important to note that the field-tested cam curves are shifted to the right because of the differences in model to prototype scale effect and uncertainty. However, the slopes are very similar.

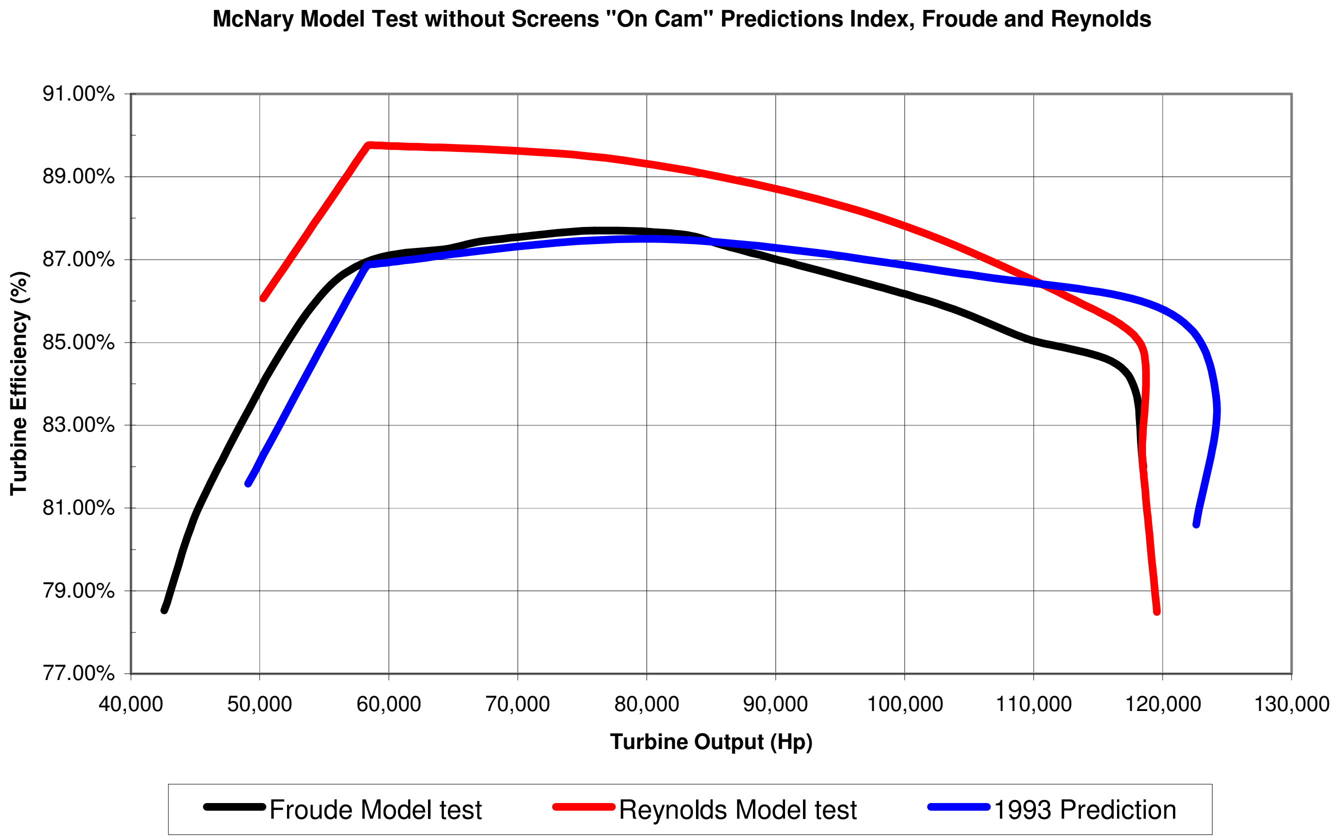

Figure B - 1. McNary comparisons for the Froude model, Reynolds model, and field-tests without screens

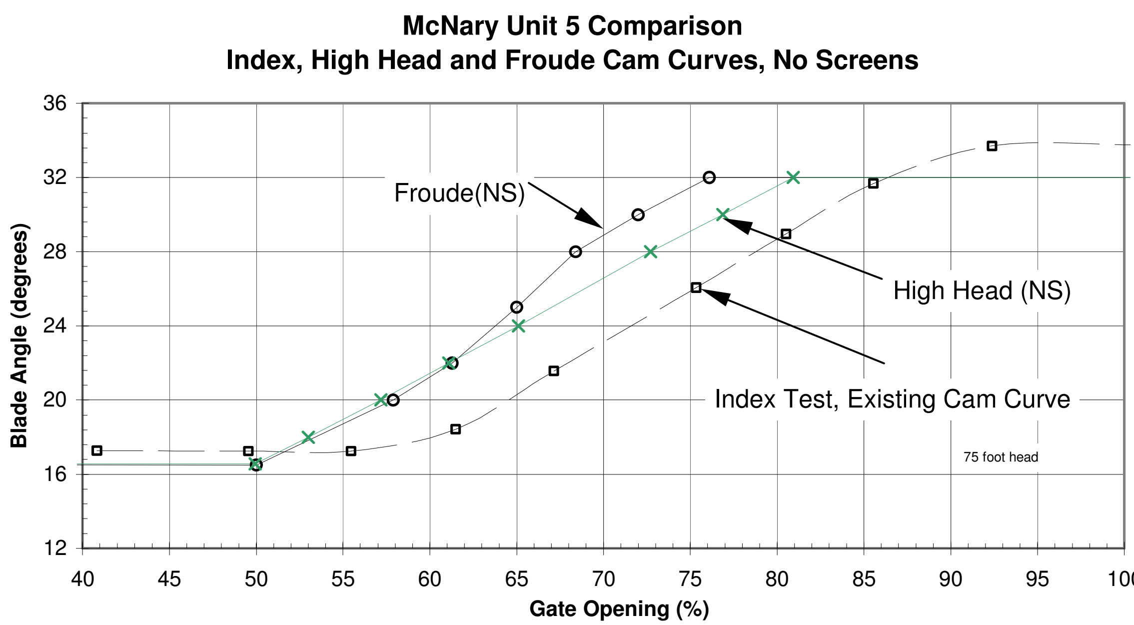

Figure B - 2. Model cam curves without screens installed

B.1.2 Index Test Duplication – With ESBS Screens

Figure B - 3 shows the results of the index test duplication with ESBS screens installed. There is a larger variation in the model predictions than without screens installed, which is to be expected given the uncertainty of the fish screens affect on hydraulic losses. The Froude technique appears to better reflect the losses associated with fish screens installed. Figure B - 4 indicates the resulting on cam curve derived from the performance. The measured model cam curves are much closer to each other. It is important to note that the field-tested cam curves are shifted to the right because of the differences in model to prototype scale effect and uncertainty, however, the slopes match well. The need to field-test turbines through index testing is clearly shown by these comparisons.

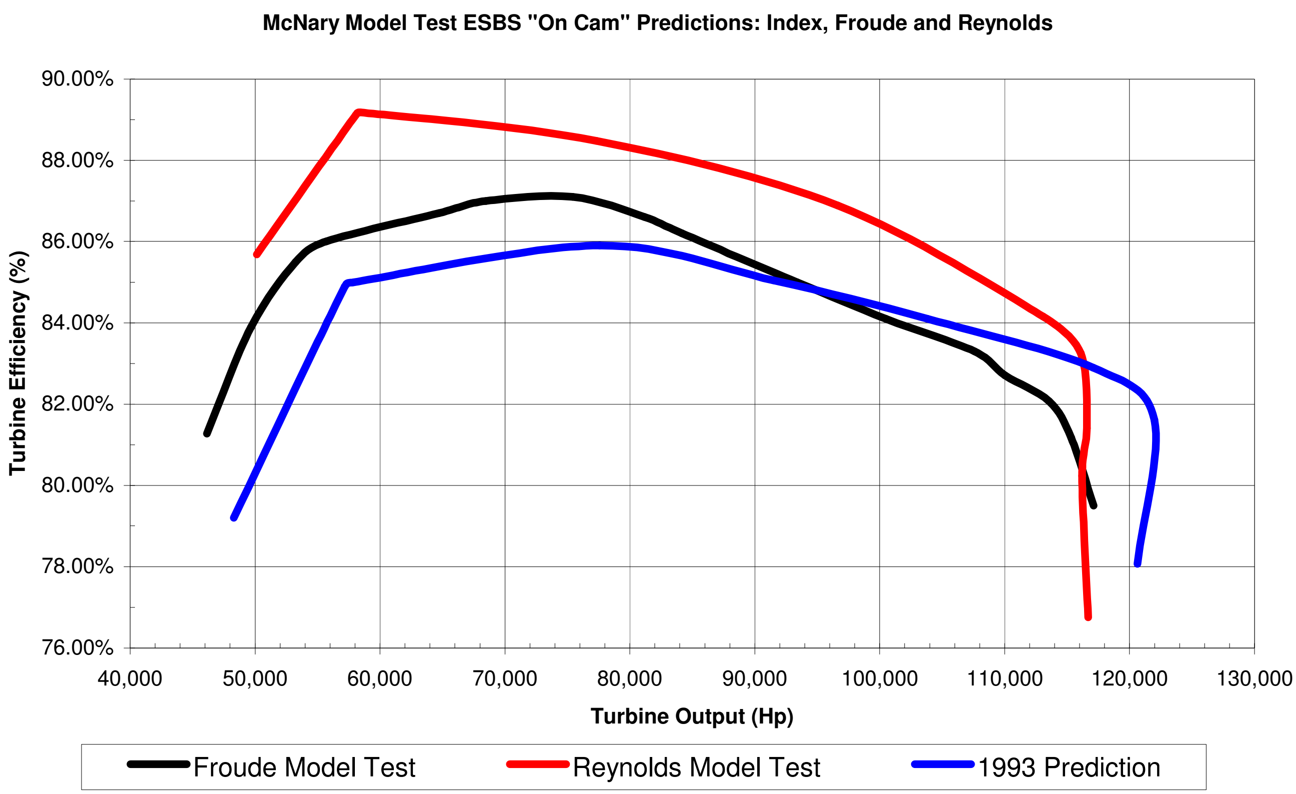

Figure B - 3. McNary comparisons for the Froude model, Reynolds model, and field-tests with ESBS screens

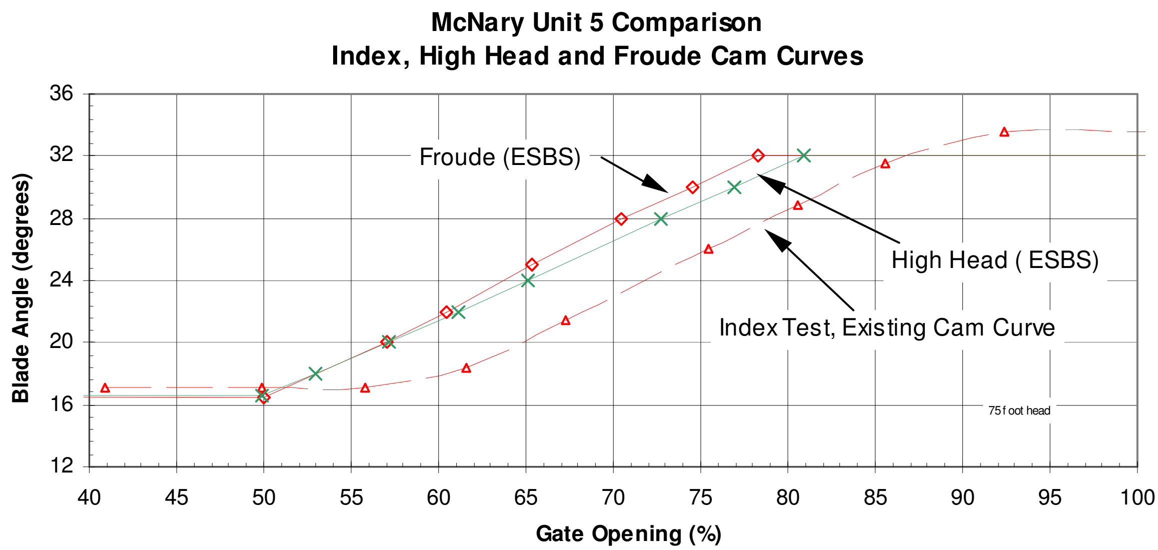

Figure B - 4. Model cam curves with ESBS screens installed

B.2 Lower Granite Performance Model

A more comprehensive investigation was done with the Lower Granite Unit 4 model testing. The use of improved methods and technology resulted in a more precise comparison. Again, the field test results are based on relative flow measurement and the model test results are based on absolute flow. The uncertainty in flow measurement affects the absolute value of the field-tested efficiency.

The index test duplication information presented for Lower Granite is different than that presented for McNary. The graphs below compare the "as found" field-tested turbine performance to a duplicate measurements using the two modeling techniques. This means the same blade-gate relationship was used for each test. Hence, all have the same on cam curves. It should be noted that on cam curves revised based on the field index testing were actually installed in the prototype and that the performance curves below do not reflect current operation.

B.2.1 Index Test Duplication – Without Screens

The comparison indicated a close correlation between both modeling techniques replicating the shape of the field-tested performance curve. Figure B - 5 shows the comparison with field measured power and relative efficiency for the 1995 field test and model test predictions of the same geometry adjusted to prototype values.

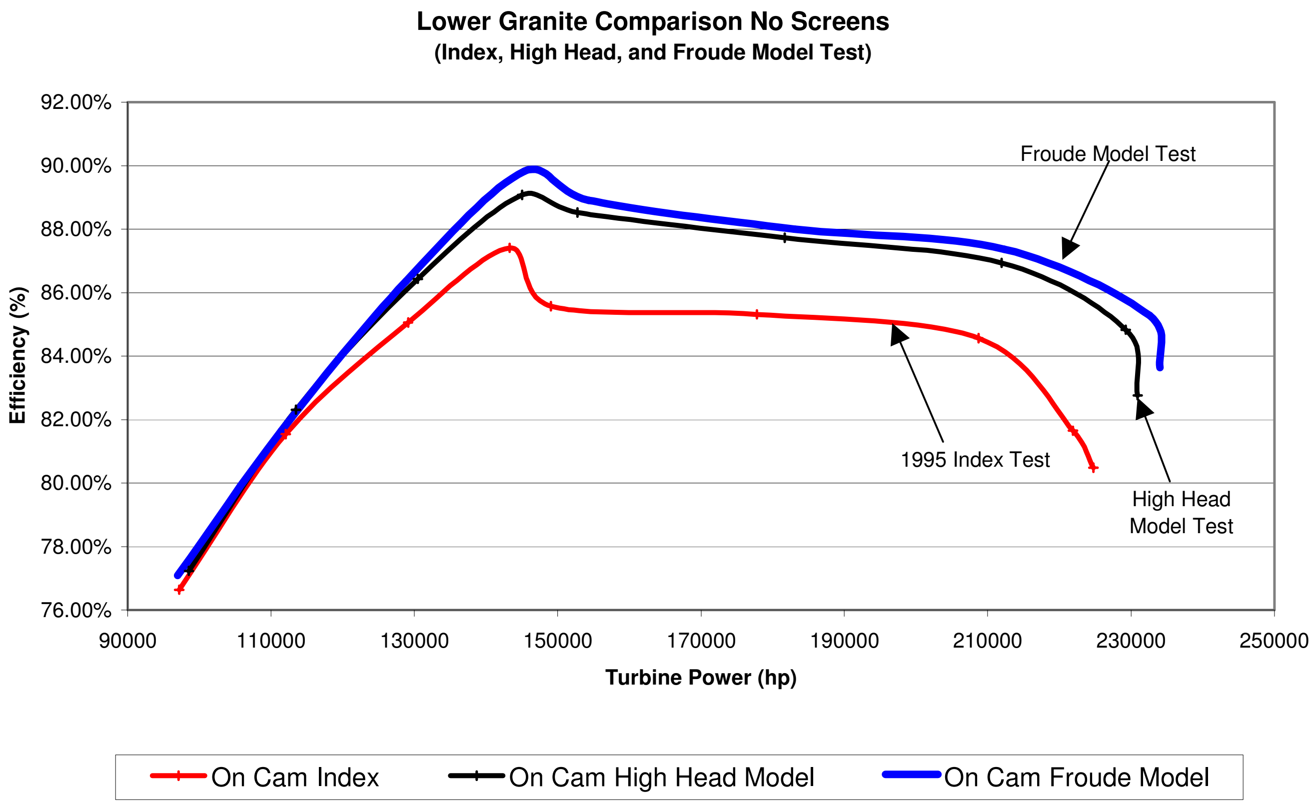

Figure B - 5. Example comparison of modeling techniques for the "As Found" field-tested cam

B.2.2 Index Test Duplication – With ESBS Screens

Figure B - 6 shows the comparison with ESBS screens installed with the field measured power and relative efficiency for the 1995 field test and model test predictions of the same geometry adjusted to prototype values with ESBS screens installed. The comparison indicated a close correlation between both modeling techniques replicating the shape of the field-tested performance curve.

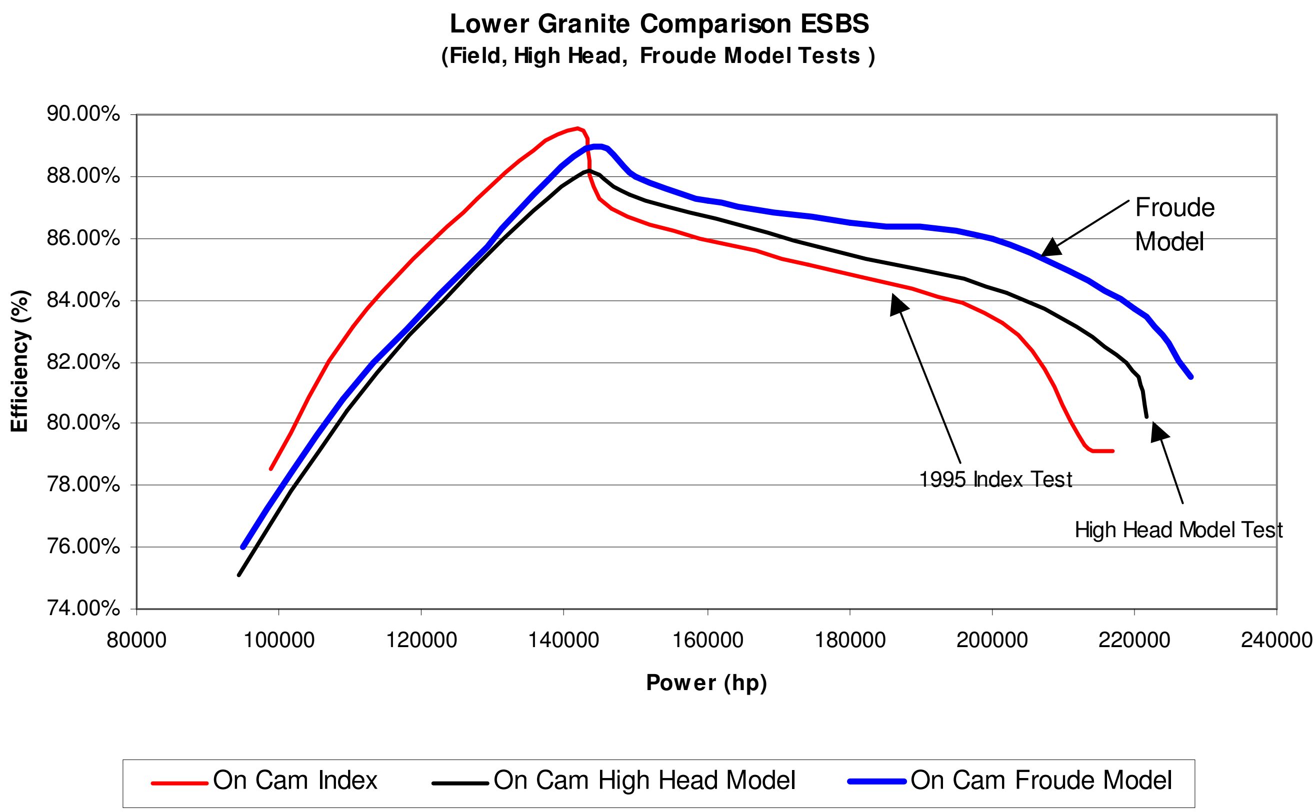

Figure B - 6. Example with ESBS comparison of modeling techniques for the "As Found" field-tested cam

B.3 Minimum Gap Runner (MGR) Performance Modeling

Investigations of potential turbine performance and environmental improvements were made on three projects: McNary, Bonneville I, and Lower Granite. The information learned from these modeling studies is partially transferable to other turbine designs.

B.3.1 McNary

The investigations of minimum gap features were initiated on a preliminary design of Chelan County's Rocky Reach replacement turbine design. This Rocky Reach investigation concentrated on the blade gap at the leading edge on the hub. The McNary initial development occurred subsequent to the Rocky Reach investigations and during the Bonneville I development. The McNary investigations included requirements for full gap elimination and increased power production, and included design information from the Dardanelle turbine rehabilitation. Results indicated that peak turbine efficiency could be improved at the cost of lowered efficiency at high runner blade angles (higher than existing) and at high power levels. This led to consideration of turbine operating range requirements, runner hub design and alteration in minimum blade angles to higher-level angles in future studies. Shown in Figure B - 7 is a comparison of the existing McNary Kaplan, the initial McNary MGR Kaplan, and a state of the art standard Kaplan.

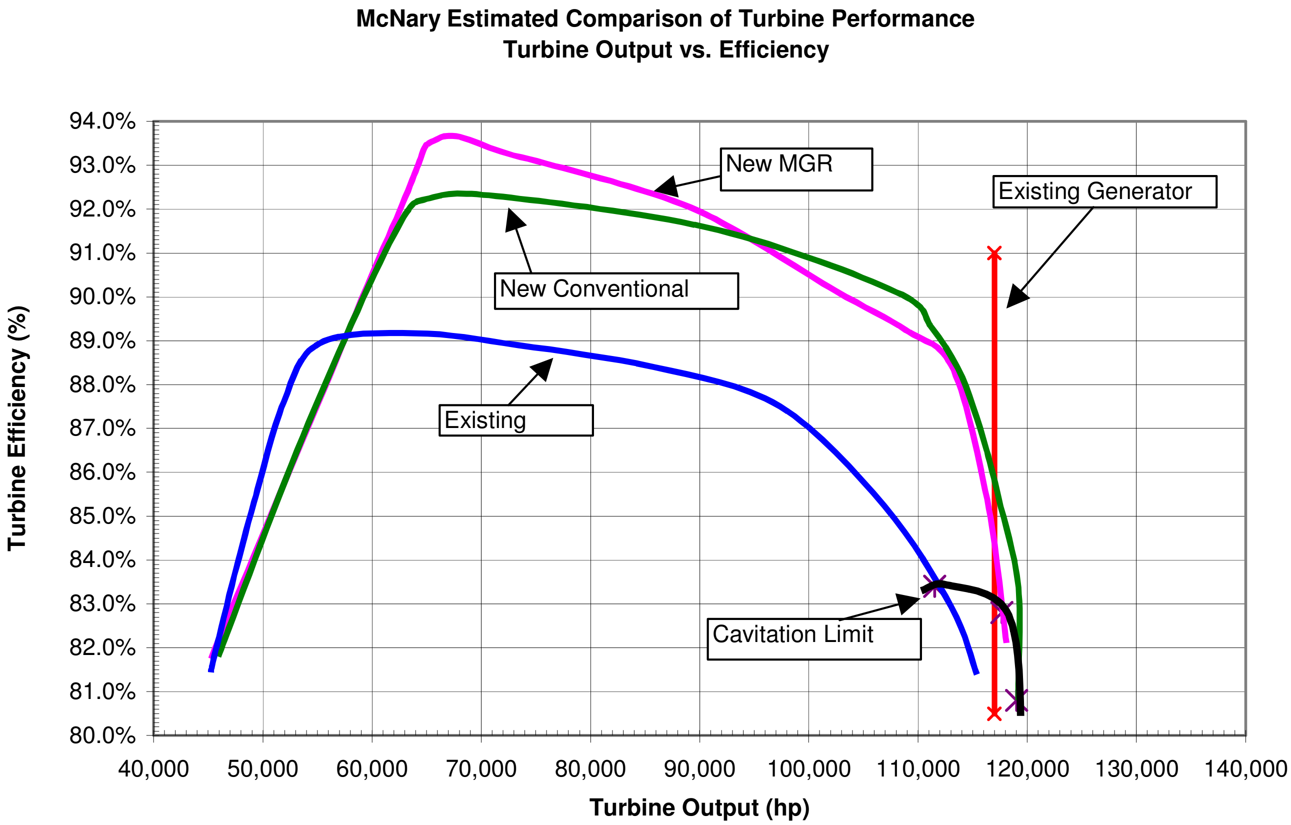

Figure B - 7. Comparison of initial McNary MGR design to other designs

B.3.2 Bonneville I

The performance model testing of the replacement turbine runner for the rehabilitation of Bonneville I Units 1 to 10 was under way in 1995. A standard Kaplan was specified with options for model testing different configurations of the basic design with potential performance and environmental benefits. The improvements made at Rocky Reach, Dardanelle, and other investigations, prompted the Corps to investigate a combination of turbine design features through model testing. The investigations resulted in the MGR design installed at Bonneville I powerhouse. The design features incorporated a spherical discharge ring, spherical hub, an alternative runner blade design, and a modified runner cone. Minimum gaps of the blades existed in the one-percent operating range of the turbine. The performance of the MGR exceeds that of a state of the art design over most of the operating range and exceeds the performance of the existing Kaplan over the entire range. The model testing results were substantiated by performance field-testing of the prototype. Figure B - 8 indicated the turbine performance of the existing turbines, a standard Kaplan turbine without minimum gap features, and the Kaplan design incorporating MGR features.

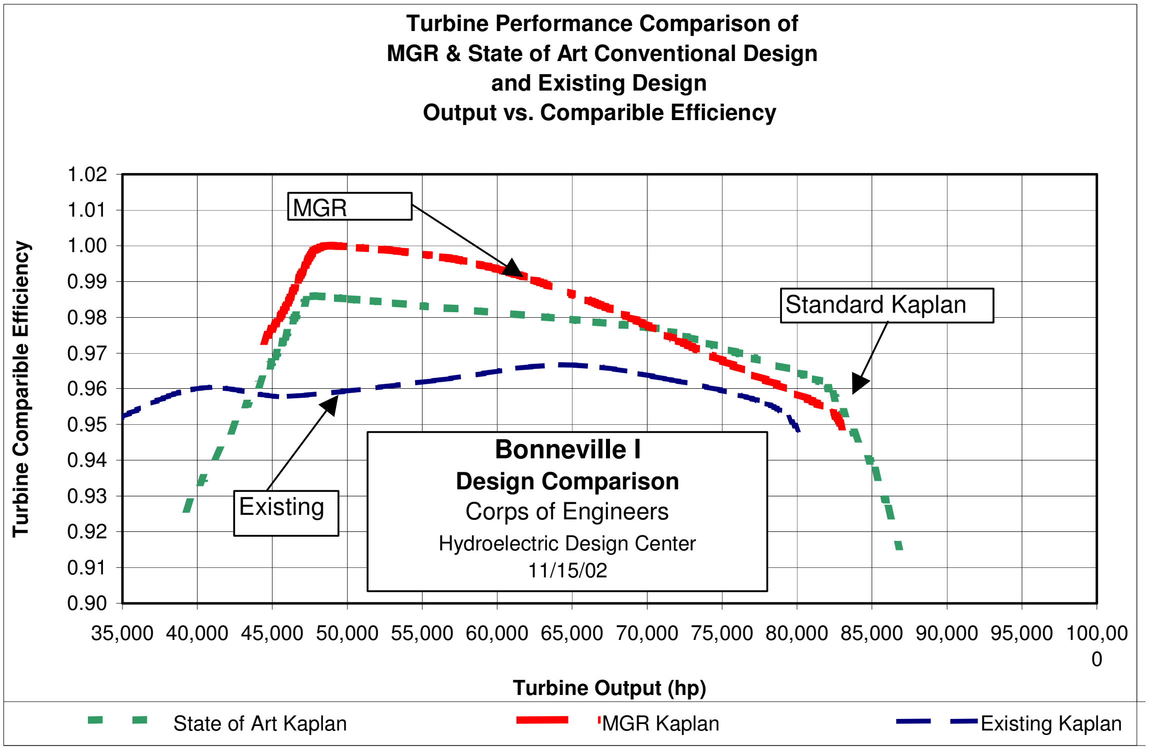

Figure B - 8. Comparison of Bonneville MGR design to other designs

B.3.3 Lower Granite

Performance model testing of a turbine design representing Unit 4 at Lower Granite was performed to evaluate alternate MGR designs. Two alternate MGR designs were investigated. The first design incorporated design features similar to the final Bonneville I design with five runner blades rather than the existing six-blade design. The second design incorporated a reduced blade operating range, MGR features and was of a six-blade design. The results of the investigation are shown in Figure B - 9. The five-blade MGR design was a significant improvement over both the Bonneville I and McNary designs with an improvement at the higher power levels over the existing design and an efficiency improvement of 2 percent. Previous investigations had revealed that the minimum gap at the runner blade periphery, spherical discharge ring design, runner blade number, minimum angle of rotation, operating angle of rotation and thickness affected the peak efficiency, cavitation limitations, and performance at high flow or power levels. A balance of conflicting design requirements was incorporated into the first design. As shown, the MGR design performance is shifted to the left from the original design and does not achieve the desired maximum power level. In addition, the five bladed design results in an unacceptable cavitation limit. The six bladed high blade angle MGR design is also shown on Figure B - 9, this design has MGR features and has a limited blade angle operating range, increases turbine efficiency by about 0.5 percent and the cavitation limitation is acceptable.

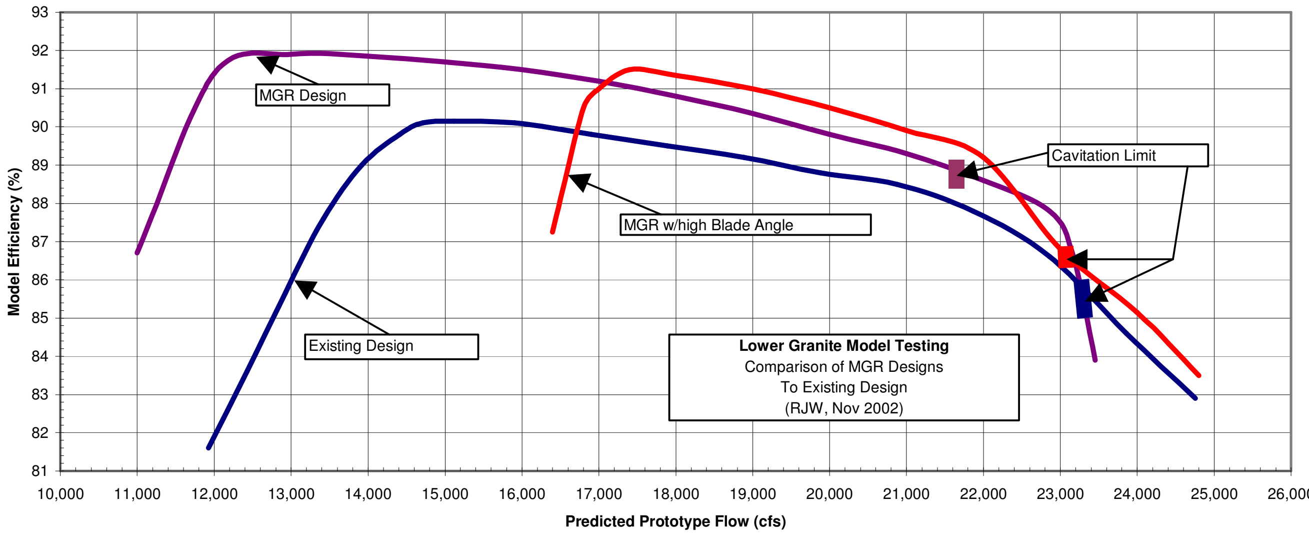

Figure B - 9. Comparisons of Lower Granite MGR designs to existing design

B.4 Draft-tube Model Studies

During the modeling investigations the effects of draft-tubes on turbine performance were investigated to improve flow conditions for fish passage both internal to the draft-tube and for improvement of downstream egress. The draft-tube is an important feature of turbine design with energy recovery of about 15 percent possible. The design of the draft-tube is coupled with the turbine runner design. This is important when turbine rehabilitation and/or replacement are considered.

B.4.1 Draft-tube Modifications

B.4.1.1 McNary Draft-tube Modifications

Two draft-tube modifications were tested in the performance model. The first is a simple change in the geometry of the butterfly shape of the existing draft-tube to a rectangular section with a reduced cross-sectional area. The second is an extension of the draft-tube rectangular area to a cross-sectional area equivalent to the original exit area. Both of the physical modifications are shown on Figure B - 10. Three additional figures are provided to identify the model turbine performance obtained by modifications. Figure B - 11 is the turbine performance of the existing draft-tube. Figure B - 12 is the performance of the first draft-tube modification, which changes the shape to a rectangular exit maintaining the existing draft-tube length. Figure B - 13 is the performance of the second draft-tube modification, maintaining a rectangular exit area and extending the draft-tube to obtain the same exit area as the exiting draft-tube. A comparison of the results of the two modifications to the existing draft-tube is shown in Figure B - 14. Some performance improvement is possible with a draft-tube modification as are potential improvements in fish passage.

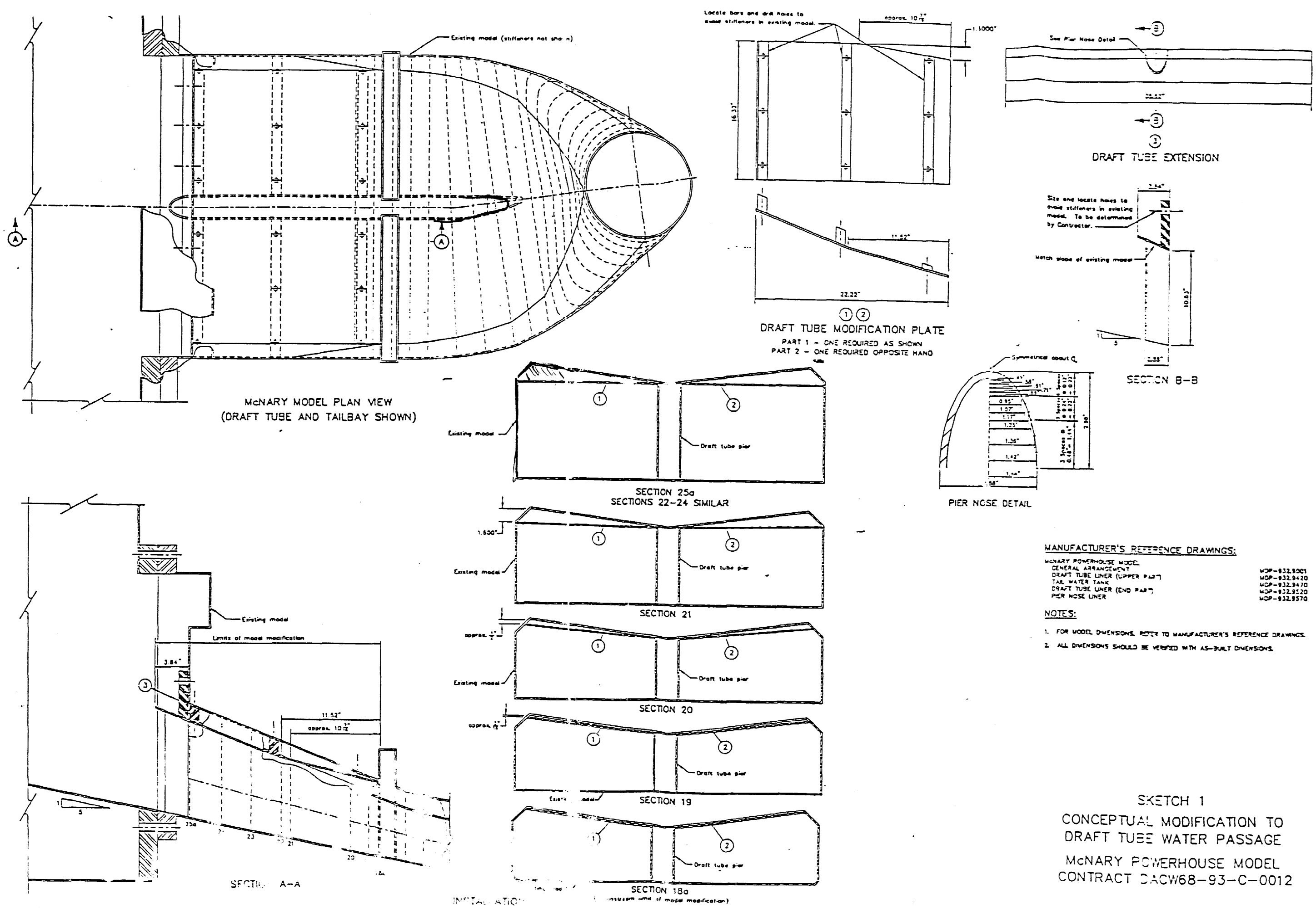

Figure B - 10. McNary draft-tube modifications

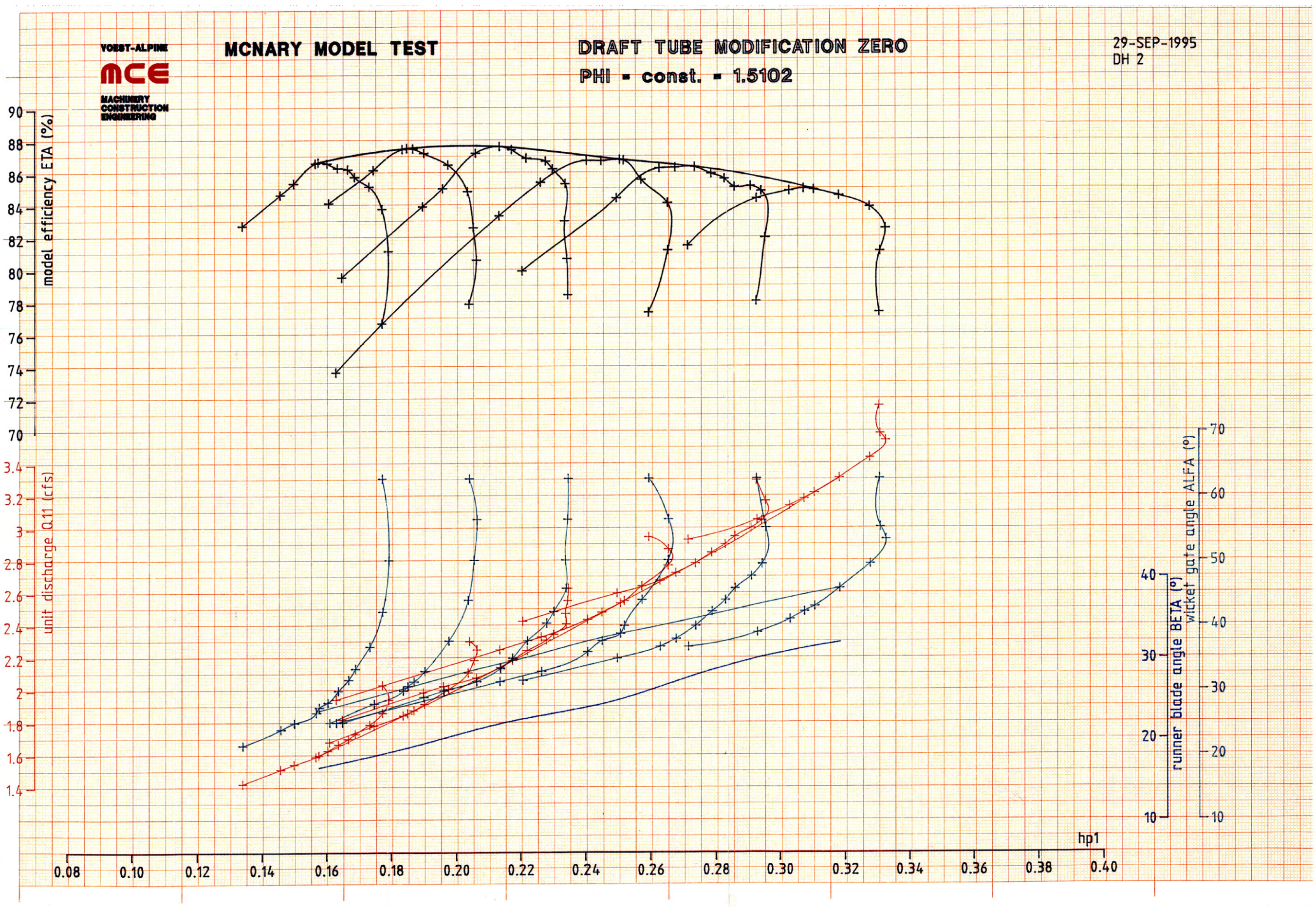

Figure B - 11. Turbine performance with McNary existing draft-tube

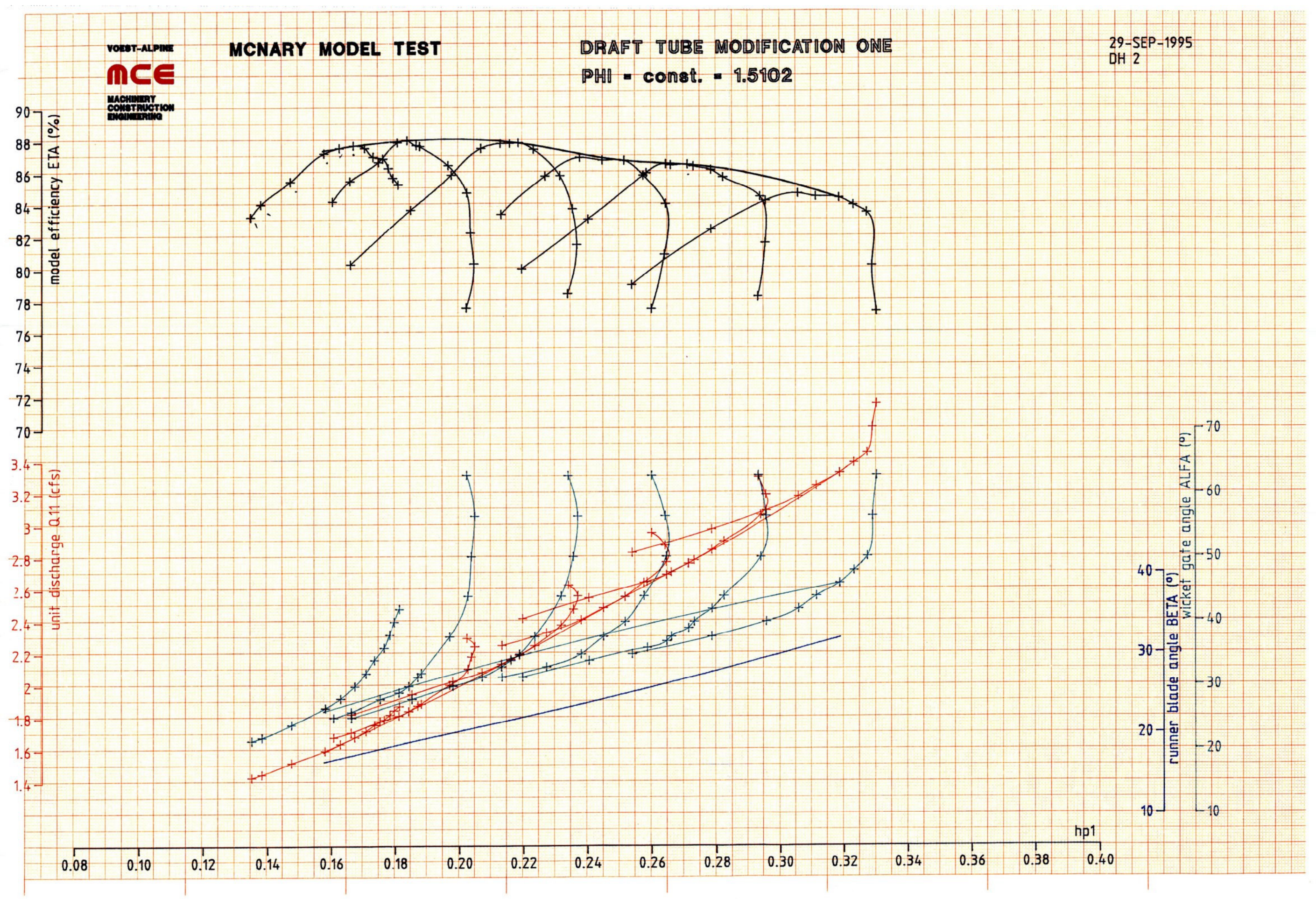

Figure B - 12. Turbine performance with McNary draft-tube modification 1

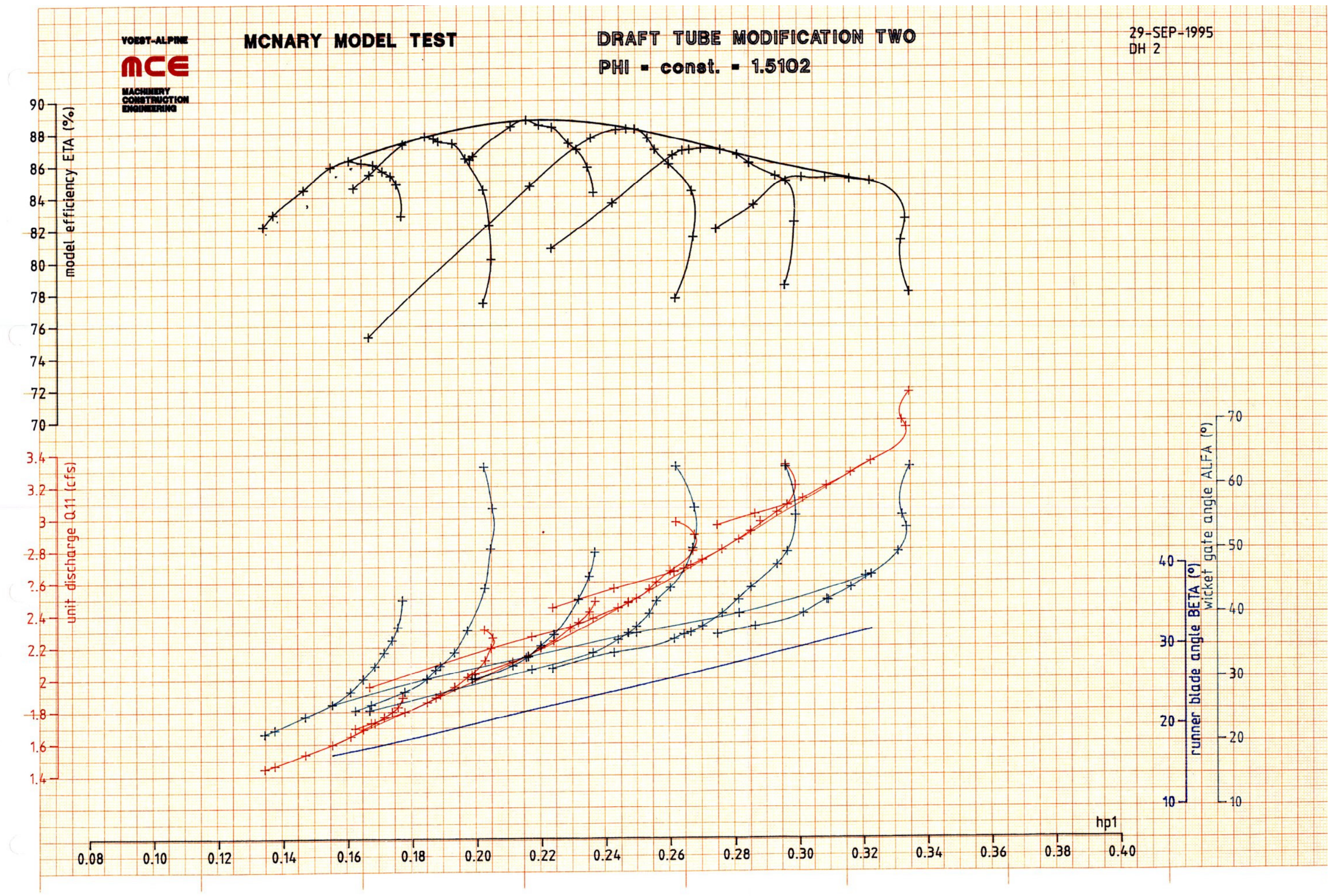

Figure B - 13. Turbine performance with McNary draft-tube modification 2

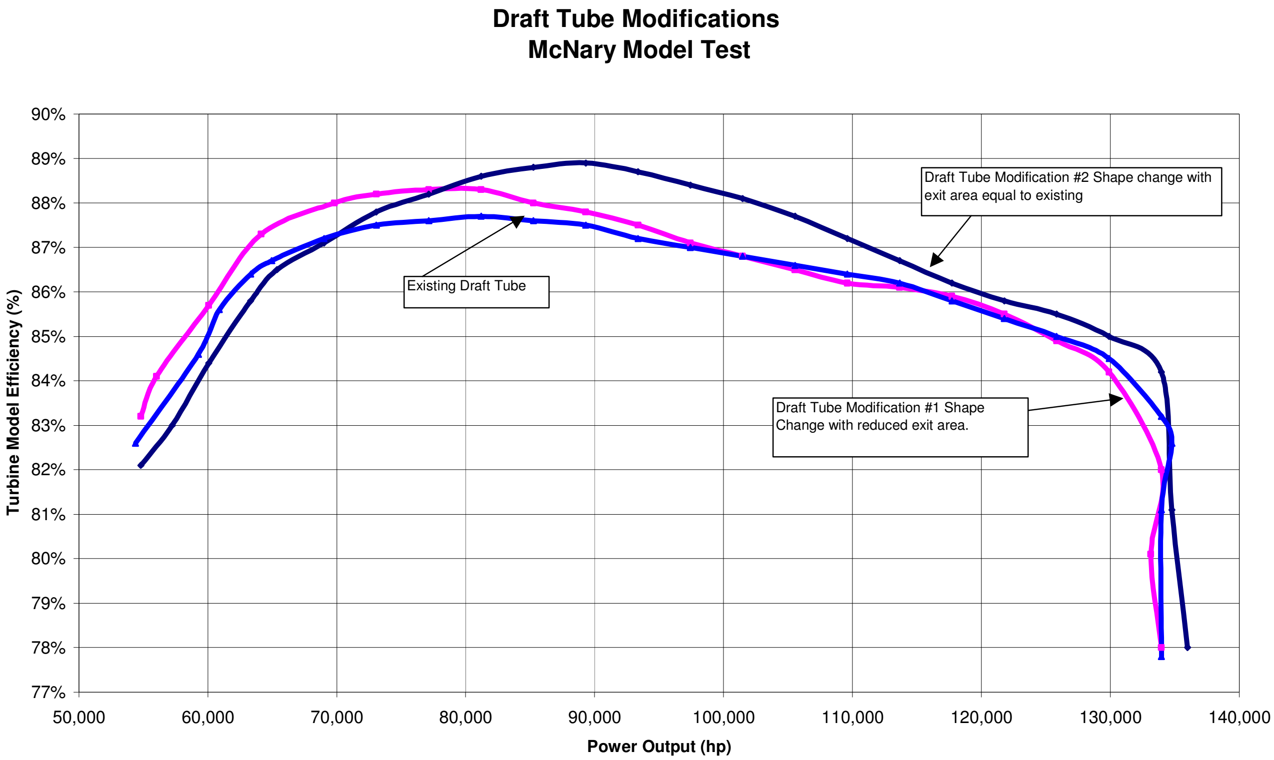

Figure B - 14. McNary draft-tube modifications

B.4.1.2 Lower Granite Draft-tube Modifications and Extensions

Two alternative draft-tube extensions were evaluated in the performance model. The selection of the modifications to be evaluated was based upon work performed at ERDC on multiple design configurations. The TSP team selected the two modifications to be performance model tested after observing the effect on flow turbulence and distribution, see Section 2.5.2.2.4. Figure B - 15 shows the long draft-tube modification that was tested and Figure B - 16 shows the asymmetric configuration. The purpose of the testing was to evaluate turbine performance effects on draft-tube modifications and extensions. The results of these investigations indicated a small improvement in performance is possible. The model performance testing was carried out without fish screens installed and with ESBS screens installed. A comparison of the performance is provided in Figure B - 17 for with ESBS screens installed and Figure B - 18 shows the performance difference without fish screens installed.

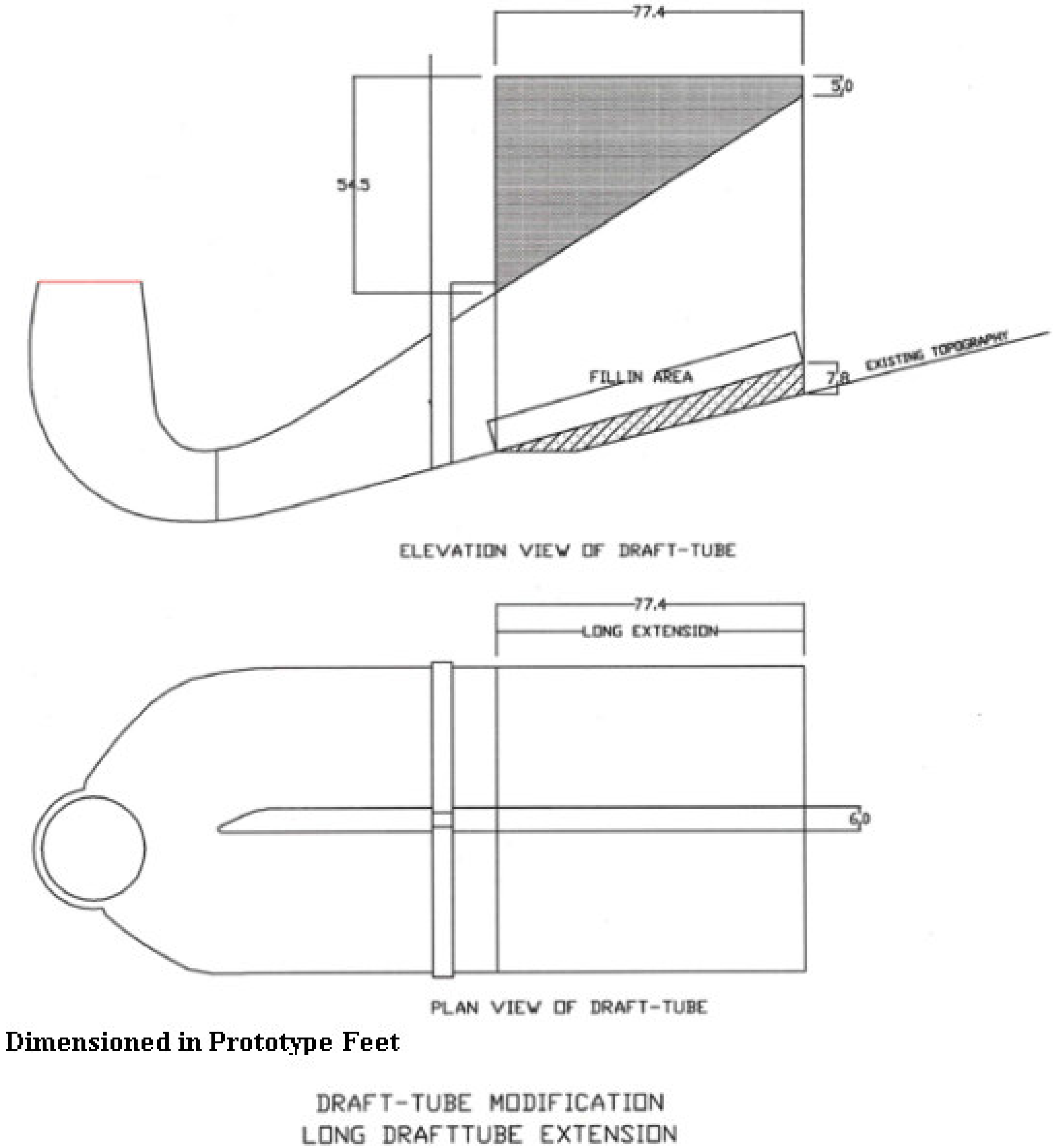

Figure B - 15. Long draft-tube extension performance tested

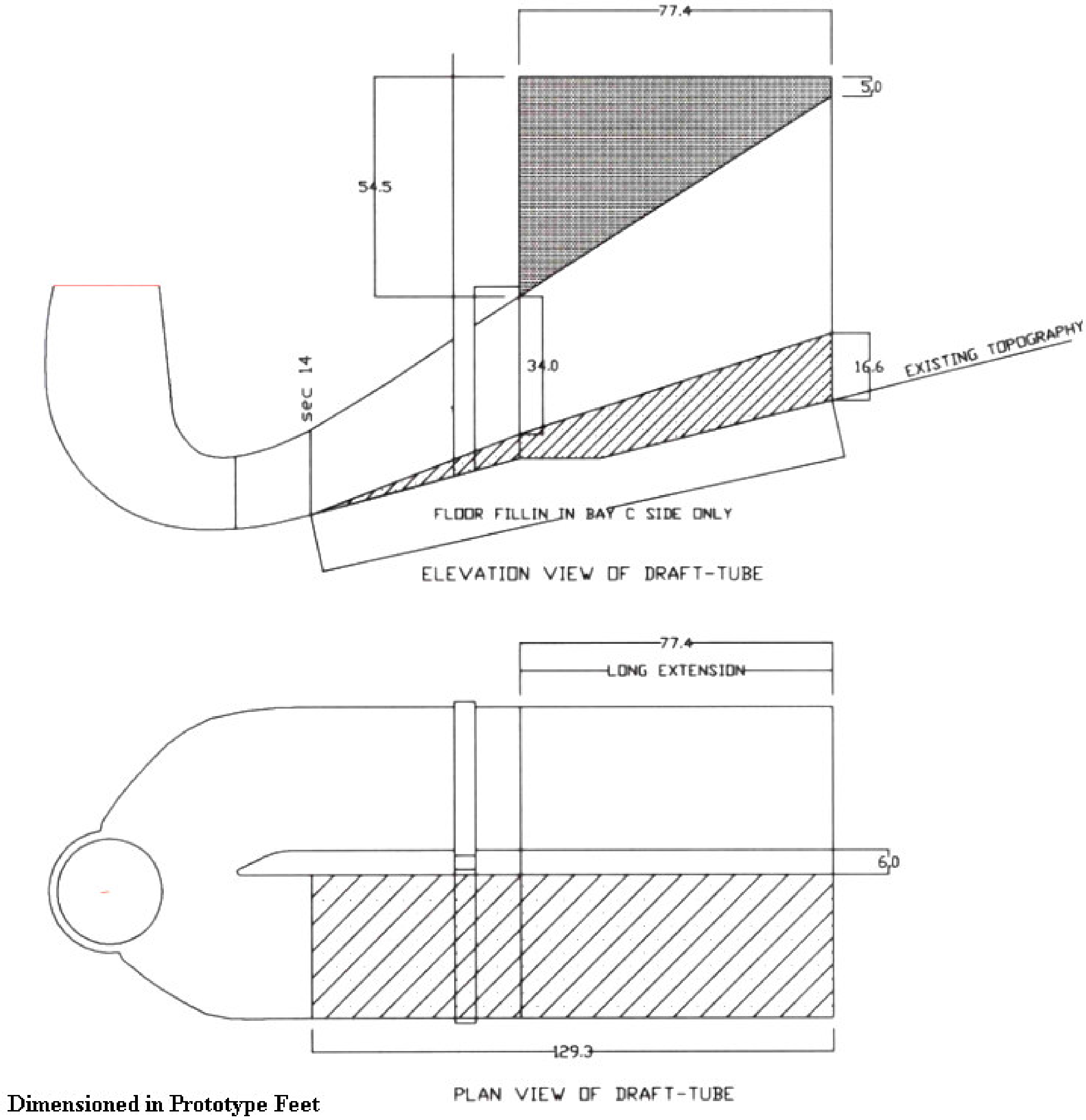

Figure B - 16. Asymmetric long draft-tube extension performance tested

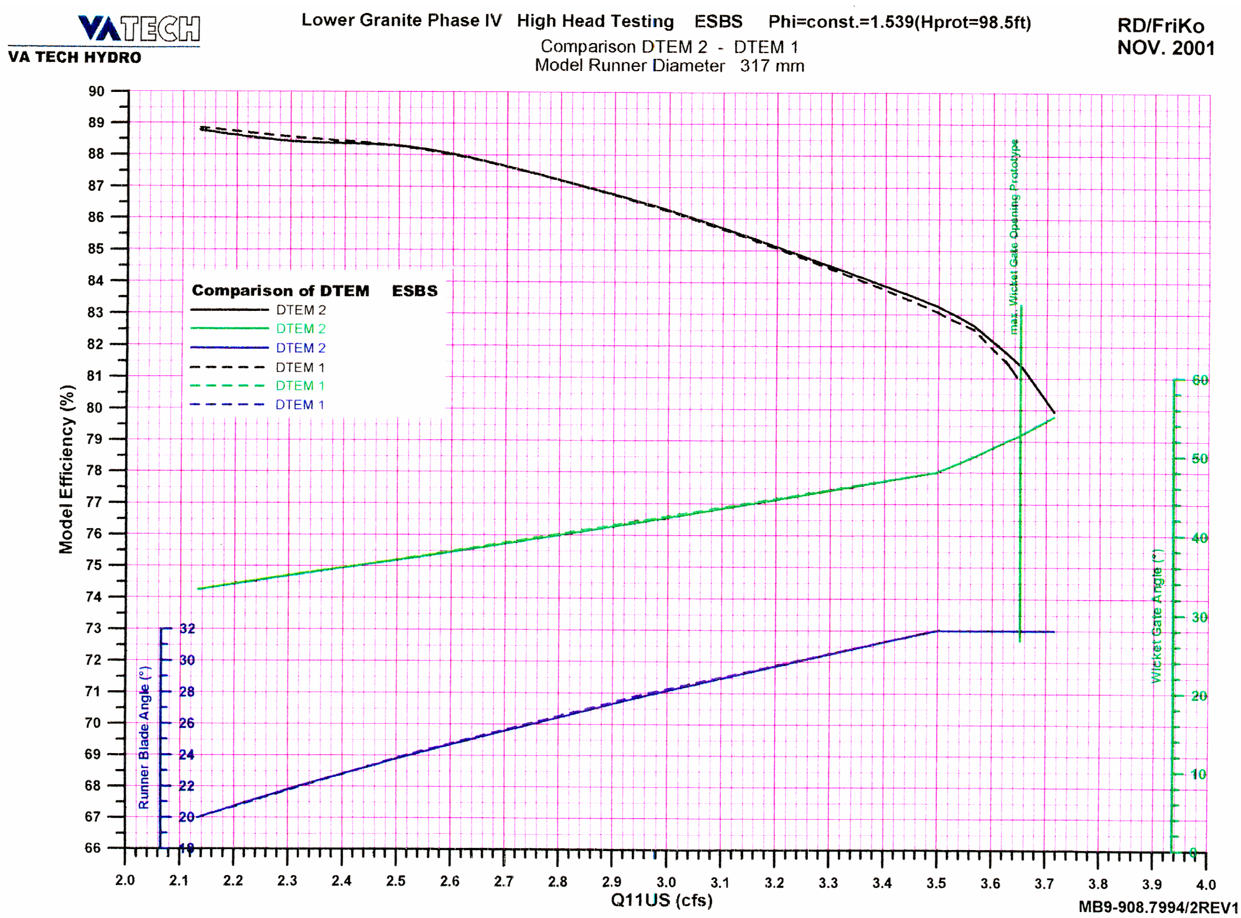

Figure B - 17. Turbine performance with long draft-tube extension - with ESBS installed

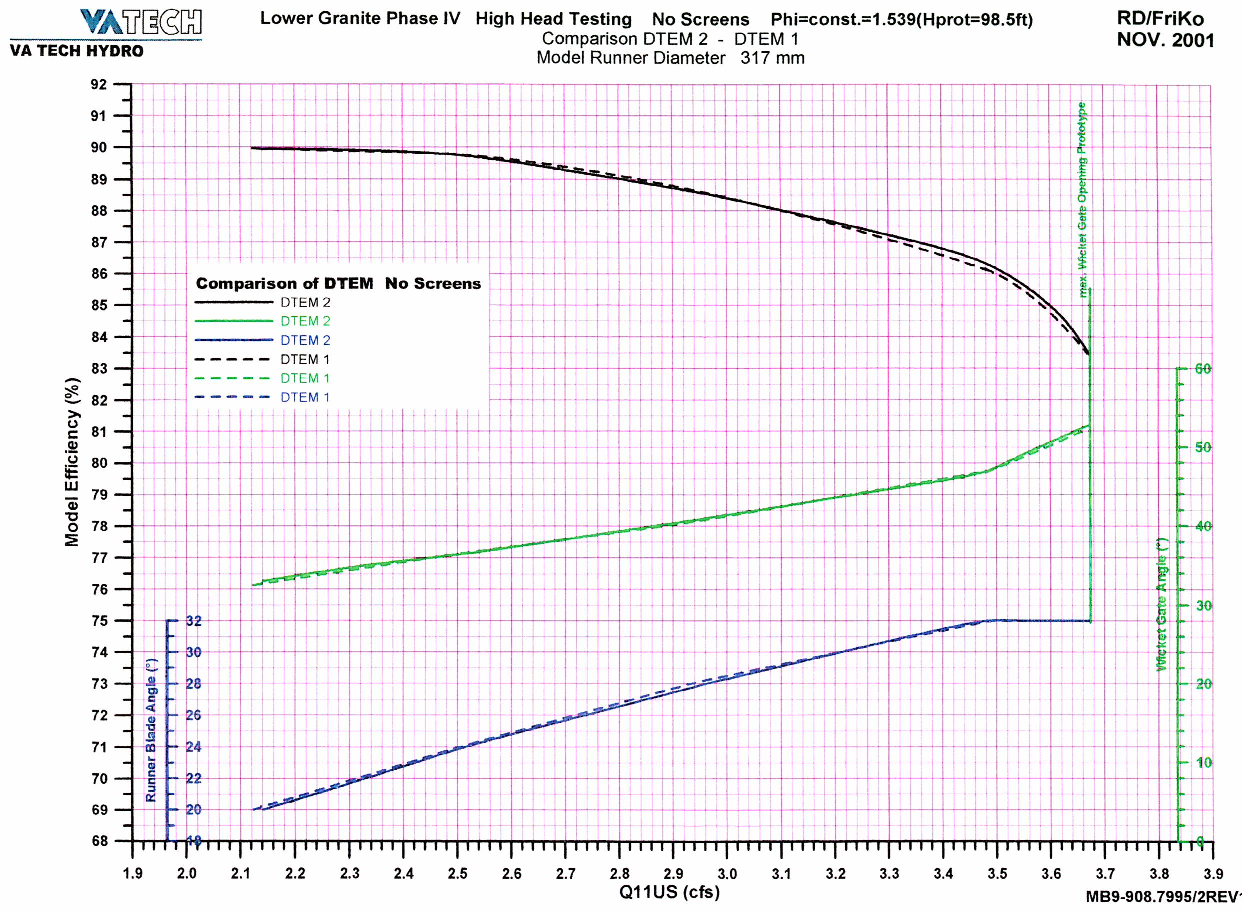

Figure B - 18. Turbine performance with asymmetric draft-tube extension - no screens

B.4.2 Draft-tube Pressure Pulsations

During the investigations of the McNary model, a series of pressure measurements were made in the draft-tube just below the turbine runner to ascertain the magnitude of pressure pulsations. These measurements were performed both with and without ESBS fish screens installed as a pilot investigation to determine the existence and magnitude of any differences between the two screen conditions. Figure B - 19 is a summary of information relating the pressure pulsation increase as a percent to average pressure in the system at various wicket gate positions, heads, and operating conditions. Figure B - 20 is an example of a reduced data set test series for the operating condition at 75 feet of head. This test series was used both with and without screens, near the best operating point for both conditions and with varying tailwater elevation. Figures B - 21 and B - 22 are examples of the recorded data for both without and with ESBS screens installed. In general, the amplitude of the pressure pulsations across the draft-tube are higher with the fish screens installed, which could be expected because of the changes in flow distribution to the runner caused by the fish screens. An evaluation of the pressure pulsation distribution across the draft-tube may be useful in determining the flow conditions entering the draft-tube elbow from various turbine runner designs or draft-tube modifications.

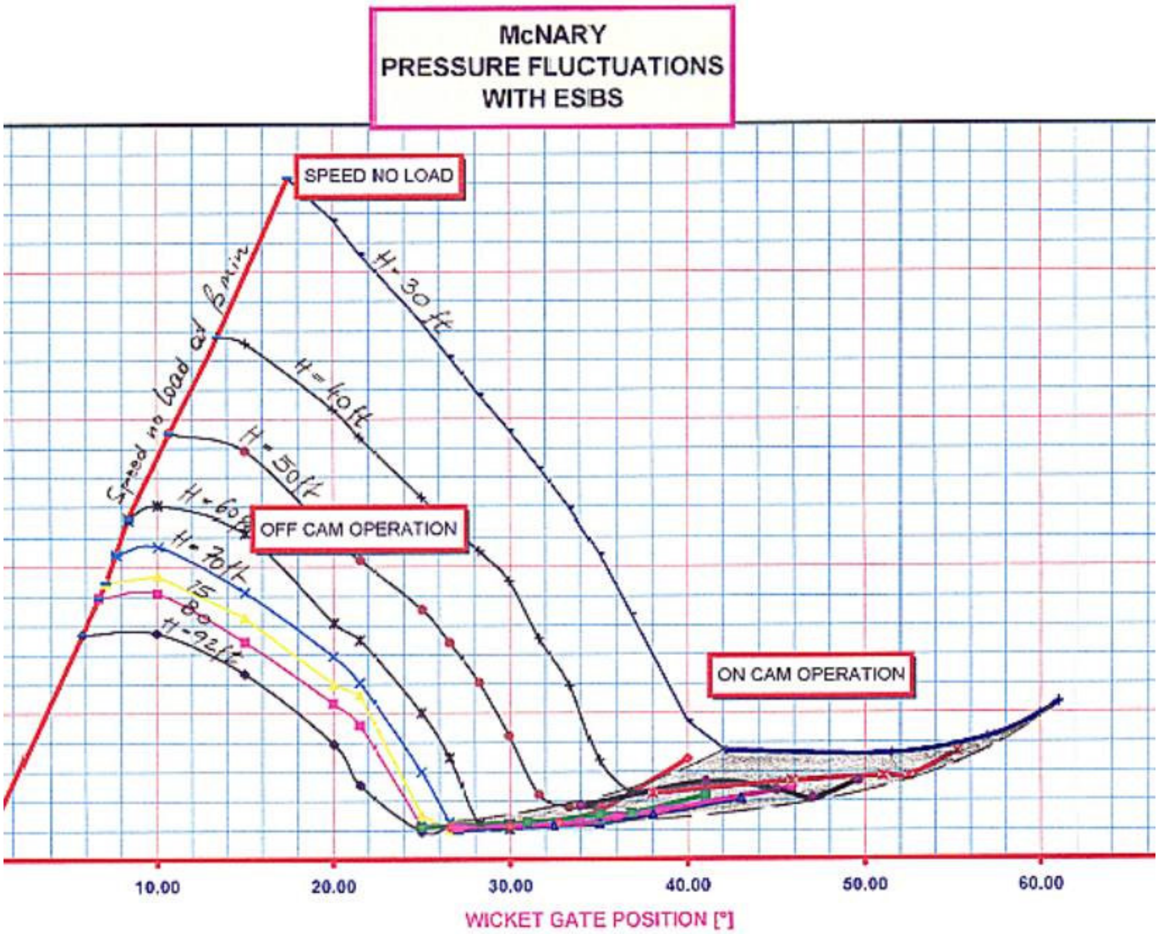

Figure B - 19. Summary draft-tube pressure pulsations with ESBS installed

VOEST-ALPINE MCE MACHINERY CONSTRUCTION ENGINEERING

MC-Nary High Head Testing / Witness Test

Drafttube Pulsations without screens

N= 85,71rpm Cl= 70,38m Hv= 0,096m
D= 7,1247m Ha= 10,25m

H_p= 75 ft

Testseries: 6255 14. Mai 1996 Measuring tap No. ① Measuring tap No. ② tape
Log-Sheet Nr.: 15

Mp	α	β	N11	Hmod	TWL	σ	dH/2	ΔH/H	dH/2	ΔH/H	ID Nr	frame	
[-]	[°]	[°]	[1/min]	[m]	[ft]	[-]	[mWC]	[%]	[mWC]	[%]		from	to
5	36,84	28,0	127,72	16,13	critical	0,4787	0,182	2,3%	0,233	2,9%	21	41999	44022
4	36,84	28,0	127,72	16,13	246	0,6484	0,0974	1,2%	0,0667	0,8%	20	39990	41999
3	36,84	28,0	127,72	16,13	257	0,7900	0,0958	1,2%	0,0659	0,8%	19	38057	39990
2	36,84	28,0	127,72	16,13	265	0,8923	0,091	1,1%	0,0666	0,8%	18	35998	38057

Drafttube Pulsations with long screens

Testseries: 6255 17. Mai 1996 Measuring tap No. ① Measuring tap No. ② tape
Log-Sheet Nr.: 32

Mp	α	β	N11	Hmod	TWL	σ	dH/2	ΔH/H	dH/2	ΔH/H	ID Nr	frame	
[-]	[°]	[°]	[1/min]	[m]	[ft]	[-]	[mWC]	[%]	[mWC]	[%]		from	to
5	35,00	25,2	127,72	8,42	critical	0,4052	0,0808	1,9%	0,098	2,3%	37	74002	76000
4	35,00	25,2	127,72	8,42	246	0,6387	0,0561	1,3%	0,055	1,3%	36	71997	74002
3	35,00	25,2	127,72	8,42	257	0,7882	0,0583	1,4%	0,0597	1,4%	35	70031	71997
2	35,00	25,2	127,72	8,42	265	0,9054	0,0575	1,4%	0,0577	1,4%	34	68005	70031

Figure B - 20. Comparison of best operating point with and without screens installed and varying tailwater

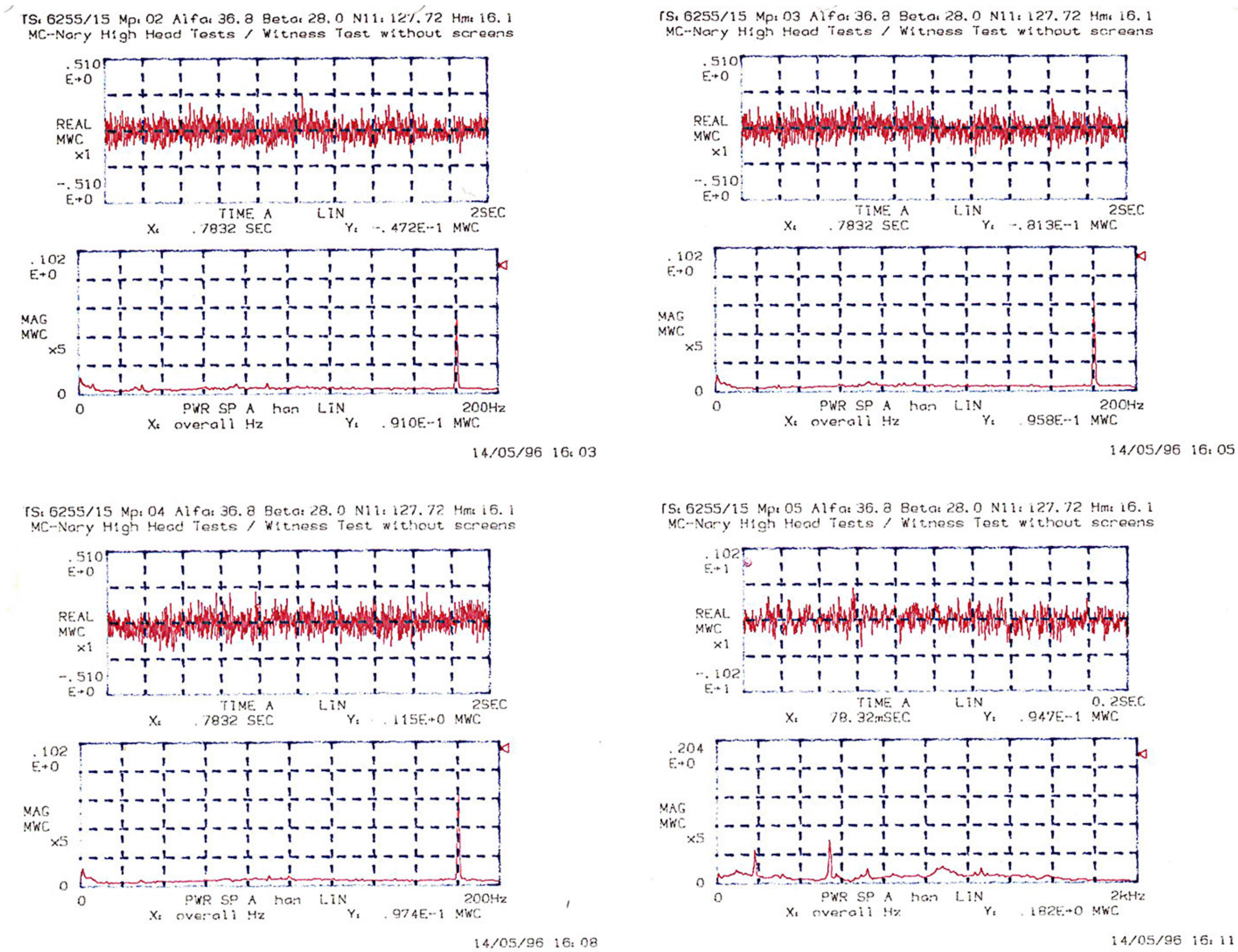

Figure B - 21. Example of recorded data with no screens installed

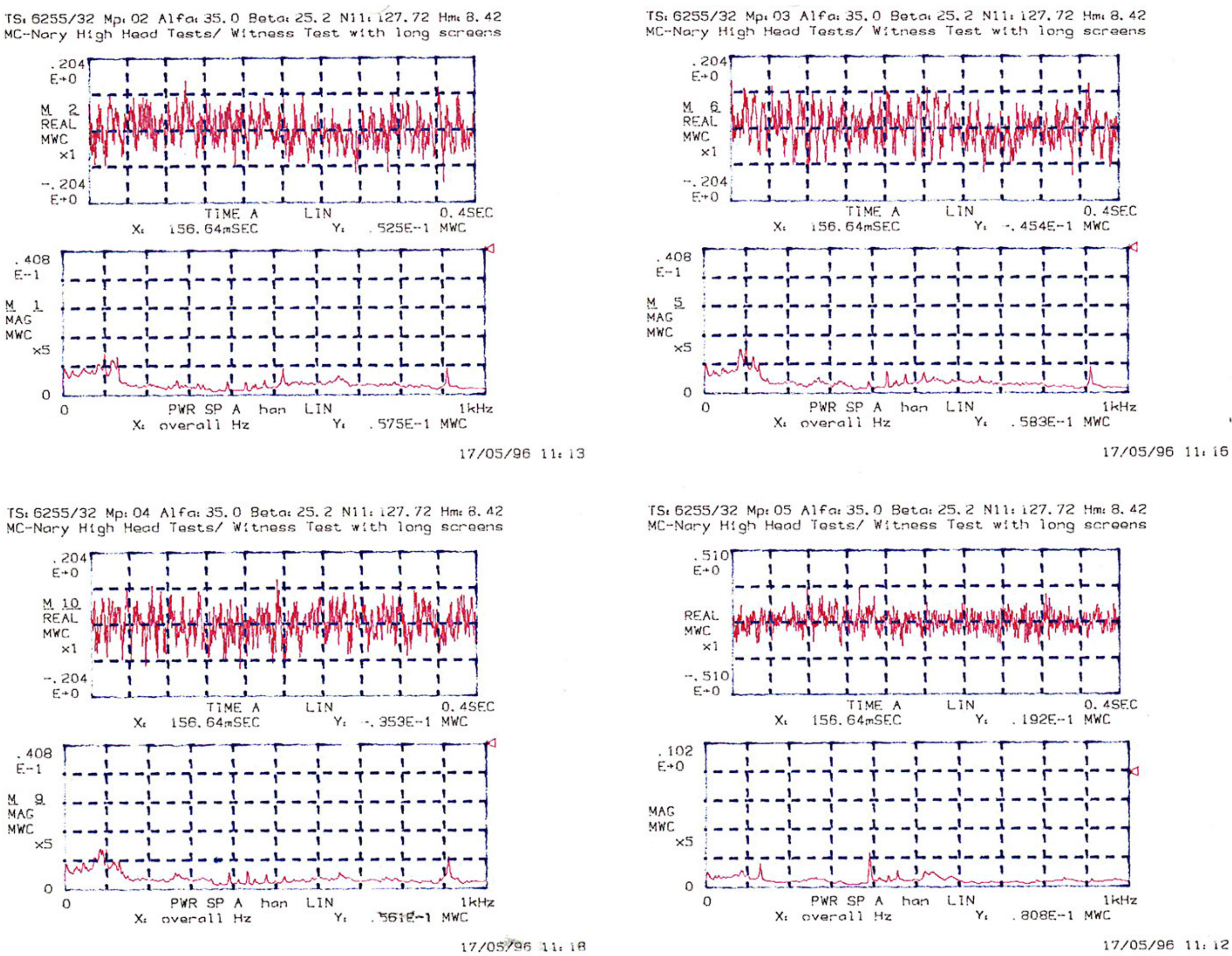

Figure B - 22. Example data of pressure pulsation with ESBS screens installed

B.5 Stay Vane/Wicket Gate Studies

B.5.1 CFD Studies

CFD studies were performed on a Lower Granite CFD model to investigate shape changes, the stay vane and wicket gate relationship, and possible performance and potential environmental improvements. Figure B - 23 shows a computer-generated view of the CFD model intake and turbine distributor. This CFD model was used to investigate a number of configurations. Initial investigations indicated improvement to the stay vanes could be beneficial. Different alignments and shapes were considered which resulted in configurations for actual model testing. Figure B - 24 is the drawing of the three stay vane modifications used in the final CFD studies. Figure B - 25 shows an example of the effect of reshaping the nose of the stay vane over the existing shape at the same operating point. Figure B - 26 shows an example CFD comparison of the opening of the wicket gate to the stay vane at two operating points within the existing one-percent operating limit.

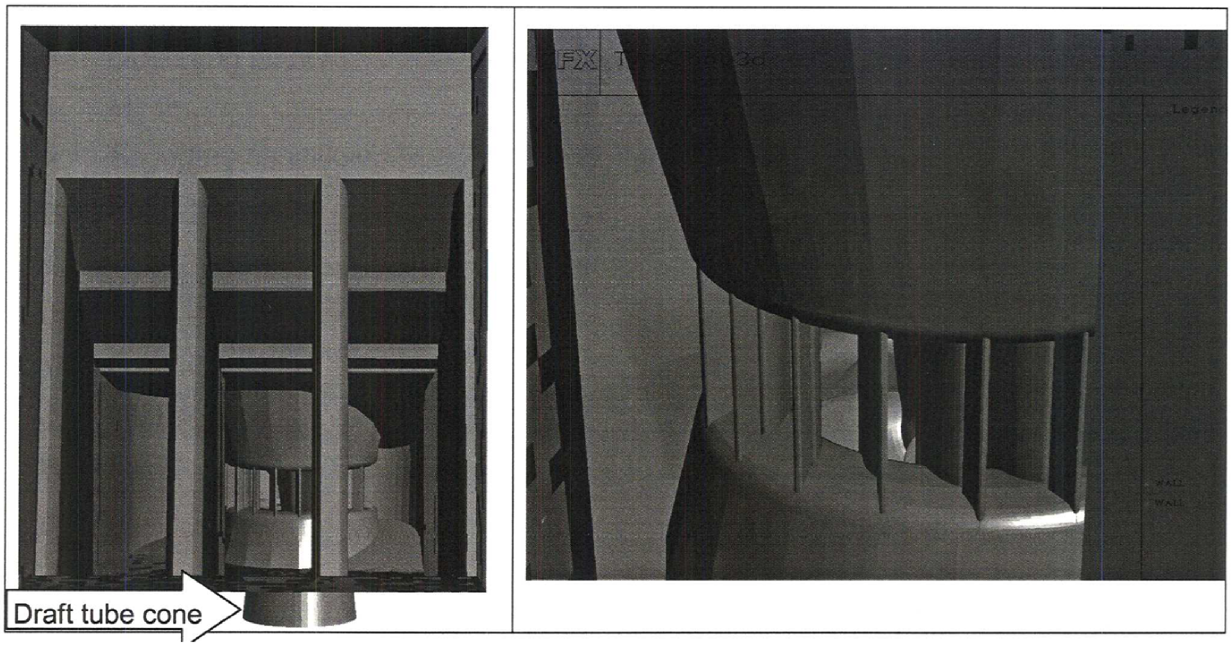

Figure B - 23. Computer generated model of intake and turbine distributor

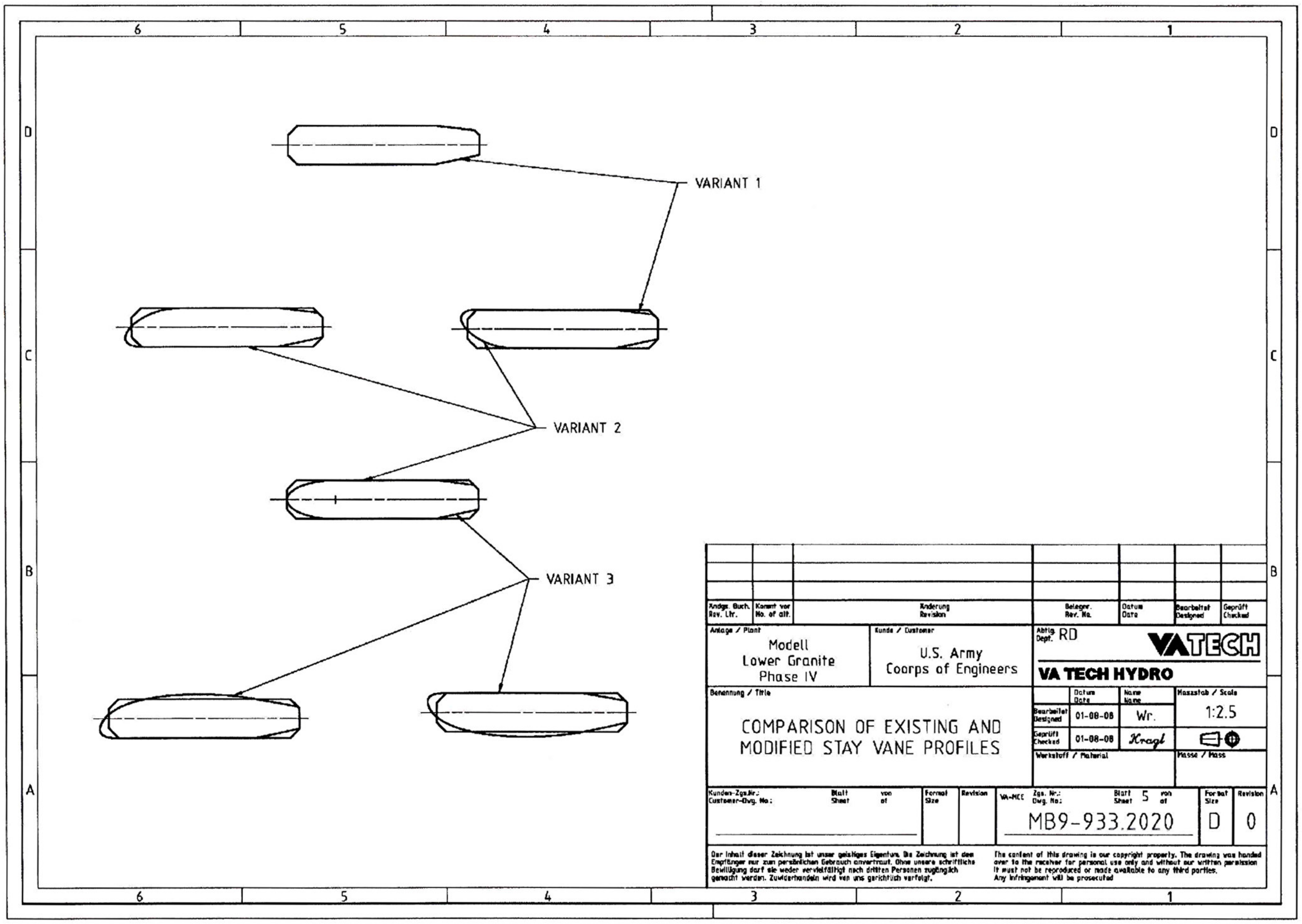

Figure B - 24. The stay vane modifications results used in the Lower Granite CFD study

VA TECH HYDRO

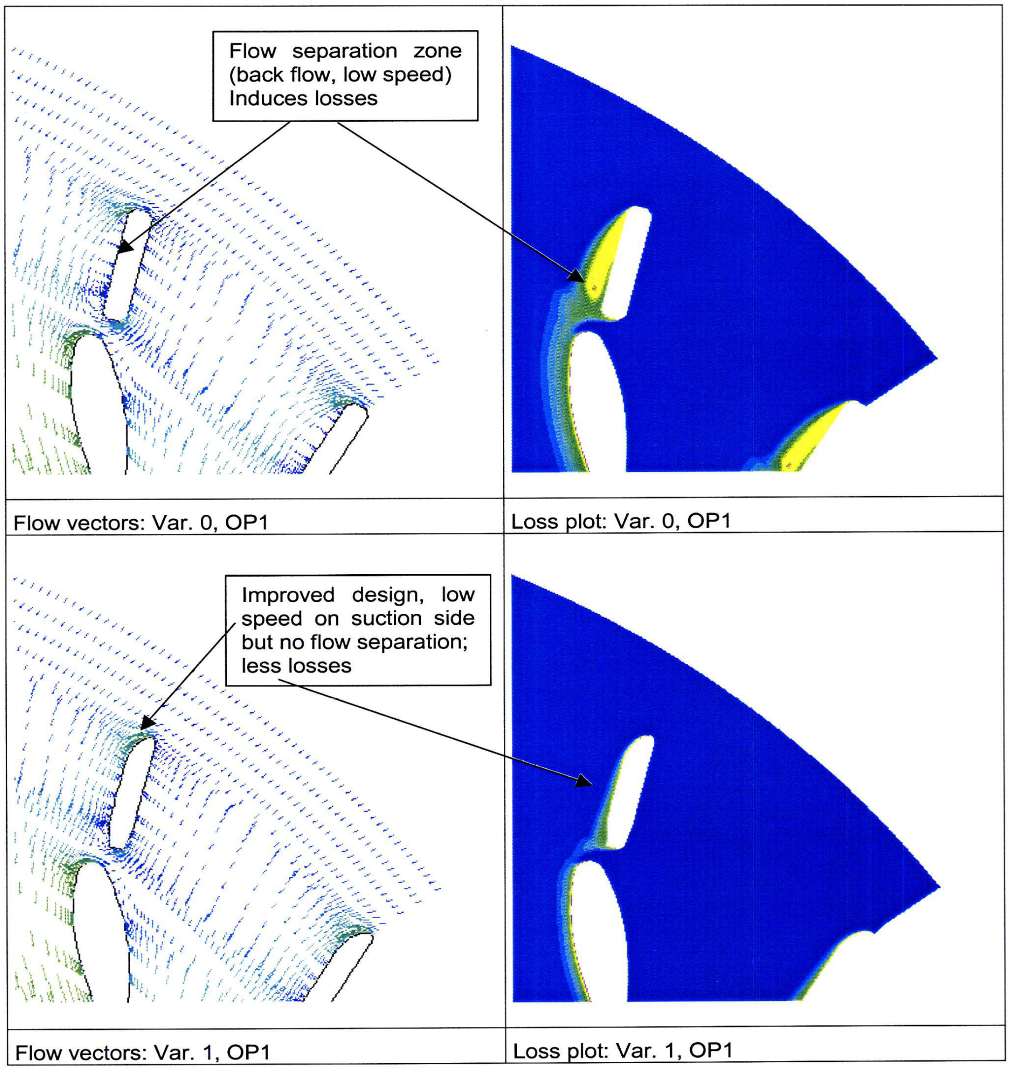

Fig. 24: Flow separation

Figure B - 25. Example CFD output showing existing stay vane and one option examined

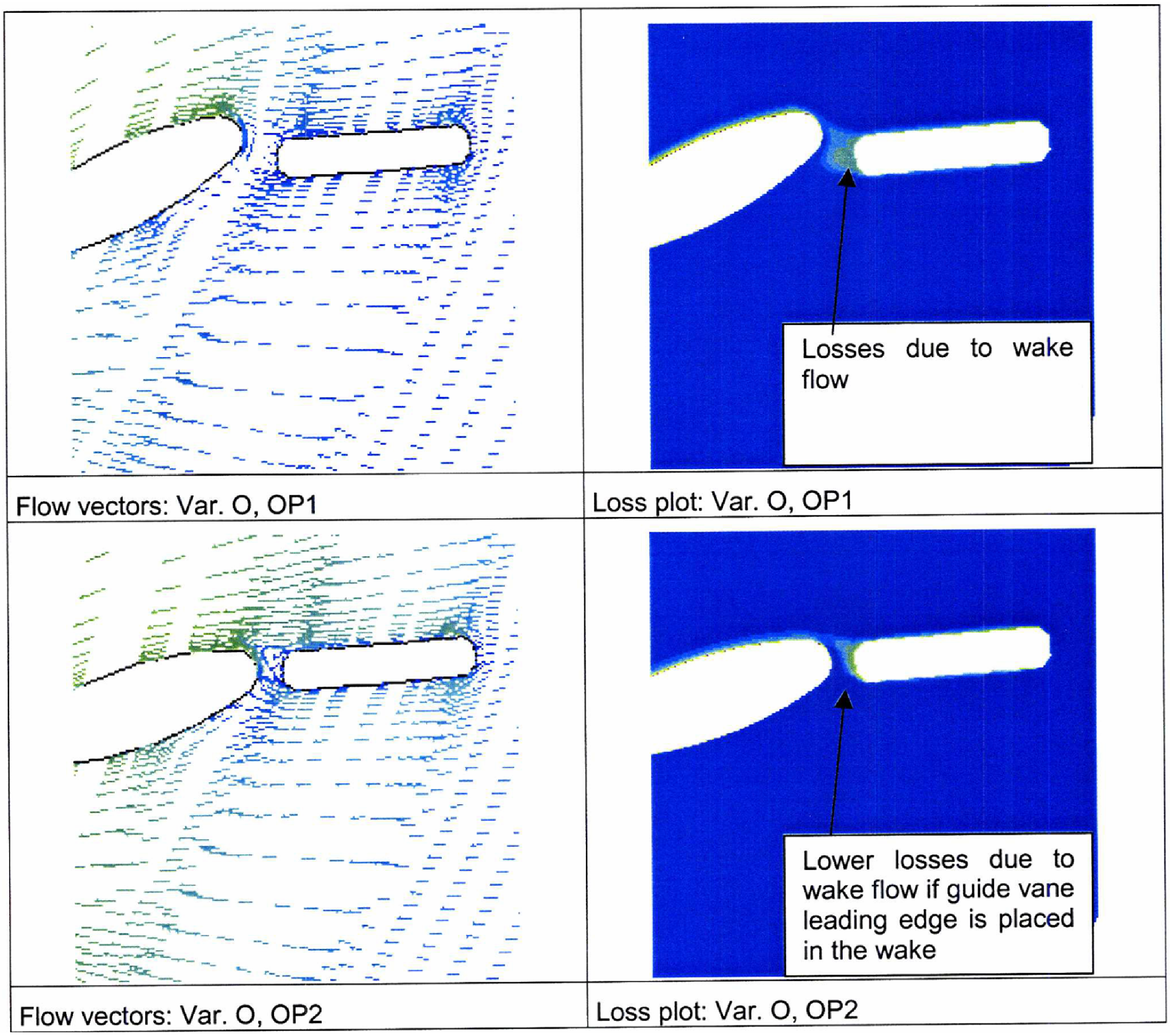

Figure B - 26. CFD output of wicket gate opening to stay vane relationship of existing geometry

B.5.2 Physical Model Performance

The final modified stay vane-wicket gate (SVWG) design was fabricated and installed in the Lower Granite model turbine and performance tested under with three different Kaplan turbine runners. The runners tested with the configuration are the existing runner, a wide operating range MGR, and a limited operating range MGR. All the turbine runners are of a different design using the final SVWG arrangement. Figure B - 27 shows the comparison of the SVWG modification with the existing Lower Granite configuration. There is measurable improvement over most of the range of operation. Figure B - 28 shows a similar comparison with the five bladed MGR turbine runner installed. The comparison shows a higher increase in efficiency over the existing arrangement and is over most of the range of turbine operation. Figure B - 29 shows the high blade angle limited operating MGR turbine runner compared to the existing SVWG configuration. There is substantial improvement in performance over the operating range of the turbine.

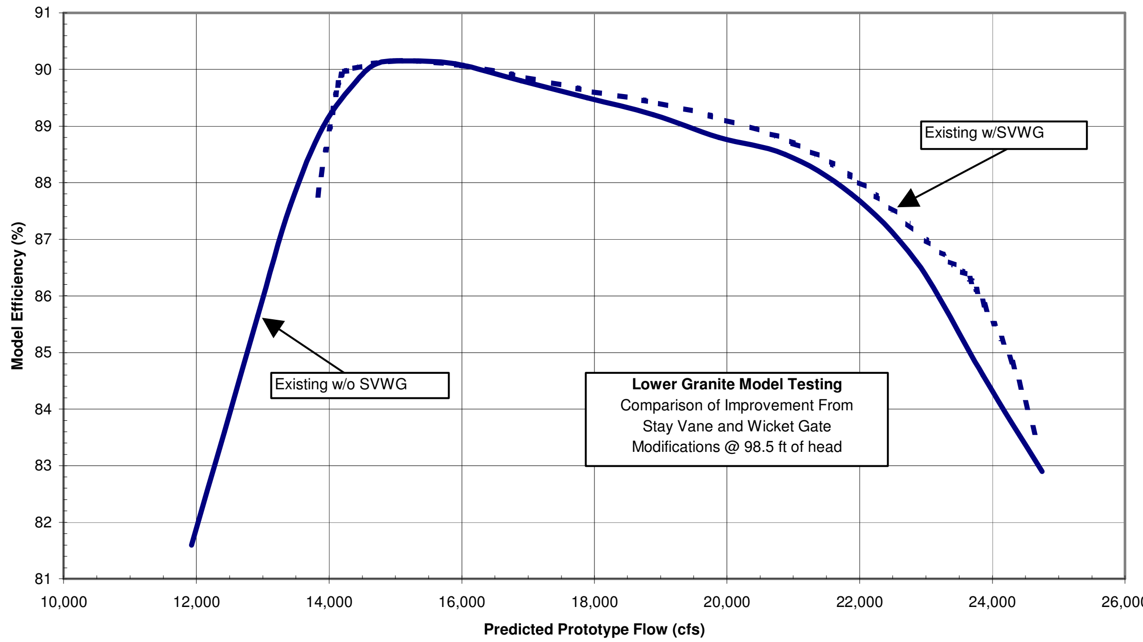

Figure B - 27. Performance improvement of the modified SVWG over the existing design

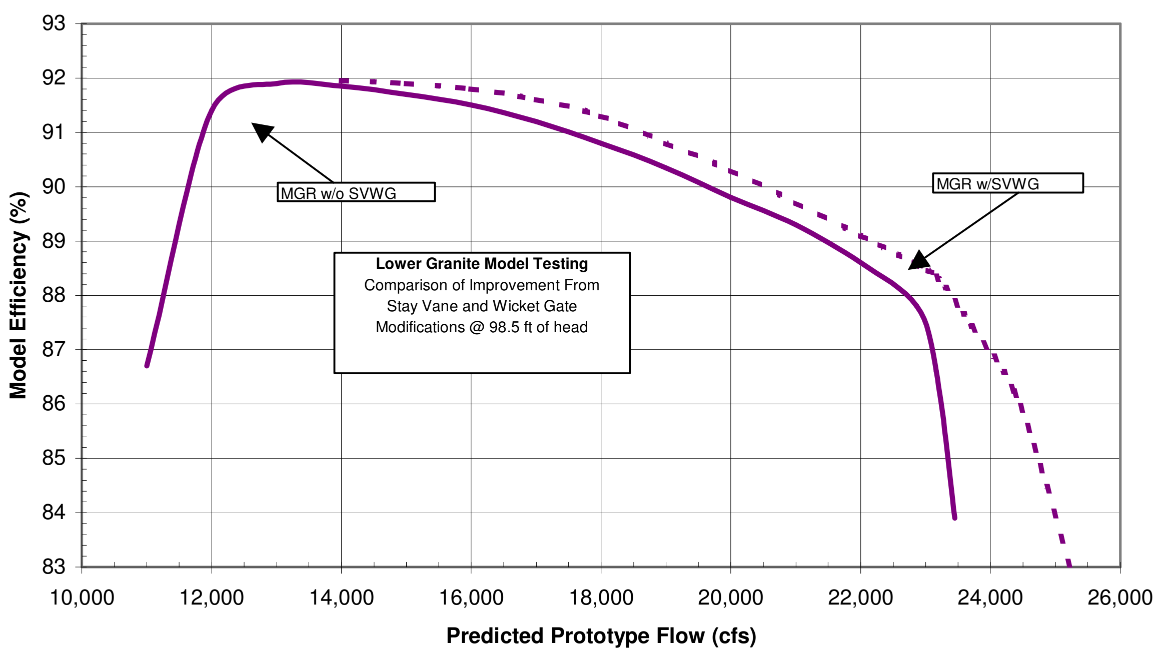

Figure B - 28. Comparison of performance for five-bladed MGR design with the modified SVWG design

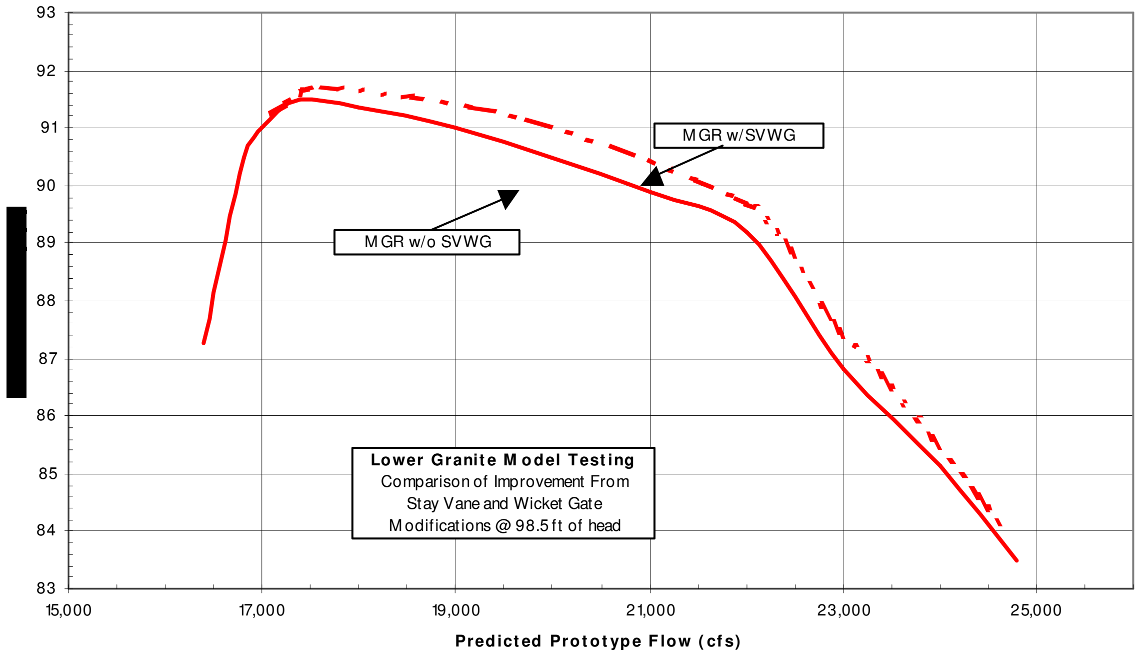

Figure B - 29. Comparison of performance: limited operating range MGR design to modified SVWG design

B.6 Alternate Relative Flow Measurements

The determination of flow in a Kaplan turbine is critical to establish the correct optimum blade-gate relationship. With fish diversion devices installed, the historical measurement system (Winter-Kennedy) produced inconsistent results. Investigations were undertaken during model testing to evaluate alternative measurement locations. The concept of the investigation was to determine stability. The model testing was performed for three conditions: no screens installed, with STS screens installed, and with ESBS screens installed. Figure B - 30 shows the various alternatives that were investigated: Winter-Kennedy taps, Peck taps at three locations, and Wittinger taps. In addition, the use of Scintillation (acoustics) as an alternate was investigated.

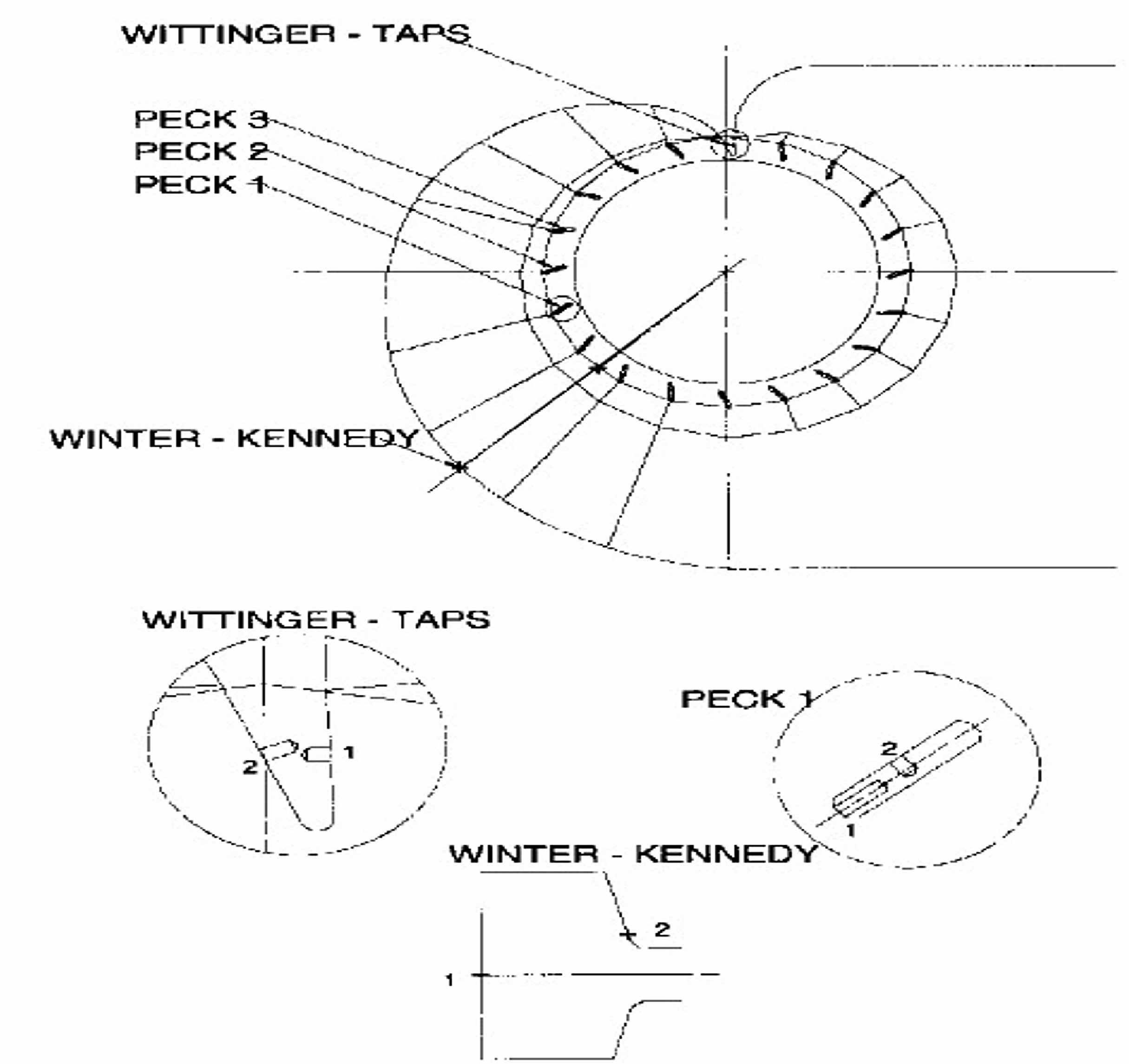

Figure B - 30. Sketch of the locations of the piezometric taps investigated during model testing

B.6.1 Winter-Kennedy Taps

Figure B - 31 shows the summary results of the testing. The Winter-Kennedy taps show reasonable stability for each of the conditions tested. This indicates that the taps could be used for installation of fish diversion devices; however, a separate calibration would have to occur for each different fish diversion device installed. The Winter-Kennedy taps appear suitable for the Lower Granite turbines, however this may not be valid for other turbines at other projects. Winter-Kennedy taps will be used as a basic measurement for flow until another method is found suitable for with fish diversion devices installed.

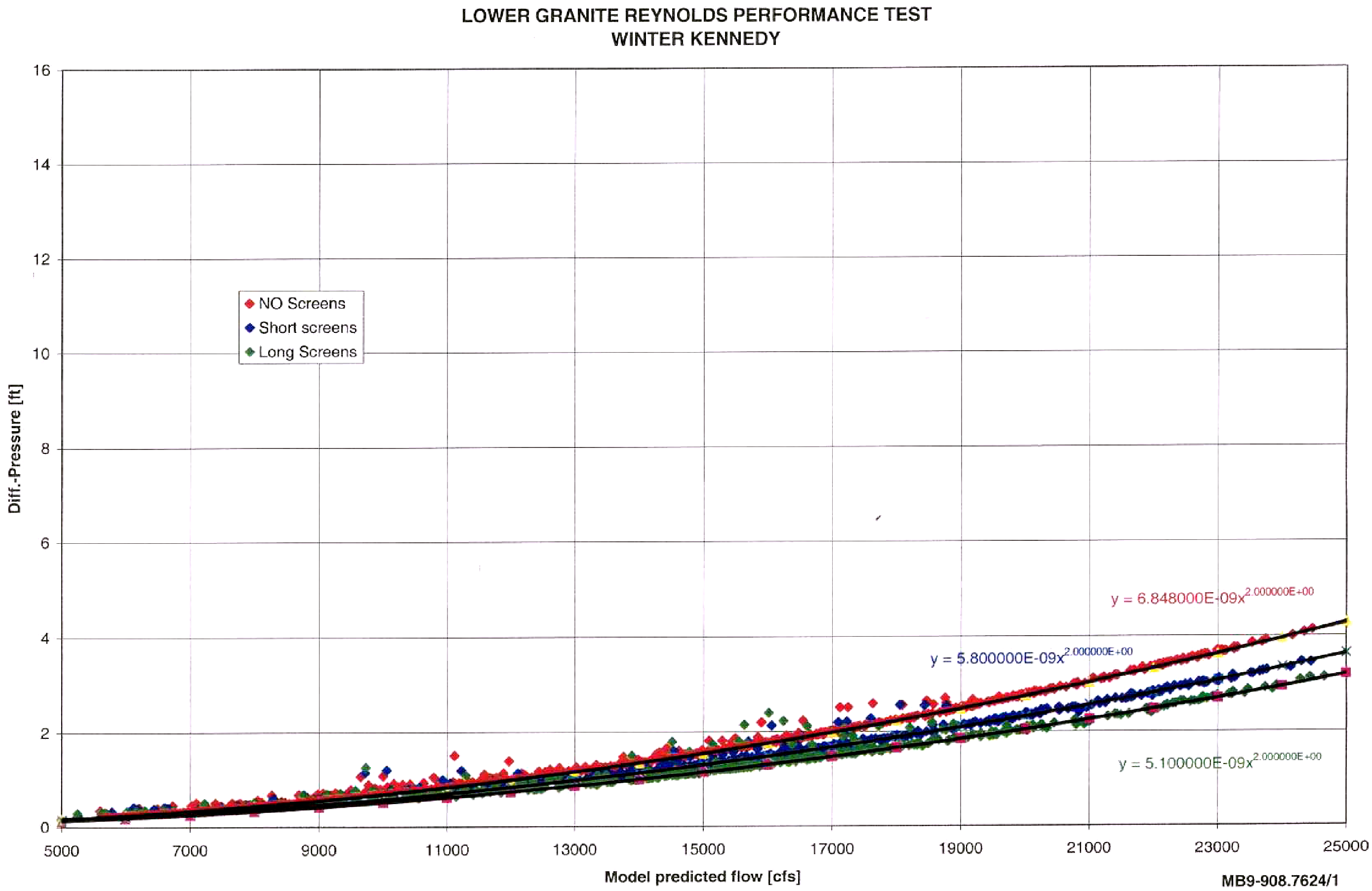

Figure B - 31. Results of Winter-Kennedy investigations

B.6.2 Peck Taps

Three sets of Peck taps were investigated. The stability of all three sets was unsatisfactory. Figures B - 32, B - 33 and B - 34 show the results of the model testing.

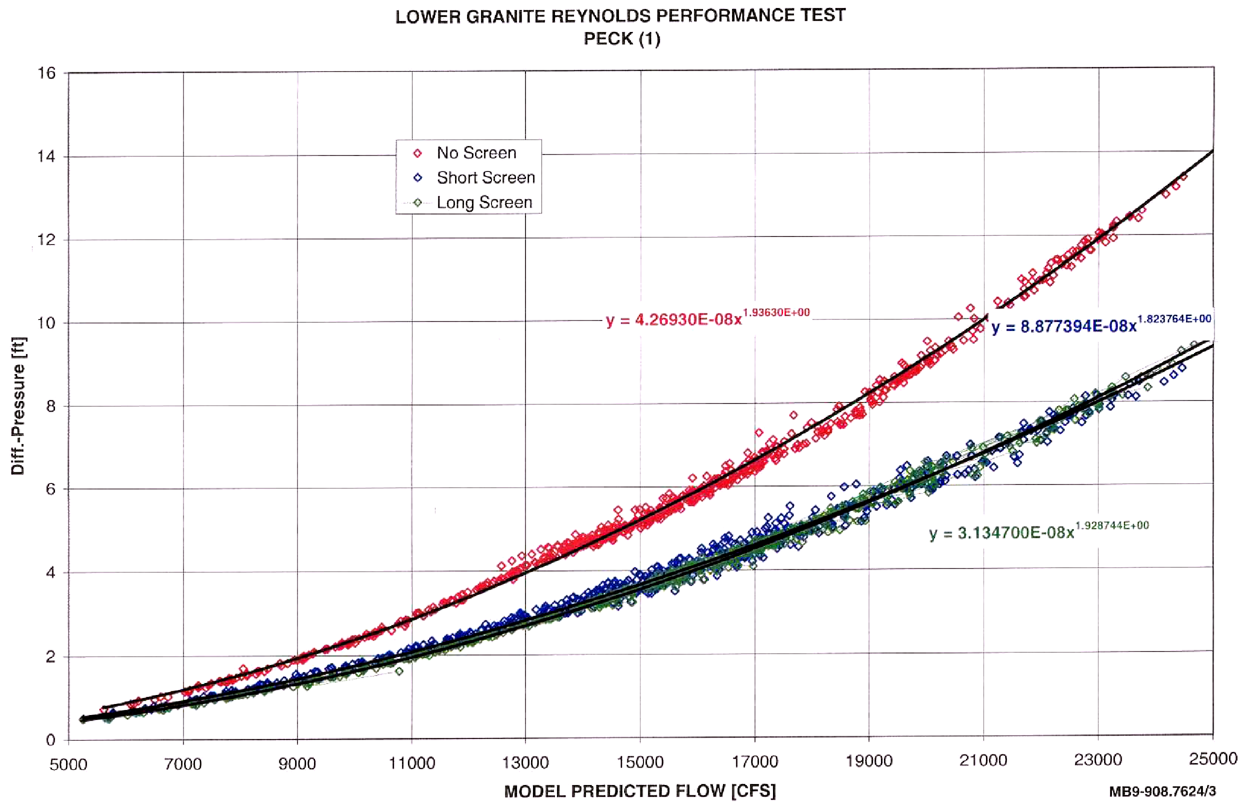

Figure B - 32. Results of Peck tap pair 1 - unsatisfactory stability

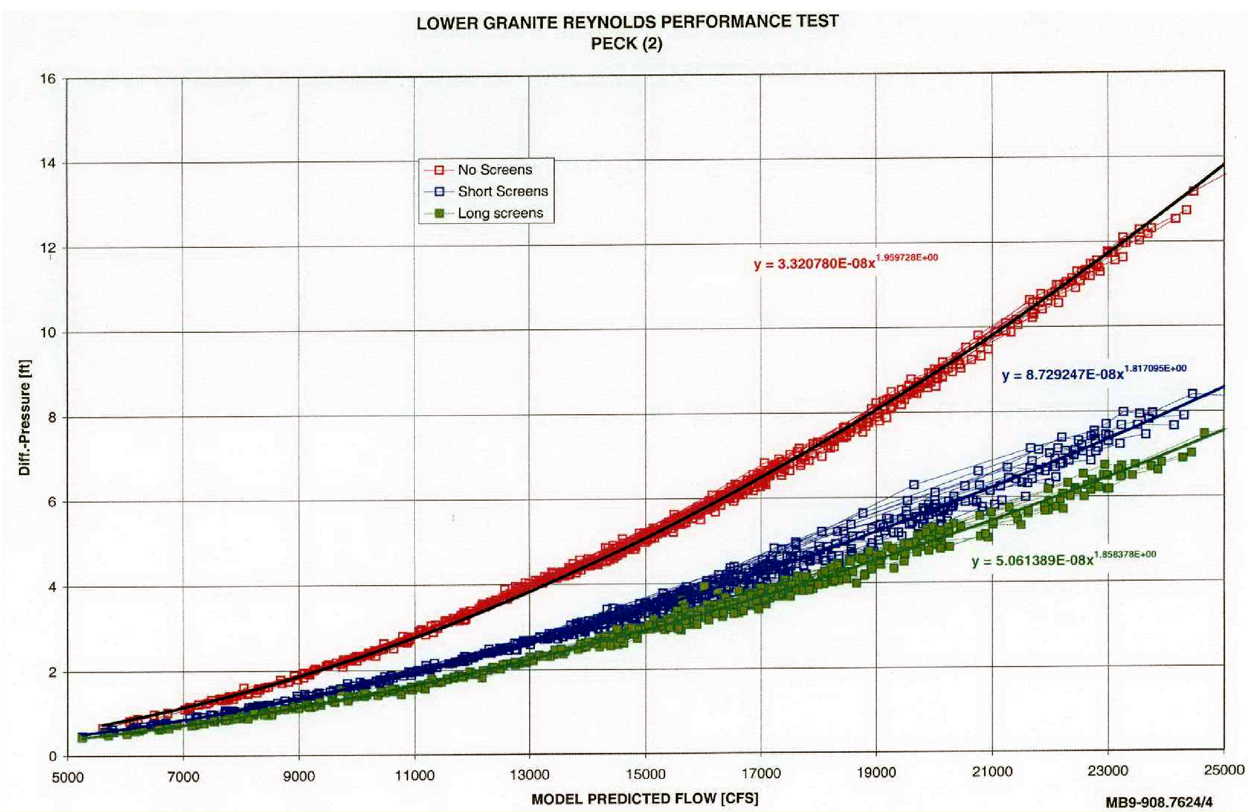

Figure B - 33. Results of Peck tap pair 2 - unsatisfactory stability

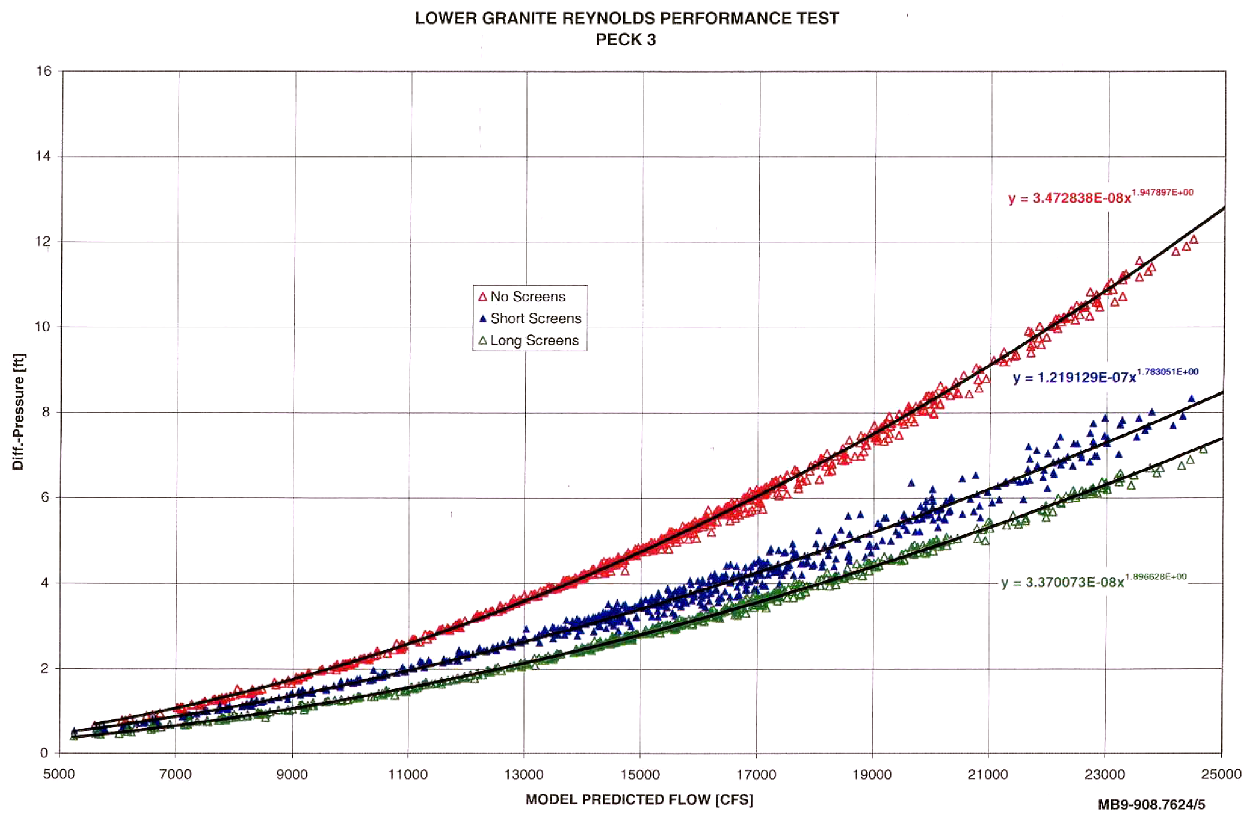

Figure B - 34. Results of Peck tap pair 3 - unsatisfactory stability

B.6.3 Wittinger Taps

A piezometric tap pair was installed in the crotch section of the turbine scroll case. These taps have the potential to measure a differential pressure, which could indicate a relative flow term or the difference in the flow distribution to the turbine. Theoretically the pressure difference should be zero should the flow entering the turbine be equally distributed. As can be seen in Figure B - 35, the flow distribution is not equal and becomes more unequal with the installation of fish screens and as flow increases. The taps may be suitable for a relative flow term with further research as to location and confirmation in a prototype.

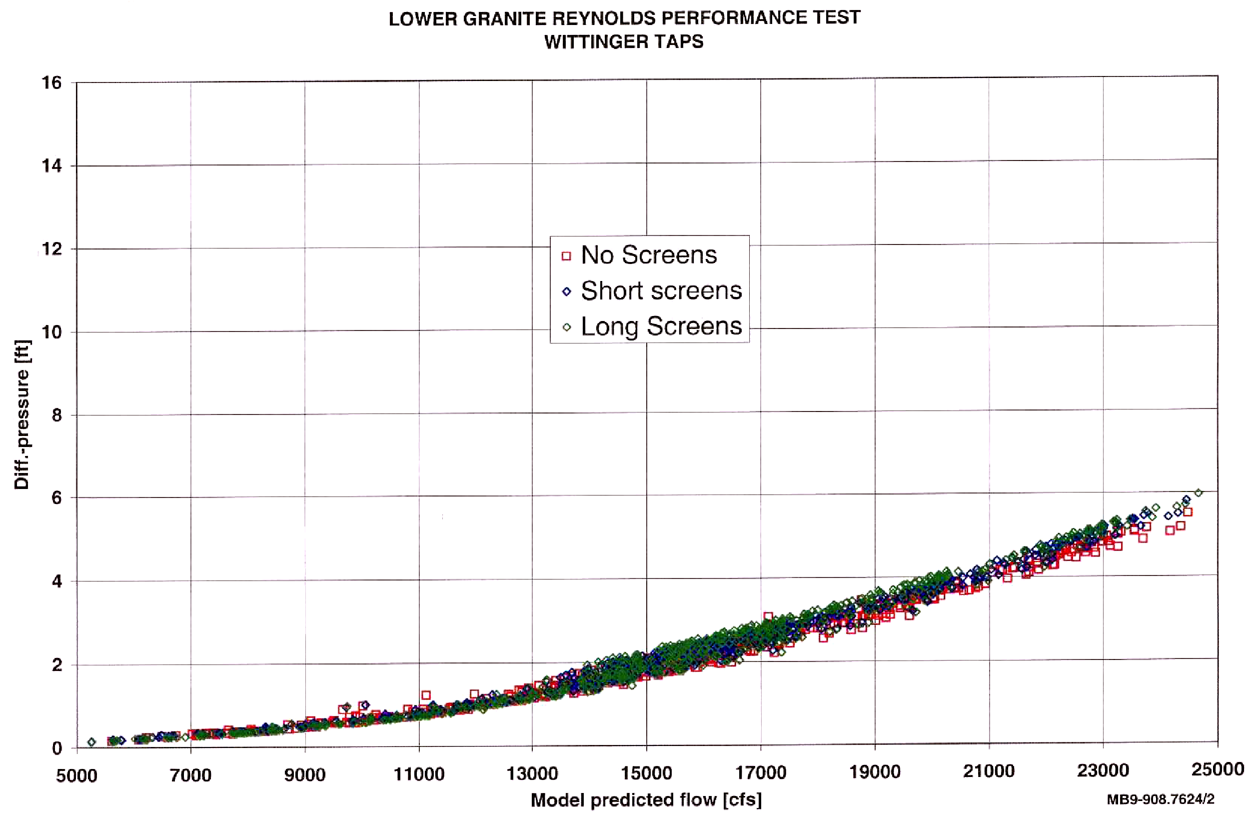

Figure B - 35. Results of Wittinger tap pair

B.6.4 Investigations of Scintillation Measurements

The use of the Acoustic Scintillation Flow Measurement technique (ASFM) has been used as an alternate to the Winter-Kennedy method when the stability of the prototype measurements of differential pressure in the Winter-Kennedy taps became unreliable or unstable. This ASFM method uses a large number of transducers mounted on three frames, which are installed in each intake bay. The use of the complete measurement array is costly and time consuming. As an alternate to using a full array of transducers, an investigation of an abbreviated number of transducers statistically located was performed by the COE. Four base case studies were evaluated and the results of the investigation follow (Hydroelectric Design Center 2003).

Based on the four case studies performed, abbreviated ASFM testing shows promise as a method of relative flow testing. The use of one bay (only) for performance testing for John Day, The Dalles, and Bonneville tests show similar cam curves when compared to full test cam curves. Using less than a full sensor array also yields satisfactory results. The minimum number of velocity measurements seems to be four.

It is recommended that five sets of sensors be placed with a uniform vertical spacing of 3 feet (0.9 m) between each sensor over a vertical range from 5 to 20 feet (1.5-6 m) above the intake floor. This arrangement should allow for application with all current intake configurations. Although four sensor sets were found to be the minimum required for relative flow testing, using five sets allows for 3 feet (0.9 m) of spacing, which will give an accurate velocity profile with a higher degree of confidence, as well as reduction of uncertainty. The vertical range for placement of sensors is likely to be applicable to all Kaplan types of similar size and flow. It is reasonable to believe that abbreviated flow testing would be applicable to other sizes of Kaplan turbines although those specifics would have to be developed separately.

As a generic guideline for sensor placement, velocity sensors should be placed in the free stream flow path. Free stream can be defined as a position where path velocity is at least 80% of the maximum path velocity for entire cross section ($V/V_{max} \geq 0.8$). Places which should be avoided would be boundary layer affected zones and placement directly behind upstream obstructions.

The following summarizes the conclusions and recommendations found that are applicable to future abbreviated flow tests:

- The sum of free stream velocities is approximately proportional to total flow.

  $$Q \mathrel{\tilde{\propto}} \sum_{i=1}^{n} V_i$$

  Q = absolute flow
  n = number of defined sensors
  V = horizontal velocity measurement

- Boundary layer flows appear not to significantly affect relative flow testing accuracy.
- Five sensor sets spaced 3 ft (0.9 m) apart placed in a vertical range from 5 to 20 feet (1.5-6 m) above the intake floor allows for the production of a fairly accurate cam curves with all intake configurations for Kaplan turbines of similar size and flow. Figure B - 36 shows the potential arrangement.
- Relative flow testing is not limited to ASFM for this application.
- No intake bay appears to perform better than any other as far a sensor placement is concerned.
- Future abbreviated flow tests should be compared to simultaneous Winter-Kennedy results to validate accuracy.

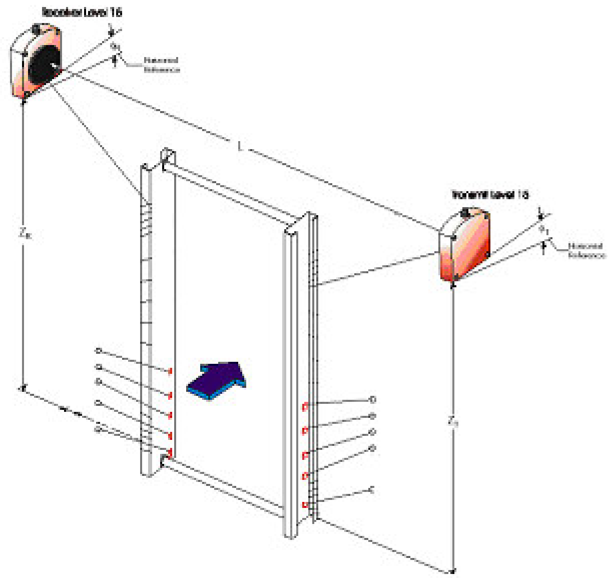

Figure B - 36. Potential location of ASFM sensors for an alternate relative flow measurement