HYDRAULIC MODEL STUDY
Wyandotte Wastewater Treatment Plant
Influent Pump Station Wet Well
Comparison of Existing and Original Wet Well Configurations
Report CEE 04-06

Project Report to
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EXECUTIVE SUMMARY

A physical hydraulic model of the flow through the influent pump station wet well at the Wyandotte Wastewater Treatment Plant was constructed at a 1:7 scale of the prototype and was tested based on Froude number scaling criteria. The purpose of this physical model study was to further investigate the poor flow conditions within the pump station wet well observed in a previous study (Wright, et al 2004). Model construction was based on blueprints and other design documents detailing pertinent dimensions and details. Other aspects of the wet well, including information on current operation strategies for the wet well, which is manually controlled by station operators, were obtained through communications with Wyandotte Waste Water Treatment Plant personnel. The model was tested for two configurations: The "original"; as the pump station was built in the early 1960's, and the "existing"; as the station operates currently following a redesign in the late 1990's

Flow tests were performed on the model of the "existing" wet well configuration for a variety of permutations of pump operation and at different wet well water surface elevations without the recycle line in operation. Preliminary tests indicated several operational conditions with poor flow behavior, which are included in a previous report (Wright, et al 2004). More comprehensive testing was then performed to determine the extent of any hydraulic problems, and to investigate a broader range of dry weather wet well operations.

Air entraining vortices were observed in the area of the wet well between the two curtain walls with the vortices entering the inlet to pump #5. These air-entraining vortices were normally observed only for wet well elevations below about 543 feet, but some were observed at somewhat higher water levels. In addition, swirl angles exceeding 5 degrees were observed at several pump inlets, in particular at pumps #3, #5, and #6. High swirl angles were observed most often at the #5 and #6 pump intakes with maximum values up to ten degrees or about twice the value generally considered to be acceptable. Flow conditions tended to be worse when multiple pumps were operated on one side of the wet well.

Modifications were made to model to replicate the "original" configuration as designed and constructed in the early 1960's. These modifications included the installation of two pipes extending from the wet well inlets upstream to the influent chambers. Flow was isolated in each inlet in order to be consistent with the actual operation of the "original" pump station design. The coarse bar screen was also relocated to its original position inside the wet well and the recycle line was removed. Additional flow tests were then performed and indicate that the "existing" configuration resulted in

worse flow conditions, particularly at higher wet well water surface elevations, compared to the "original" configuration under the same flow conditions. This is due to the fact that the bar screen, as located in the "original" configuration, destroys vorticity in most cases, or at the very least forces a location shift that mitigates vortex severity. For the "original" configuration, pump #5 still had significant problems with air entraining vortices, particularly when used in conjunction with pumps #2 and #6, for water levels less than 544'. Swirl was less severe in almost all pumps under the "original" configuration.

The effects of the modifications made in the late 1990's to the pump station are assessed to be as follows:

- An increase in both surface and sub surface vortices. Specifically, air entraining vortices now occur in association with pumps #4, #5, and #6, where as only #5 exhibited unacceptable flow conditions in the "original" pump station design.
- A general increase in pre-rotation of flow entering the pump intakes. Almost all swirl angles observed in testing the "existing" configuration were greater than those observed in testing the "original" configuration.

INTRODUCTION

The Wyandotte Wastewater Treatment Plant influent pump station has a total pumping capacity of 200 mgd (310 cfs), achieved with six pumps with different pumping capacities. The firm pumping capacity is 150 mgd. The pump station was constructed in the early 1960's, then modified in 1998. The modification included replacing the original pumps with new pumps (of approximately the same pumping capacities) and changing the inlet into the wet well by creating a junction chamber for the influent sewer lines. The coarse bar screen was also relocated from the wet well to a screen chamber following the junction chamber, and a recycle line was installed. Since the modifications to the pump station were completed, the pumps have experienced bearing failures, excess vibration, unusual pump noise, and the shafts of two pumps have been broken. An earlier study, (Wright, et al 2004) identified several unacceptable flow conditions and outlined a plan to mitigate the observed adverse hydraulic conditions. The purpose of this phase of the physical model study was to examine the flow conditions within the influent pump station wet well in both the "existing" and "original" configurations to determine whether modifications made to the pump station in the late 1990's created hydraulic conditions within the wet well that may be responsible for the reported problems with pump performance.

Vortices and inlet swirl have a detrimental effect on the operation of pumps, lowering efficiency and increasing wear. Severe vortexing can also lead to pump vibration, cavitation and impeller pitting. The testing sequence included the following components:

- Examination of surface vortex patterns, including air entrainment;
- Examination of subsurface vortex patterns;
- Measurement of swirl in flow into individual suction inlets;

For the "existing" configuration, flow tests were conducted on both dry and wet weather pump combinations, as well as individual pumps, in order to obtain a large data set in which to compare the "existing" and "original" station designs. The "original" pump station configuration testing repeated most previous testing combinations, but focused on problems that were identified in testing the existing pump station configuration.

GENERAL SYSTEM DETAIL

In the "original" pump station configuration, flow entered the pump station by means of two six-foot diameter influent sewers that discharged directly into the wet well. The two influent sewers contribute flow from different service areas and are hydraulically independent. The flow split between the two interceptors is variable but at least for dry weather flow is assumed to be consistent with the contracted capacity which implies that approximately 60 percent of the inflow comes through the interceptor entering the west side of the pump station. The wet well is constructed in the interior of a 50-foot diameter circular caisson. The inflow enters the wet well through inlet openings with an invert elevation of 537.5 ft. The inflow passes through a coarse bar screen of ½ in. bars with three-inch vertical openings. In the "original" pump station configuration, the bar screen was located within the wet well and had a top elevation of approximately 546 ft. The flow drops down, from the inlets, to the wet well floor elevation of 530 ft and through the pump intakes in the back wall of the wet well. Figures 1 and 2 show schematics for the "original" configuration taken from portions of the as-built drawings of the pump station. Figure 2 indicates more detail on the bar screen configuration. The wet well itself only occupies a small fraction of the 50 foot diameter caisson with the wet well wall located twelve feet into the wet well from the inlet openings. Curtain walls approximately twelve feet off the station centerline on either side of the wet well restrict the flow from spreading further laterally. Flow entering the two outside pumps, #4 and #6, must first pass through six-foot wide by ten-foot high openings in these curtain walls. This configuration is depicted more completely in Figure 3.

In the "existing" configuration, flow enters the pump station through the same two six-foot diameter influent sewers that are terminated in a junction chamber that was installed ahead of the wet well inlet. The two inflows enter the sides of the junction chamber, combine and pass through a coarse bar screen now located in a screen chamber ahead of the wet well, and flow into the wet well. The original sections of the influent pipes that passed through the wet well wall were retained in the reconstructed pump station. A schematic of the wet well's "existing" configuration is indicated in Figure 3.

Six pump intakes arranged along an internal wall within the caisson lift the flow into the wastewater treatment plant. These pumps have different pumping capacities varying from 10 to 50 million gallons per day (mgd). With the identification system employed at the wastewater treatment plant, the nominal pumping capacities of the six pumps are as follows:

Pump	**Pumping Capacity (mgd)**
1	10
2	20
3	30
4	40
5 & 6	50

The smallest pump has a vertical suction inlet while the other five are flush mounted in the wet well wall opposite the inlet. Looking at the pump intakes from right to left from the inlet into the wet well, the pumps are ordered as follows: #6, #2, #5, #1, #3 and #4. The four smallest pumps are fixed speed pumps while the two larger ones have variable speed drives and are currently operated to vary the pumping capacity between about 30 and 50 mgd. Each pump, as replaced in 1998, has an over-design capacity of approximately 10-15% of listed pumping capacity. This over-design was to account for anticipated future performance losses due to impeller wear such has been observed in the pumps that were replaced. The over-design implies that the smaller four pumps are currently pumping more than their listed capacity since they are fixed-speed pumps, while this is not necessarily true of the largest pumps, #5 and #6 with variable speed motors. At least one pump, #2, has been observed to produce flows of 117% of its rated pumping capacity of 20 mgd.

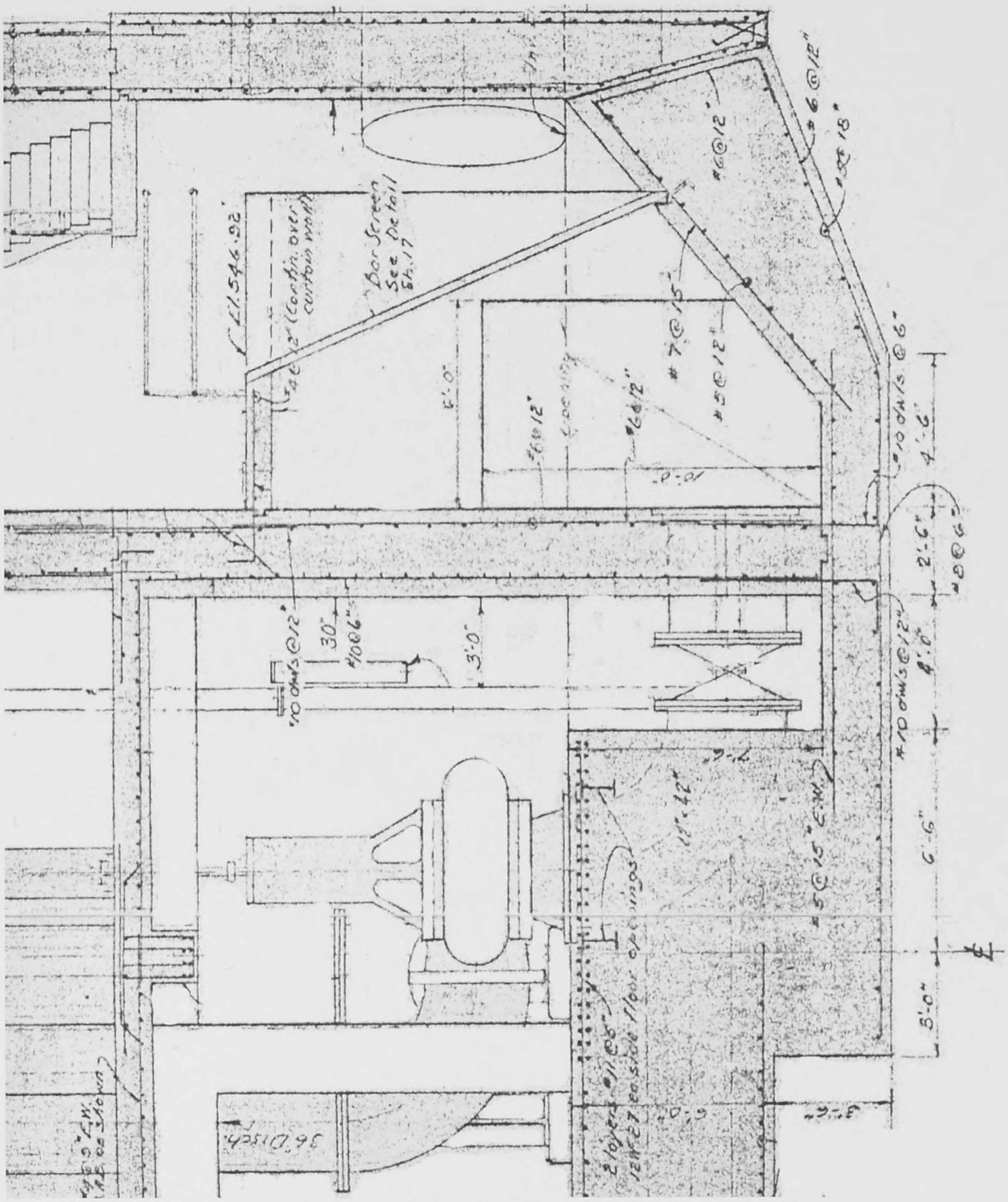

Figure 1. Cross-section of the “original” Configuration of the Wet Well.

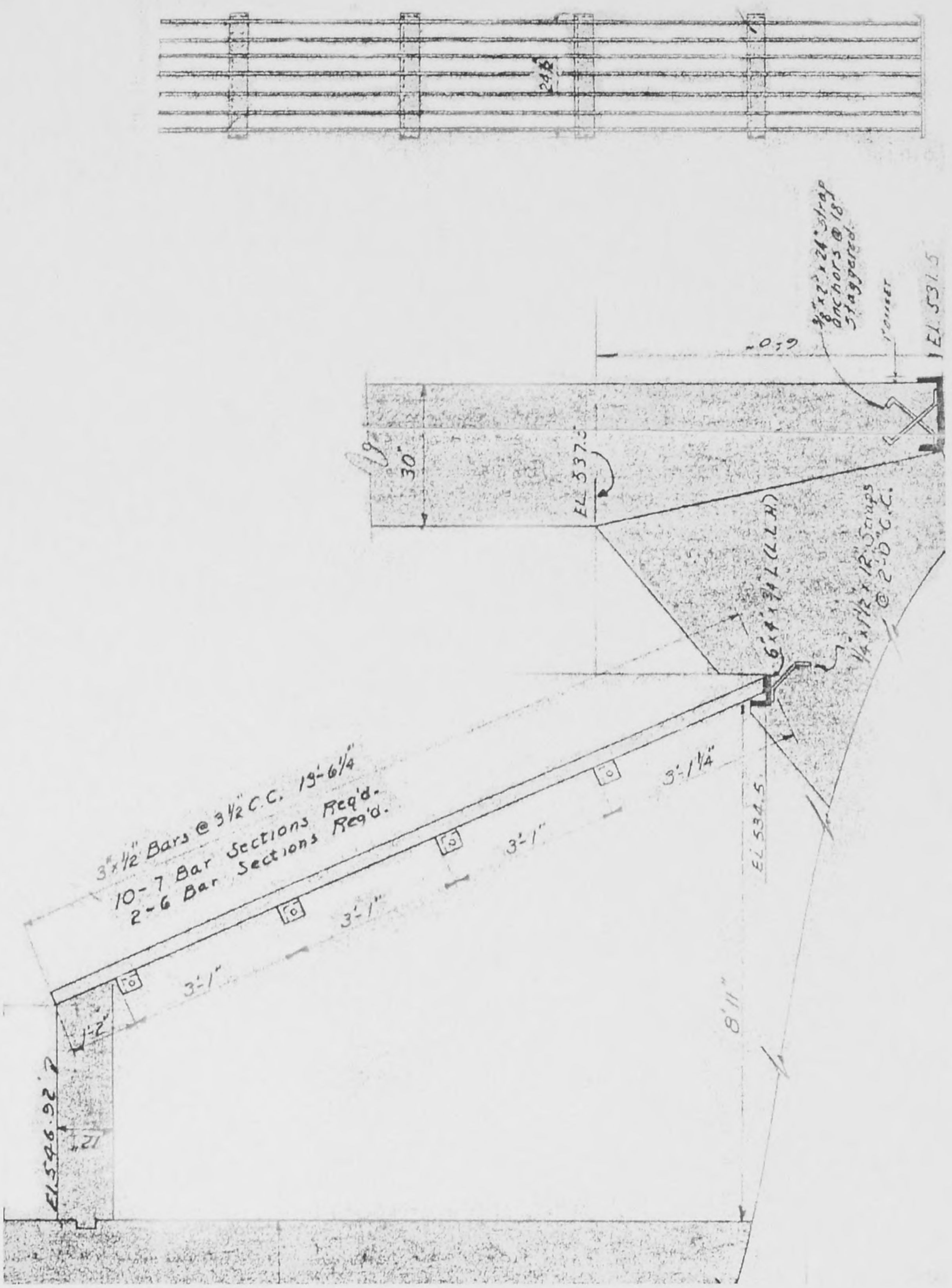

Figure 2. Detail of the Coarse Bar Screen Within the Wet Well.

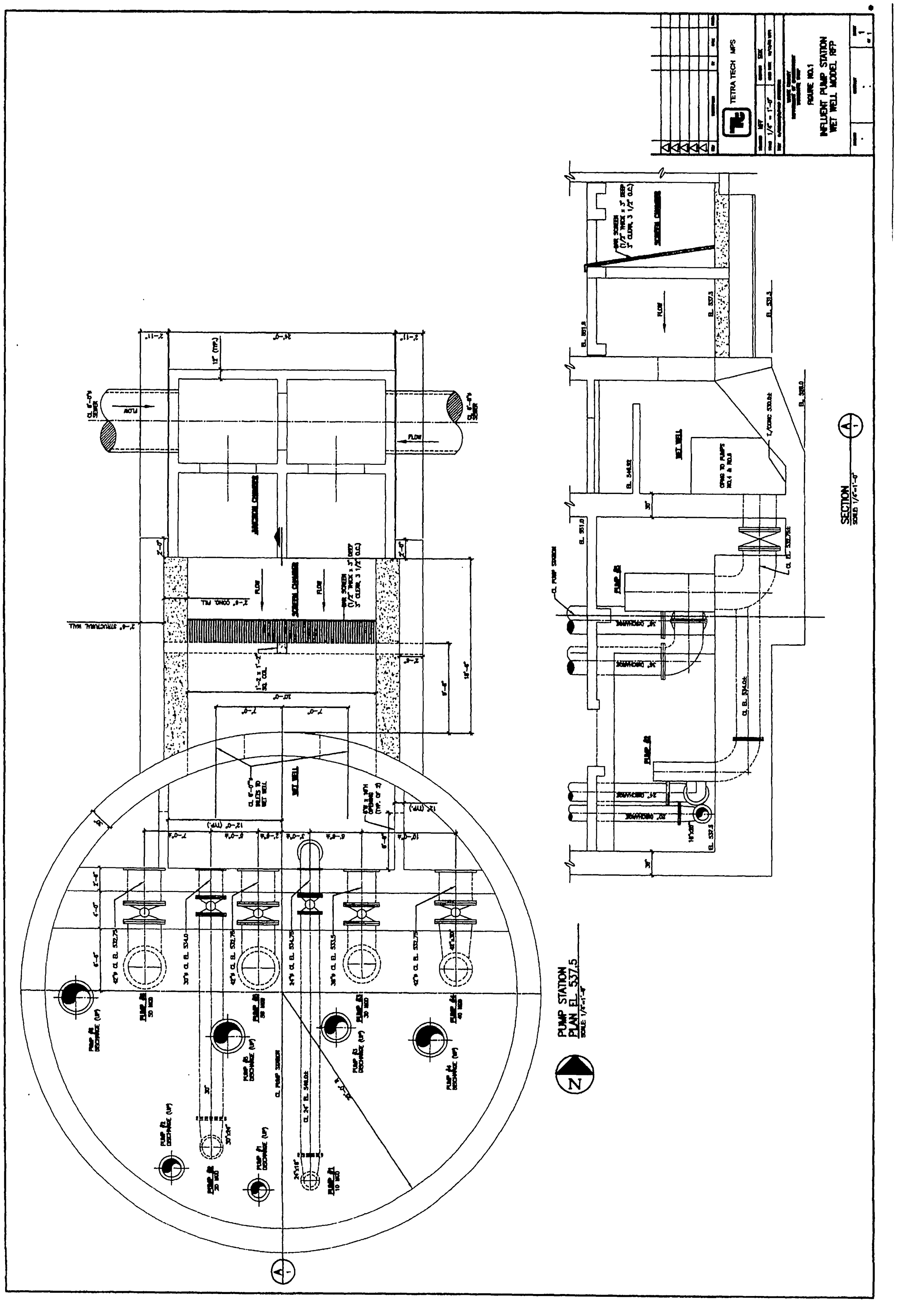

Figure 3. Wet Well Schematic for "existing" Configuration.

In addition to the flow entering the wet well through the influent sewers, a recycle line, added in the modifications installed in the late 90's, returning primary sludge and internal plant drain flow to the wet well through a 42-inch diameter pipe with an invert elevation of approximately 551.4 ft. Typical inflows through this recycle line are on the order of 4-6 mgd, and enters the wet well directly above pump #6. In the current study, the recycle line was not used as to more accurately compare flow conditions between the two model configurations. The previous study by Wright, et al (2004) indicated that the recycle line had little effect on swirl angles or vortex formation but did influence air entrainment into pump #6.

The pump station is currently operated manually with wet well elevations generally maintained in the range of 542 to 545 feet. A typical pump operating plan has been provided and is included in Table 1. For dry weather flow, a typical pumping capacity is reported to be 70 mgd. In addition to the pumps listed for 70 mgd in Table 1, the variable speed pumps (#5 and #6) could be used in combination with either pump #3 or #4 operating the variable speed pumps at less that their rated capacity. In these combinations, one of the variable speed pumps would be operated at 40 mgd or 30 mgd respectively.

Table 1. Pump Station Operating Plan.

Rate	Pumps Combinations
20 MGD	#2
30 MGD	#1 and #2, #3 alone, #5 alone at reduced speed, #6 alone at reduced speed
40 MGD	#4, #5 alone at reduced speed, #6 alone at reduced speed
50 MGD	#2 and #3, #5 alone, #6 alone
60 MGD	#2 and #4
70 MGD	#2 and #5, #2 and #6, #3 and #4
80 MGD	#3 and #5, #3 and #6
90 MGD	#4 and #5, #4 and #6
100 MGD	#5 and #6

For higher flow rates the wet well elevations may range up to a high level limit of 548.5 feet and the following pump operation scenarios have been suggested as likely ones:

Rate	Pumps
130 MGD	#3, #5 and #6
150 MGD	#2, #3, #5 and #6

MODEL DESCRIPTION

Modeling Criteria

Physical models to examine flow behavior in free surface flow are performed using Froude number similarity, which fixes the relations between model and prototype conditions once the physical model scale has been selected. A more detailed discussion can be found in the previous report, (Wright, et al, 2004).

Model Testing Facilities

The model study was conducted in the Civil and Environmental Engineering Hydraulics Laboratory located in the G.G. Brown Building at the North Campus of The University of Michigan.

Model Construction

The physical model was constructed at a scale ratio of 1:7. This general model size was selected to keep the Reynolds numbers previously defined in Wright, et al (2004) to be greater than the recommended minimum values suggested by Padmanabhan and Hecker (1984) with the exception of the smallest capacity pump, pump #1. All relevant detail of the influent sewers, the junction and screen chambers (including the bar screen) and the wet well were reproduced at this scale from dimensions provided in a series of documents including copies of the blueprints of the as-built drawings for the "original" pump station and CAD drawings for the more recent modifications. In instances where the drawings were unclear or where apparent discrepancies between drawings existed, WWTP personnel were contacted for clarification. In general, the model was constructed from exterior plywood and PVC (piping and sheet) and allowed operation over the range of wet well elevations up to 548.5 feet.

Individual pumps are not used in the model, but all pump inlet piping is reproduced at the correct scale up to the location of the suction inlet to each pump. The pump suction lines were constructed from Plexiglas so that the rotating cruciforms used to measure the inlet swirl angles could be visually observed to determine the swirl angles. All six pump suction lines were joined into a common manifold connected to a recirculating pump which removes the flow from the wet well, through the desired pump suction lines, and back around to the inlet conduits (the two influent sewers as well as the recycle line). The maximum model discharge rate of approximately 800 gpm (232 cfs prototype) was achieved with a single recirculation pump. The flow distribution was regulated by means of a butterfly valve on each of the six pump suction lines and with separate valves on each of the inflow source lines to obtain the desired total flow and control the flow distribution among individual lines. The flows were metered in each individual suction line by means of installed flow meters. Since the flow distribution among the two influent sewers can vary (two independent interceptors), these flows were visually adjusted to divide them as desired. The flows were approximately equal for all tests on the "existing" model configuration, and most tests on the "original" configuration. Visual inspection indicated that the west inlet carried slightly more flow than the east inlet with the control gate valves fully open. Additional testing was performed with a higher percentage of the flow entering through the west inlet.

An overall view of the physical hydraulic model is provided in Figure 4, while close-ups of various aspects of the model construction are provided in Figures 5 to 10. These figures concentrate on the portions of the model that were altered in order to reproduce the "existing" and "original" wet well configurations. Figures 5-8 are for the "existing" wet well while Figures 9 and 10 indicate the "original" wet well as reproduced in the model. In Figure 5, the wet well is seen with no bar screen present and a small portion of the upstream screen chamber is visible to the right side of the image. Figure 6 is looking at the bar screen in the screen chamber with the circular openings in the wet well wall visible in the background. Figure 7 looks upstream over the top of the bar screen towards the junction chamber while Figure 8 shows the upstream end of the junction chamber with the inflow interceptor entering the west side of the junction chamber. Figure 9 looks down into the wet well in the "original" configuration with the bar screen located between the curtain walls while Figure 10 shows the addition of the two inflow pipes actually placed within the model screen chamber to represent the inlet configuration in the "original" pump station.

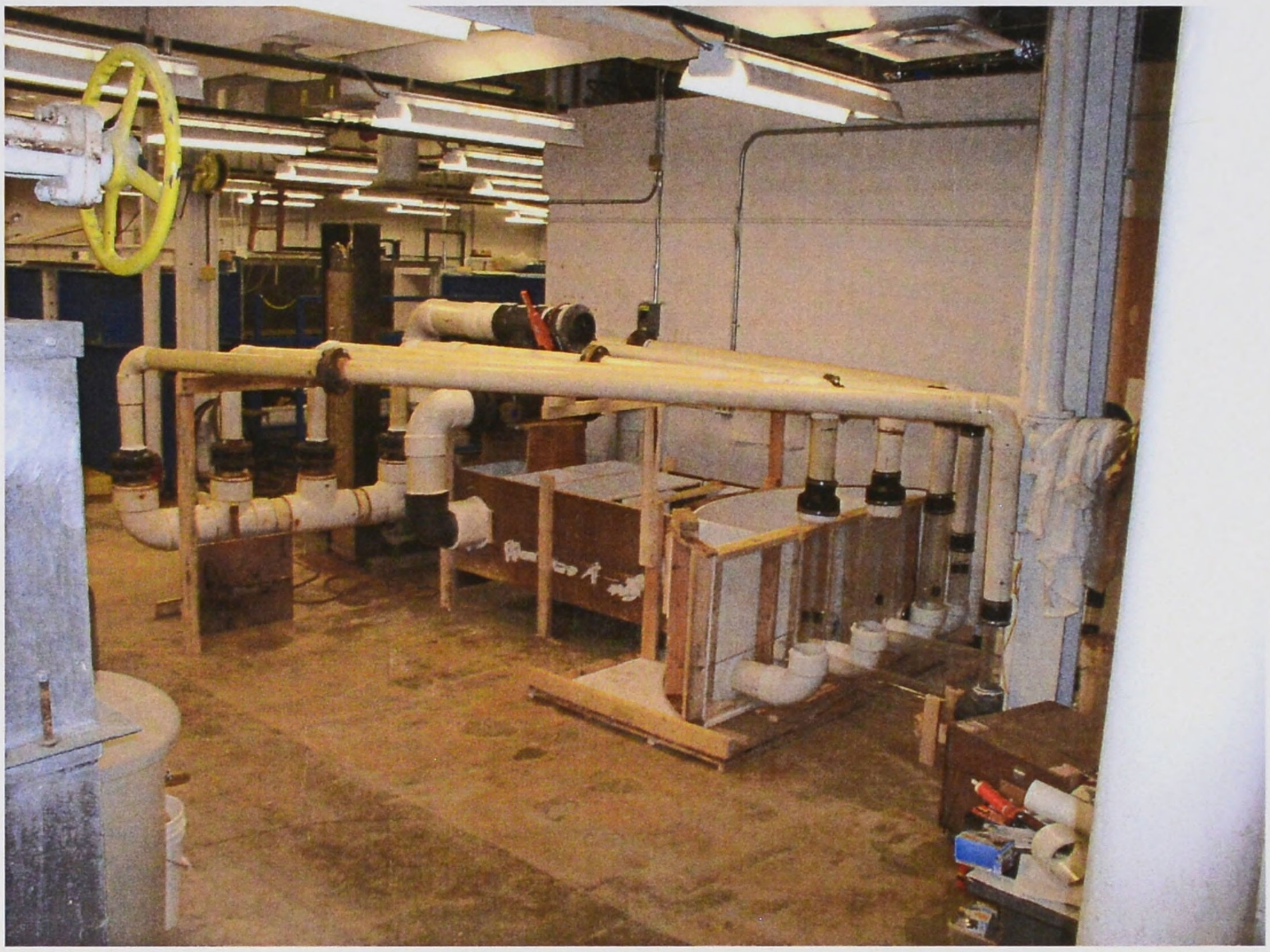

Figure 4. Wyandotte WWTP Influent Pump Station physical hydraulic model.

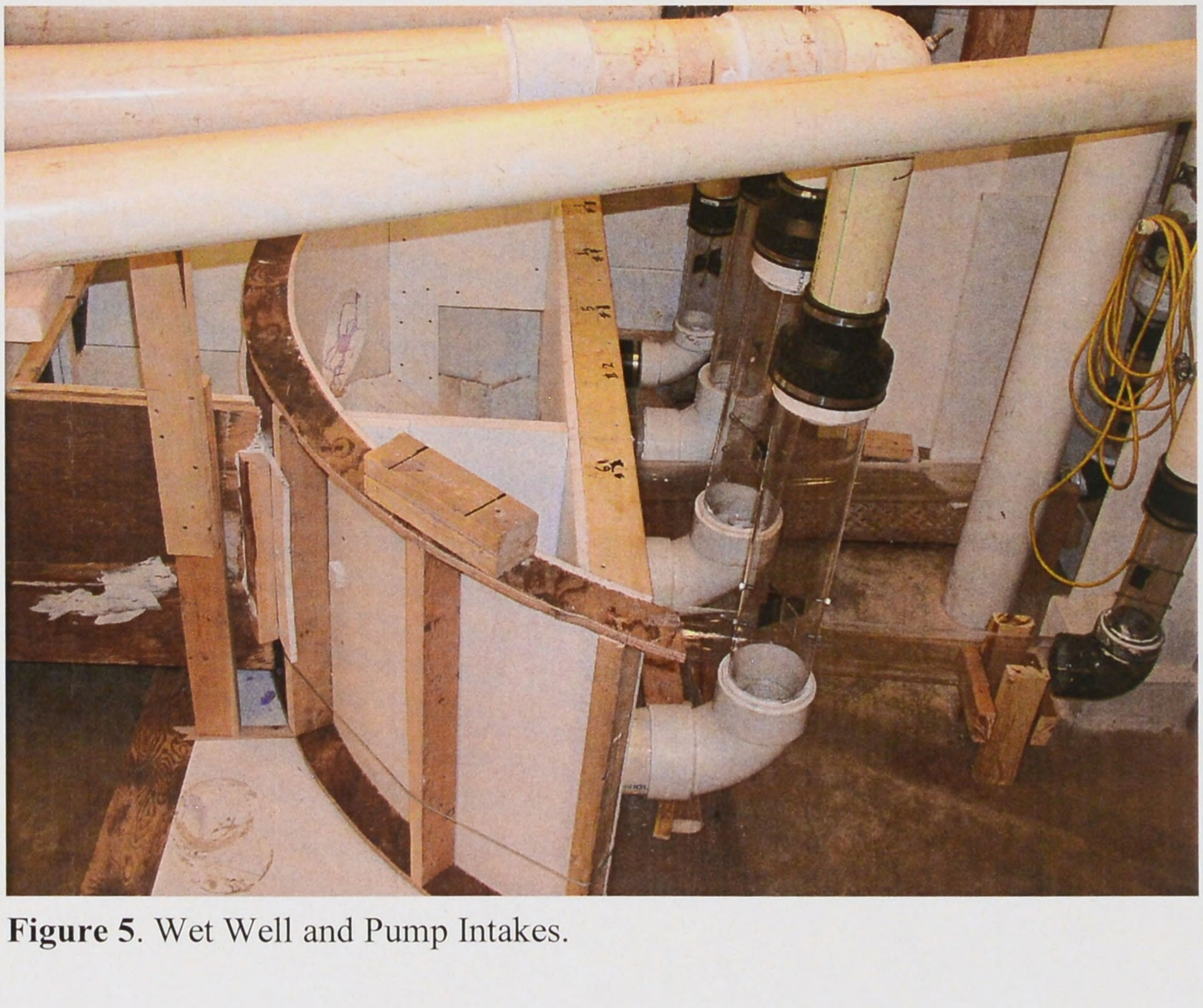

Figure 5. Wet Well and Pump Intakes.

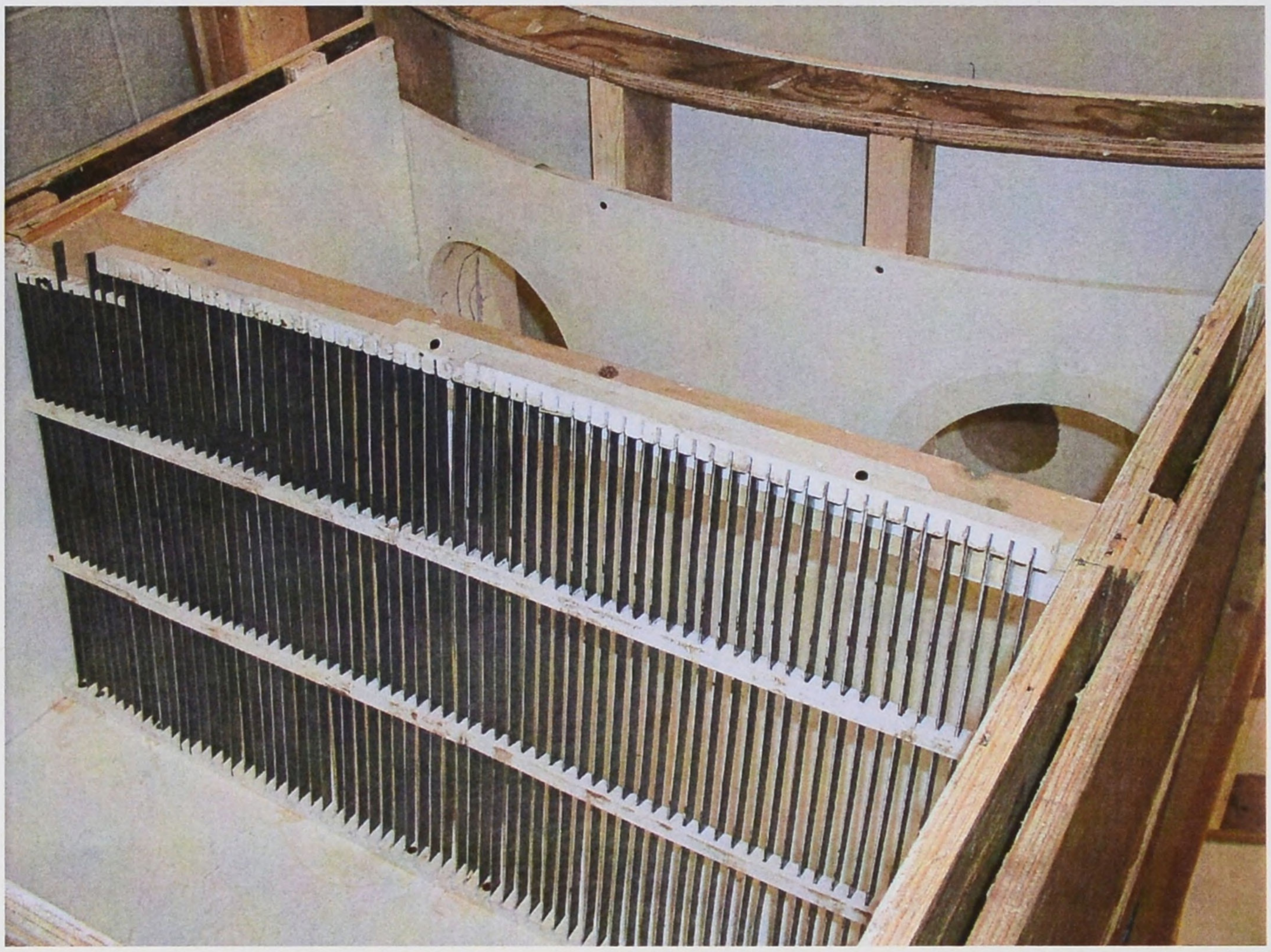

Figure 6. Bar Screen within the Junction Chamber

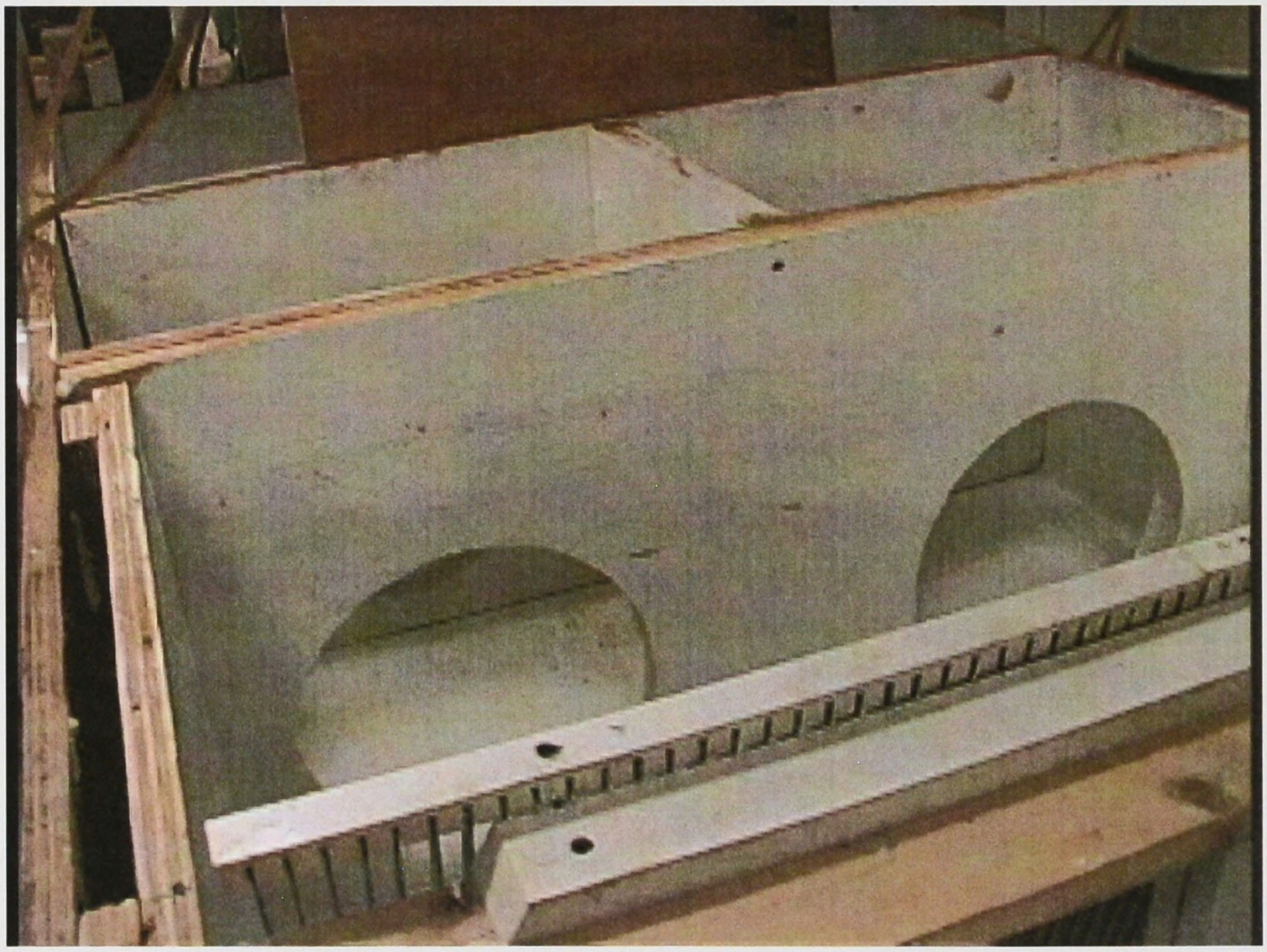

Figure 7. Junction Chamber Upstream of the Bar Screen.

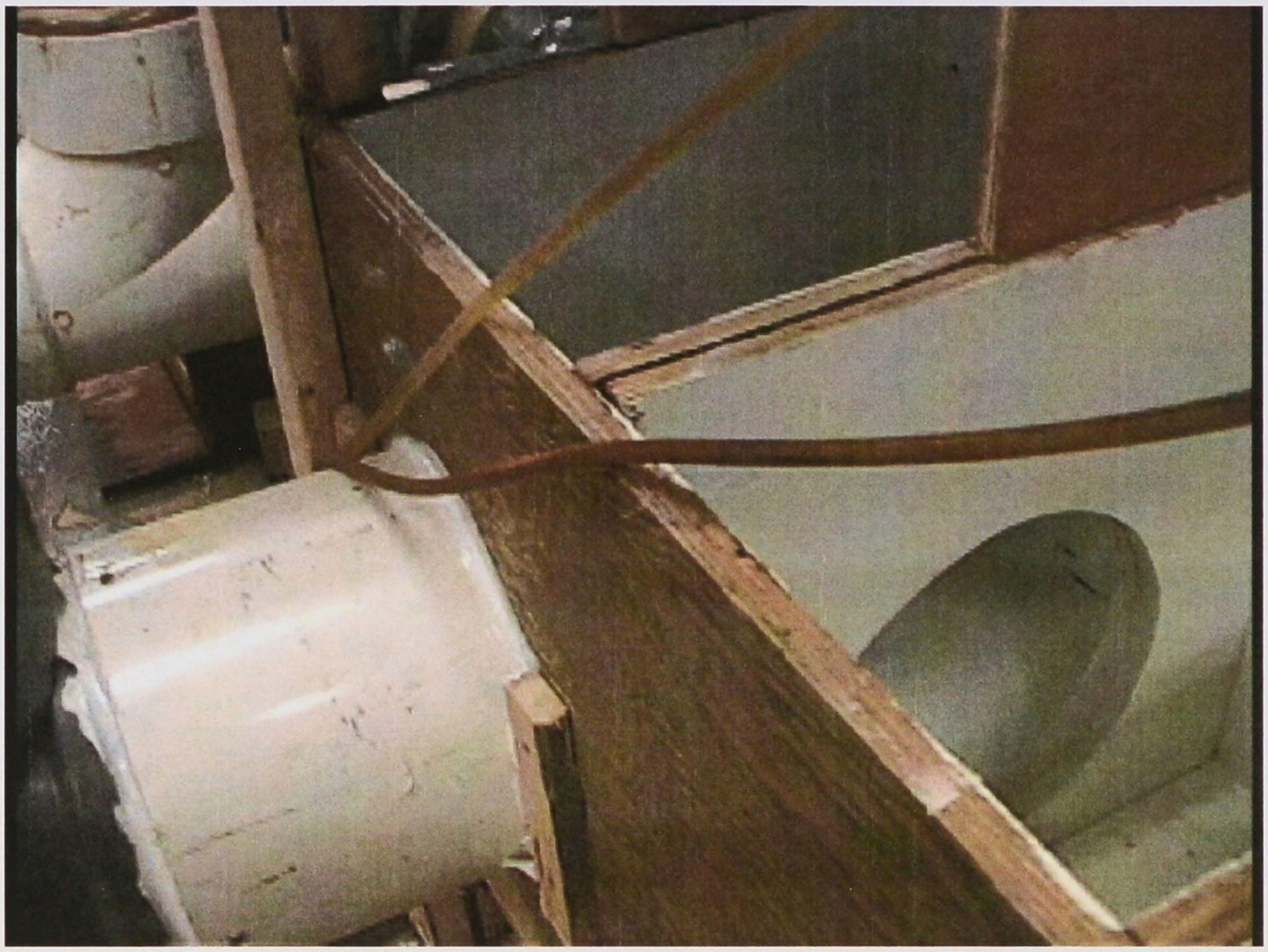

Figure 8. Upstream End of the Junction Chamber Showing West Inlet.

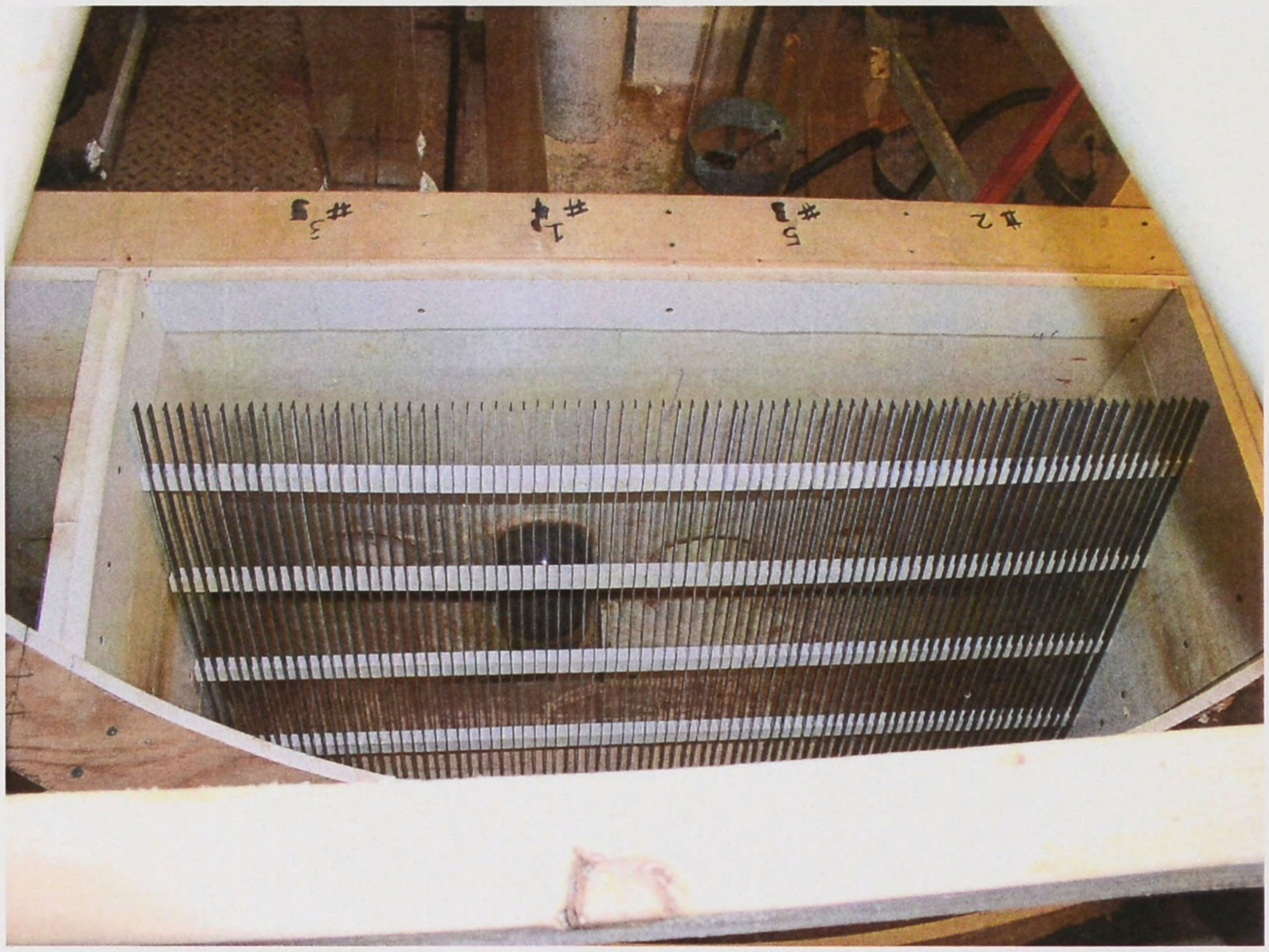

Figure 9. Bar Screen within Wet Well in "original" Configuration.

Figure 10. Model Modifications to represent "original" Inlet Conditions.

Instrumentation

Flow rates were measured using pipe orifice meters constructed to ASME specifications (Streeter and Wylie, 1985). In the case of the lines from pumps 5 & 6, the flows were measured with calibrated elbow meters. There were at least 10 upstream diameters of straight pipe and five diameters downstream from the orifice plates in order to minimize approach flow influences on the meter behavior following Hydraulic Institute standards. Pressure differences were measured with water-air differential manometers.

The presence of surface and subsurface vortices were investigated visually including the injection of dye into the model. Pertinent observations were recorded both on digital video and in a permanent record of notes indicating location and strength of any vortex motion observed.

The swirl angles were measured with a rotating cruciform, the function of which is to rotate with the component of tangential flow in the pump suction line. This zero pitch vane is indicated in one of the installations in Figure 11. Standard specifications of 0.8

of the pipe diameter for the length and diameter of the cruciforms were utilized in the construction. The cruciform is mounted so that it rotates freely on a hub installed on the pipe centerline. One vane is colored to orient the cruciform, especially in a rapidly rotating flow. Rotation counts were recorded to the closest quarter turn over 1 minute counting intervals. Repetitions of the counts generally produced rotation counts that were within one revolution; depending on the particular pump intake, one revolution represents between about 0.15 - 0.5 degrees of swirl angle.

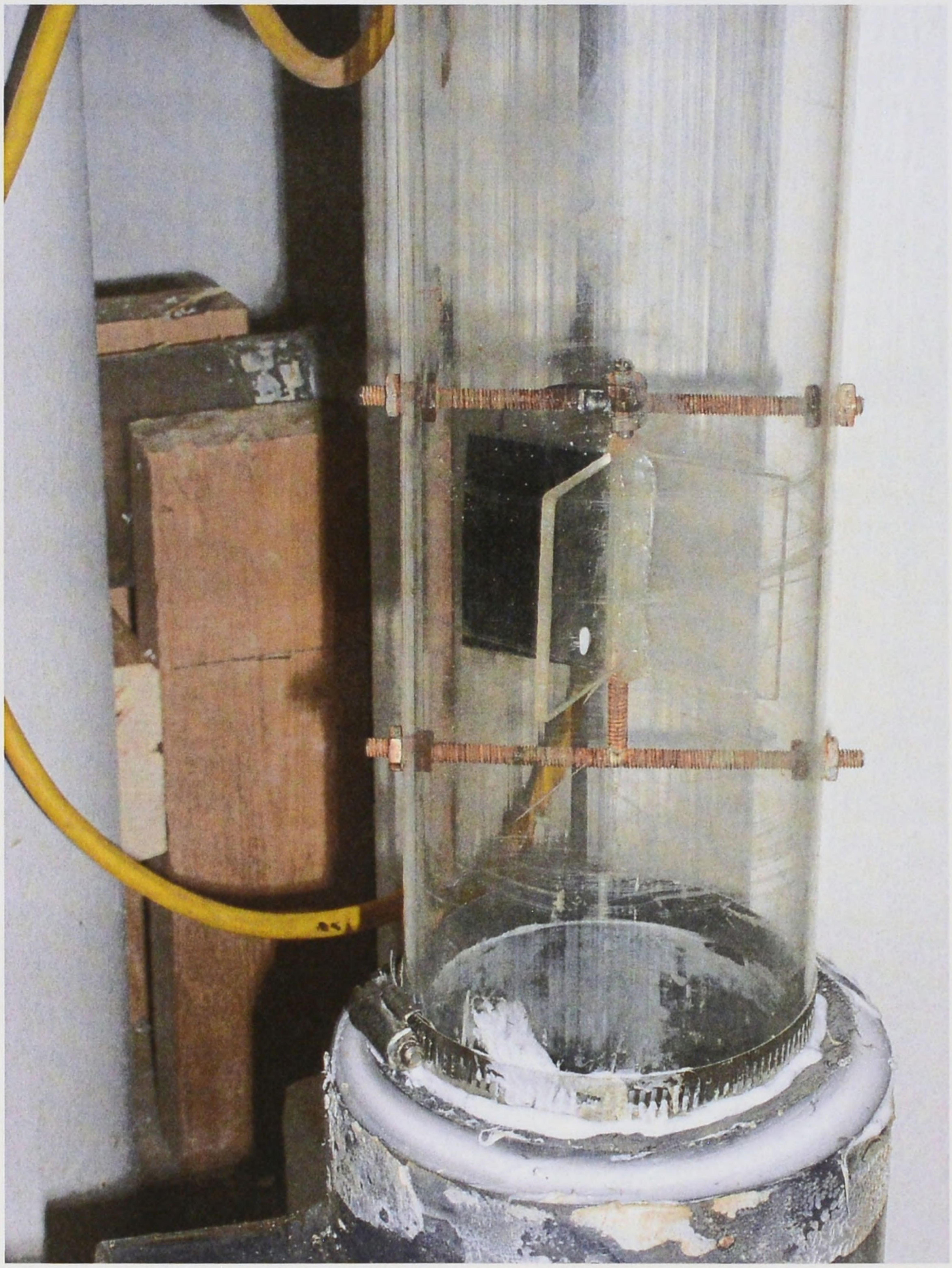

Figure 11. Rotating Cruciform installed in one of the suction lines.

TESTING PROCEDURES

Tests were performed by adjusting the flows for the desired pump operation scenario and fixing the water level to a prescribed wet well elevation. The wet well elevation was measured in a stand tube connected to the wet well in the same location as the actual bubbler stand-tube that is used to measure wet well elevations in the prototype. Since between one and five pumps could be in operation at any time, there were many possible permutations that could be considered in the testing. In order to quickly determine the worst flow conditions in the previous study, various combinations of pumps ranging from one pump to four pumps were tested, generally at both the 543' and 546' water levels specified as the operating range in the original information provided describing pump station operation.

Several pump combinations were then tested at water level intervals of 1 foot ranging from 542' to 546' for both the "original" and "existing" configurations of the model. In addition various individual pumps were tested for completeness. Since the worst flow conditions generally occur at the highest flow rates, all pumps were tested at their maximum design flow rate, including pumps #5 and #6, which are variable speed pumps. Tests were also conducted for dry weather conditions in which pumps #5 and #6 were used at variable speeds so that the total flow rate summed to 70 mgd. Tests included the following:

1. All observations of surface vortices were classified with respect to their appearance. Specifically, this involves a designation of the visual appearance of the vortex strength ranging from surface swirl to an air core vortex that exists all the way to the pump intake. Following Padmanabhan and Hecker (1984), the classification system is as follows:

Type 1: Surface swirl
Type 2: Surface dimple: coherent swirl
Type 3: Dye core to intake; coherent swirl throughout water column
Type 4: Vortex pulling floating trash but not air to intake
Type 5: Vortex pulling air bubbles to intake
Type 6: Solid air or vapor core to intake

No surface vortex more severe than an intermittent Type 2 dye core is generally regarded as an acceptable flow state. This was determined by visually examining the water surface for dimples and injecting dye to look for organized motions extending downwards to one of the suction intakes. Any vortices persisting less than about 10 seconds are considered to be intermittent.

2. Observations of subsurface vortices were made by dye injections into the model and observing the tendency for any organized vortex motion. Acceptance criteria allow no coherent subsurface vortex with organized swirl and core (Type 2).

3. With respect to entrance condition into the pump suction line, the swirl angle of the entering flow was measured in all inlet lines with a rotating cruciform. The swirl angle, θ, is defined by:

$$\theta = \tan^{-1} (\pi ND/U)$$

where N is the revolutions per unit time of the rotating cruciform, D the pipe diameter and U the average axial flow velocity (the line discharge divided by the pipe cross sectional area). Swirl angles of less than 5 degrees are generally considered as acceptable for axial flow pumps (Knauss, 1977).

For the purposes of a permanent data record with respect to the general observations of the flow and the model construction, a videotape was made of relevant portions of the model testing sequence. A digital video camera (capable of conversion to 1/2 inch VHS format) was used to record the details of the model construction and various portions of the testing sequence.

EXISTING CONFIGURATION TEST RESULTS

Introduction

A previous report (Wright, et al, 2004) documented several aspects of poor flow conditions associated with the "existing" pump station configuration. In this report, those measurements and observations are repeated as well as additional testing results in order to more completely document the flow behavior in the existing wet well. In the presentation below, observations are separated into dry weather and wet weather flow conditions. Although the division is somewhat arbitrary, the prototype flow rate of 70 mgd is selected as the division between dry and wet weather flows. In general, experiments performed for the "existing" wet well configuration were then repeated for the "original" configuration in order to provide a direct basis for comparison between the two wet well configurations. A presentation of results for the "original" wet well configuration follows this section.

Vortices and Other Flow Conditions

In general, intake conditions were observed to be reasonably satisfactory, but a number of unacceptable flow conditions were noted in the existing pump station testing which involved the investigation of a number of combinations of one, two, three, four, or five pumps in operation. A list of these follows:

- Air entrainment due to the presence of Type 6 (air-entraining) vortices. These vortices tended to be intermittent in nature and were most common at low water levels. Pumps #5 and #6 running together caused air-entraining vortices (into pump 5) at water levels below 543'. Pumps #2 and #6 together caused air-entraining vortices to enter Pump #2 at water levels below about 543.5'. Pumps #3 and #4 created air-entraining vortices below elevations of about 543'; these appeared to be always drawn into the pump #3 intake. Simultaneous operation of pumps #2, #3, #5, and #6 caused air-filled vortices to intermittently enter the intakes of pumps #2 and #5 at 543' with an especially large amount of entrained air into pump #5. A number of these flow conditions were recorded on video. Figure 12 shows the air entrained into pump #5 for a wet well level of about 543' for a flow condition in which pumps # 2, 3, 5 and 6 were in simultaneous operation. Figure 13 indicates the manifestation of this air-entraining vortex within the wet well. For high station flow rates the air entraining vortices tended to not be very persistent due to the high level of turbulence in the wet well but when formed, entrained larger air volumes. The vortices were more organized and entrained smaller volumes of air on a more persistent basis at lower station flow rates.

- Other coherent surface vortices; these were generally observed at all pump intakes in at least some of the conditions tested but would generally meet the criteria discussed previously, as in most cases, the vortices were intermittent. Their degree of persistence varied among the specific tests.

Figure 12. Air entrainment into Pump #5 for a low wet well level with Pumps # 2, 3, 5, and 6 in operation.

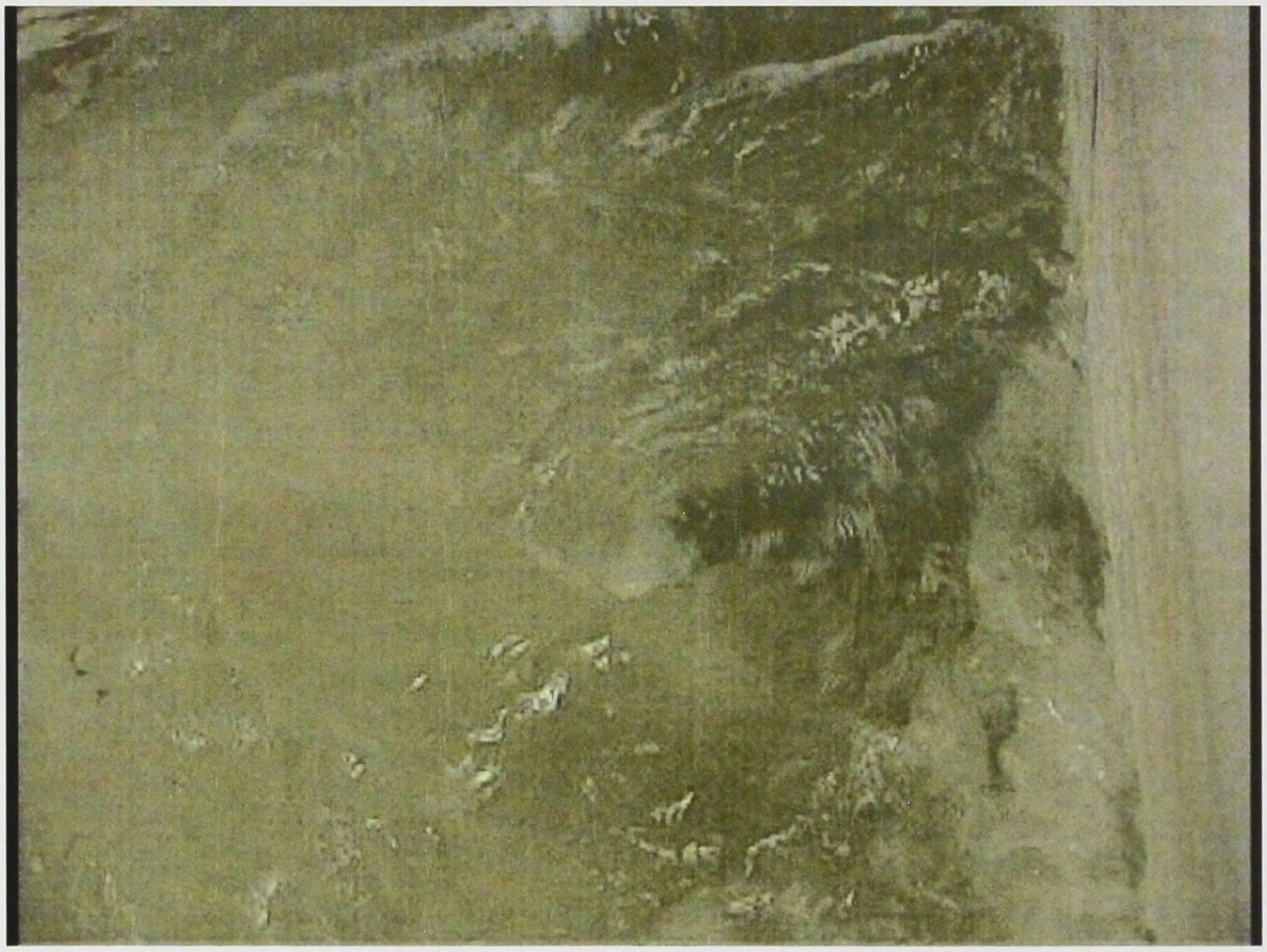

Figure 13. Vortex formation at Pump #5 at high state flow rates and low wet well levels.

- Excessive swirl angles are discussed in more detail below. In most cases, the unacceptable swirl angles were only marginally above the five degree limit, but in a few cases, they ranged up to a maximum of approximately ten degrees. The swirl angle exceedances were observed in Pumps 3-6; these are the highest capacity pumps. Pumps #1 and #2 never indicated large swirl angles and these two are considered to provide acceptable flow conditions with the exception of air entraining vortices that were sometimes observed when the adjacent, large capacity pumps #5 and #6 were operated in combination with pump #2.

The sources of much of this undesirable flow behavior were readily apparent. The flow entering the wet well through each of the two inlets can have inflow velocities ranging up to nearly five feet per second. BHRA guidelines (Prosser, 1977) generally call for approach velocities to pump intakes below one foot per second. The short distance between the inlets and the wall in which the pump inlets are located will result in very little attenuation of the inflow velocity. This high velocity impinges on the wall and begins to spread laterally in both directions along the wall. In cases of high inflow rates, surface vortices that appeared to be associated only with the impinging flow were observed to form on either side of the impinging flow. This statement is made since these vortices were observed even in cases where no pumps were in operation in front of one of the two inflow sections. The vorticity generated by this impinging flow was however transferred into a nearby pump inlet if it was operating. Air entraining vortices could then form at low wet well water levels. At sufficiently high station flow rates, these vortices were periodically disturbed by the turbulence due to the high velocities - within the wet well, but they quickly reformed. At higher wet well elevations, the vortices were more persistent, but the submergence was sufficient to prevent air entrainment.

Pump #6 exhibited the most consistently high swirl angles because the flow impinging on the back wall of the wet well flowed laterally into the confined space in the corner of the wet well where this pump was located. This flow was then forced to turn again to enter the pump intake, generating additional vorticity. Strong turning of the flow is often associated with poor intake conditions (Arboleda and El-Fadelm, 1996). At lower water levels, the surface vortex pulled to the pump #6 intake formed to the inside of the curtain wall, but at higher water levels, the surface vortex shifted to the other side of the curtain wall. This shift often resulted in a significant increase in the swirl angle at higher water levels.

Swirl Angles

- Swirl angles were measured for various combinations of one through five pumps in operation at high flow conditions in part to determine those conditions that result in largest swirl angles. The results are presented in Tables 2-4. Table 2 summarizes the results of pump combination testing at wet weather flow conditions (greater than 70 mgd) while Table 3 summarizes individual pump testing. Table 4 summarizes various pump combinations tested for dry weather flow rates of 70 mgd. Initially, tests were performed at either a low water level of 543 ft or a higher level of 546 ft. Several different flow configurations were observed to approach the five degree level at either low or high water levels. This led to additional testing for a few cases that indicated higher swirl angles in the preliminary testing in which the water level was varied in 0.5 or 1 ft increments. These additional tests showed that highest swirl angles were often observed in the 544-545 ft range. In some cases, the measured swirl angles were above the limits generally recommended for axial flow pumps especially for pump #6, the large capacity pump in the corner of the wet well. Pump #5 also indicated several instances where the swirl angle criterion was exceeded, particularly with regard to high wet well flows (140 mgd) and pump #3 also experienced one exceedance of the 5 degree criterion.

- For dry weather operation, excessive swirl was observed in pumps #3, #4, and #6. The instances in which unacceptable swirl occurred were generally associated with pump combinations that load flow to one side of the wet well. For example, pumps #3 and #4 had excessive swirl for various water levels when they were operating together, thus channeling all flow to the east side of the wet well. A similar situation was noted when pumps #2 and #6 were operated on the opposite side of the wet well. Table 4 summarizes swirl testing for dry weather operations. No other swirl angle exceedances were noted for dry weather flow conditions in which nonadjacent pumps were used to obtain the 70 mgd flow rate.

- For pumps on either side of the wet well, pumps #4 and #6, the swirl angles tend to increase with wet well water surface elevation. However, for pumps between the curtain walls (#3 and #5), swirl generally is the greatest at lower wet well water elevations.

- These tests were conducted without the recycle line in operation. The effect of the recycle line on the swirl angles is discussed in more detail in a previous report, (Wright, et al. 2004), but was found to have little effect on swirl or vortex formation.

Table 2. Swirl angles associated with various high-flow conditions in "existing" design.

Pump Combination	Pump #	Flow Rate (MGD)	Water Level (ft)	Swirl Angle
5, 6 100 mgd	5	50	543	-1.62
	6	50	543	-1.21
	5	50	546	-2.63
	6	50	546	-1.21
3,4,5 120 mgd	3	30	544	0.51
	4	40	544	-1.40
	5	50	544	-0.40
	3	30	545	0.00
	4	40	545	0.60
	5	50	545	-1.62
	3	30	546	3.82
	4	40	546	-0.70
	5	50	546	1.62
3,4,6 120 mgd	3	30	544	-0.51
	4	40	544	2.49
	6	50	544	-2.02
	3	30	545	2.21
	4	40	545	-4.58
	6	50	545	2.02
	3	30	546	3.06
	4	40	546	-1.10
	6	50	546	2.39
3,5,6 130 mgd	3	30	543	-3.31
	5	50	543	1.92
	6	50	543	-3.43
	3	30	546	-5.09
	5	50	546	-0.40
	6	50	546	-3.03
2,3,4,5 140 mgd	2	20	543	0.00
	3	30	543	0.00
	4	40	543	-2.89
	5	50	543	10.01
	2	20	544	0.67
	3	30	544	0.25
	4	40	544	-2.89
	5	50	544	9.62
	2	20	545	0.61
	3	30	545	1.02
	4	40	545	1.30
	5	50	545	4.84
	2	20	546	1.46
	3	30	546	3.06
	4	40	546	-3.98
	5	50	546	6.04
1,2,3,4,5 150 mgd	1	10	544	-1.95
	2	20	544	0.12
	3	30	544	0.25
	4	40	544	2.19
	5	50	544	6.04
	1	10	545	0.71
	2	20	545	1.34
	3	30	545	2.04
	4	40	545	-3.29
	5	50	545	7.64
	1	10	546	0.53
	2	20	546	1.10
	3	30	546	3.56
	4	40	546	-3.78
	5	50	546	6.24
2,3,5,6 150 mgd	2	20	543	0.79
	3	30	543	-3.06
	5	50	543	8.43
	6	50	543	-6.64
	2	20	546	1.4
	3	30	546	-2.17
	5	50	546	-1.21
	6	50	546	-5.14

Note: negative sign denotes counterclockwise rotation when looking down on model, positive sign denotes clockwise rotation.

Table 3. Swirl angles for individual pumps in "existing" design.

Pump Combination	Pump #	Flow Rate (MGD)	Water Level (ft)	Swirl Angle
2 20 mgd	2	20	543	2.13
	2	20	544	0.73
	2	20	545	1.46
	2	20	546	1.95
3 30 mgd	3	30	543	-0.64
	3	30	544	-1.91
	3	30	545	-2.93
	3	30	546	-3.82
4 40 mgd	4	40	543	-1.30
	4	40	544	-0.30
	4	40	545	0.00
	4	40	546	-0.70
5 50 mgd	5	50	543	0.00
	5	50	546	-0.40
6 50 mgd	6	50	543	-5.04
	6	50	546	-5.54

Note: negative sign denotes counterclockwise rotation when looking down on model, positive sign denotes clockwise rotation.

Table 4. Swirl angles for two pump combinations associated with dry weather flow in "existing" design.

Pump Combination	Pump #	Flow Rate (MGD)	Water Level (ft)	Swirl Angle
2,5 70 mgd	2	20	543	0.91
	5	50	543	-0.61
	2	20	546	0.49
	5	50	546	-1.62
2,6 70 mgd	2	20	542	3.40
	6	50	542	-2.70
	2	20	543	1.90
	6	50	543	-2.60
	2	20	544	3.00
	6	50	544	-6.40
	2	20	545	3.50
	6	50	545	-8.80
	2	20	546	3.20
	6	50	546	-6.60
3,4 70 mgd	3	30	542	1.50
	4	40	542	-0.60
	3	30	543	2.20
	4	40	543	-0.30
	3	30	544	5.80
	4	40	544	3.80
	3	30	545	4.20
	4	40	545	5.20
	3	30	546	4.10
	4	40	546	2.00
3,5 70 mgd	3	30	543	-1.53
	5	40	543	4.84
	3	30	544	-0.64
	5	40	544	3.94
	3	30	545	-3.18
	5	40	545	0.81
	3	30	546	-1.66
	5	40	546	0.30

Pump Combination	Pump #	Flow Rate (MGD)	Water Level (ft)	Swirl Angle
3,6 70 mgd	3	30	543	-2.67
	6	40	543	-0.13
	3	30	544	-2.04
	6	40	544	-0.55
	3	30	545	-4.33
	6	40	545	-1.10
	3	30	546	-3.06
	6	40	546	-1.47
4,5 70 mgd	4	40	543	-0.80
	5	30	543	4.44
	4	40	544	-2.09
	5	30	544	0.30
	4	40	545	-1.20
	5	30	545	0.81
	4	40	546	-0.80
	5	30	546	0.40
4,6 70 mgd	4	40	543	-3.98
	6	30	543	-0.28
	4	40	544	-2.39
	6	30	544	-1.38
	4	40	545	-3.58
	6	30	545	-0.92
	4	40	546	-2.64
	6	30	546	0.92

Note: negative sign denotes counterclockwise rotation when looking down on model, positive sign denotes clockwise rotation.

ORIGINAL CONFIGURATION TEST RESULTS

Vortices and Other Flow Conditions

Similar to the testing of the "existing" configuration, intake conditions were observed to be reasonably satisfactory, but a number of unacceptable flow conditions were observed after the model was re-constructed to represent the "original" wet well configuration. These unacceptable conditions were observed for various combinations or one, two, three, or four pumps. A list of these follows:

- Air entrainment due to the presence of Type 6 (air-entraining) vortices. Only three instances of these vortices were found during testing of the "original" design, all of which formed behind the bar screen and involved pump #5. In the case of pump #5 operating by itself, the vortex was intermittent for wet well levels between 542 and 543.5 feet; but rather large, thus resulting in a significant amount of air entrainment into the pump intake. Pumps #5 and #6 in combination resulted in a large stable vortex at similar wet well elevations. This vortex caused an unacceptable amount of air to enter into pump #5 as the air core went all the way to the pump inlet. Pumps #3, #4, and #5 in combination resulted in a vortex similar to the one described above. However, the vortex was larger and much more stable, no longer moving around in the wet well. Also the vortex was present at wet well elevations of up to 544 feet.

- Other coherent surface vortices; these were generally observed at all pump intakes in at least some of the conditions tested but would generally meet the criteria discussed previously, as in most cases, the vortices were intermittent. Their degree of persistence varied among the specific tests and wet well elevations.
- Excessive swirl angles are discussed in more detail below. The number of instances with excessive swirl was reduced compared to the "existing" wet well configuration with most of the problems occurring in pumps #3 and #5. The unacceptable swirl angles were only marginally above the five degree limit.

The reasons for the mitigation, or eradication, of undesirable flow conditions is apparently due to the effect that the coarse bar screen has on the flow within the wet well. Specifically, the bar screen will serve to destroy rotation in flow impinging on it as would be the case of vorticity associated with flow separation from the flow entering into the wet well from the inlets. After passing through the bar screen, the flow is more diffused than with the open wet well configuration. At high water elevations, the bar screen itself prevents vortex formation due to the water surface close to the pump intakes impinging on the back side of the bar screen. The only air-entraining vortex observed was located directly behind the screen at an elevation of 544 feet or lower, and when the water level was raised slightly, the vortex would encounter the screen and was destroyed. Figure 14 indicates a schematic diagram of this observation.

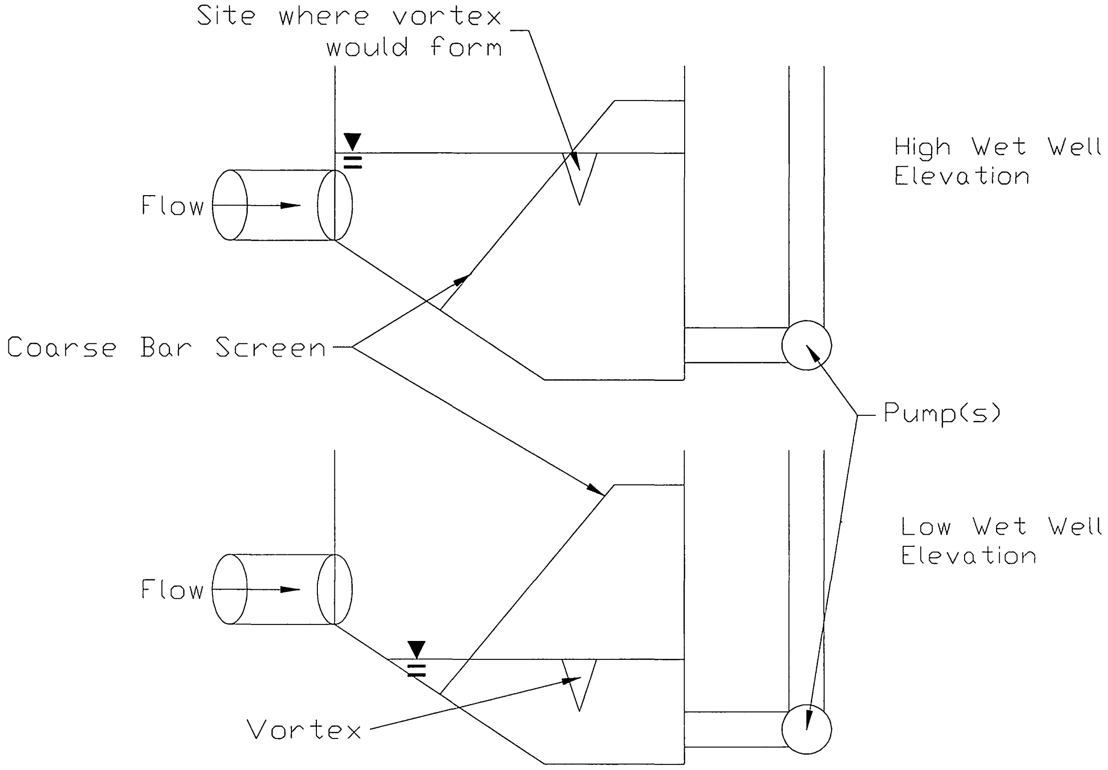

Figure 14. Diagram of vortex formation for high and low wet well elevations

Swirl Angles

- Swirl angles were measured for various combinations of one through four pumps in operation in order to examine the effects that the modification made to the pump station had on hydraulic conditions. Table 5 summarizes the results of pump combination testing for wet weather flow conditions and Table 6 summarizes individual pump testing. Testing was conducted on nearly all pump combinations tested previously for the "existing" wet well configuration and at 1-foot increments for wet well levels between 542 and 546 feet. At high flow rates, excessive swirl angles were observed only in pump #5. Again this excessive swirl occurred at relatively low wet well water levels. Pump #3, when operating singly, was observed to have excessive swirl at low water levels and is essentially at the five degree limit for the case of pumps #2, 3, 4 and 5 in operation. Pump #6 exhibited consistently larger swirl angles than the other pumps operated alone, but remained below the five degree level.
- For dry weather flow, pump #3 exceeded the swirl angle criteria for all water levels when operated in tandem with pump #4. This is due to the effect of channeling flow to only one side of the wet well similar to the situation in the "existing" wet well configuration. Table 7 summarizes two pump combination swirl testing for dry weather

flows of 70 mgd. Pump #6, while exhibiting higher swirl angles, never exceeded the five degree limit. Again, the number of exceedances of the five degree limit was decreased compared to the “existing” wet well configuration.

A summary of all flow conditions that exceeded a five degree swirl angle is provided in Table 8.

Table 5. Swirl angles associated with various high flow conditions in "original" design.

Pump Combination	Pump #	Flow Rate (MGD)	Water Level (ft)	Swirl Angle
5,6 100mgd	5	50	542	-0.40
	6	50	542	-1.01
	5	50	543	-1.21
	6	50	543	-1.56
	5	50	544	-2.12
	6	50	544	-2.48
	5	50	545	0.40
	6	50	545	-4.22
	5	50	546	0.91
	6	50	546	-3.12
3,4,5 120 mgd	3	30	542	3.69
	4	40	542	-1.25
	5	50	542	0.91
	3	30	543	3.31
	4	40	543	0.15
	5	50	543	0.71
	3	30	544	2.67
	4	40	544	0.70
	5	50	544	1.62
	3	30	545	2.93
	4	40	545	-0.30
	5	50	545	1.31
	3	30	546	1.66
	4	40	546	-1.69
	5	50	546	1.01
3,4,6 120mgd	3	30	542	1.78
	4	40	542	-0.70
	6	50	542	4.04
	3	30	543	2.94
	4	40	543	1.66
	6	50	543	-0.37
	3	30	544	2.80
	4	40	544	1.64
	6	50	544	-0.64
	3	30	545	1.29
	4	40	545	-0.89
	6	50	545	-0.55
	3	30	546	1.66
	4	40	546	-1.05
	6	50	546	1.56
3,5,6 130 mgd	3	30	542	1.91
	5	50	542	2.43
	6	50	542	-0.74
	3	30	543	-1.78
	5	50	543	2.73
	6	50	543	-2.21
	3	30	544	-3.06
	5	50	544	1.21
	6	50	544	-1.65
	3	30	545	-3.06
	5	50	545	0.81
	6	50	545	-0.46
	3	30	546	-3.18
	5	50	546	1.72
	6	50	546	1.29
2,3,4,5 140 mgd	2	20	542	-0.06
	3	30	542	4.96
	4	40	542	-1.20
	5	50	542	4.24
	2	20	543	0.30
	3	30	543	4.07
	4	40	543	0.55
	5	50	543	5.84
	2	20	544	0.24
	3	30	544	2.67
	4	40	544	0.75
	5	50	544	5.14
	2	20	545	0.30
	3	30	545	1.27
	4	40	545	-0.20
	5	50	545	4.84
	2	20	546	0.24
	3	30	546	2.17
	4	40	546	-2.19
	5	50	546	3.43
2,3,5,6 150 mgd	2	20	542	0.55
	3	30	542	-0.51
	5	50	542	1.52
	6	50	542	-2.39
	2	20	543	0.43
	3	30	543	-1.78
	5	50	543	4.04
	6	50	543	-3.95
	2	20	544	0.85
	3	30	544	-2.80
	5	50	544	2.93
	6	50	544	-4.04
	2	20	545	0.67
	3	30	545	-3.18
	5	50	545	3.23
	6	50	545	-3.40
	2	20	546	0.24
	3	30	546	-1.78
	5	50	546	0.81
	6	50	546	0.37

Note: negative sign denotes counterclockwise rotation when looking down on model, positive sign denotes clockwise rotation.

Table 6. Swirl angles for individual pumps in "original" design.

Pump Combination	Pump #	Flow Rate (MGD)	Water Level (ft)	Swirl Angle
2	2	20	542	-0.67
20 mgd	2	20	543	-0.49
	2	20	544	-0.12
	2	20	545	-0.06
	2	20	546	0.06
3	3	30	542	5.21
30 mgd	3	30	543	1.53
	3	30	544	1.66
	3	30	545	0.51
	3	30	546	3.31
4	4	40	542	-1.25
40mgd	4	40	543	0.00
	4	40	544	-0.45
	4	40	545	-0.95
	4	40	546	-0.20
5	5	50	542	1.21
50 mgd	5	50	543	1.21
	5	50	544	0.91
	5	50	545	1.21
	5	50	546	0.03
6	6	50	542	-2.11
50 mgd	6	50	543	-3.49
	6	50	544	-4.40
	6	50	545	-3.58
	6	50	546	-4.04

Note: negative sign denotes counterclockwise rotation when looking down on model, positive sign denotes clockwise rotation.

Table 7. Swirl angles for two pump combinations associated with dry weather flow in "original" design.

Pump Combination	Pump #	Flow Rate (MGD)	Water Level (ft)	Swirl Angle
2,5 70 mgd	2	20	542	0.61
	5	50	542	0.81
	2	20	543	0.00
	5	50	543	-0.20
	2	20	544	0.49
	5	50	544	0.61
	2	20	545	-0.12
	5	50	545	1.31
	2	20	546	1.04
	5	50	546	1.31
2,6 70 mgd	2	20	542	1.77
	6	50	542	-4.04
	2	20	543	2.31
	6	50	543	-4.04
	2	20	544	0.24
	6	50	544	-3.58
	2	20	545	0.91
	6	50	545	-3.49
	2	20	546	0.97
	6	50	546	-4.95
3,4 70 mgd	3	30	542	5.34
	4	40	542	-0.20
	3	30	543	6.10
	4	40	543	0.20
	3	30	544	5.59
	4	40	544	-0.10
	3	30	545	5.84
	4	40	545	-0.05
	3	30	546	6.35
	4	40	546	0.30
3,5 70 mgd	3	30	542	-2.29
	5	40	542	-0.81
	3	30	543	-3.18
	5	40	543	0.40
	3	30	544	-3.69
	5	40	544	2.53
	3	30	545	-4.58
	5	40	545	0.61
	3	30	546	0.36
	5	40	546	0.00

Pump Combination	Pump #	Flow Rate (MGD)	Water Level (ft)	Swirl Angle
3,6 70 mgd	3	30	542	-3.31
	6	40	542	-1.29
	3	30	543	2.93
	6	40	543	-2.11
	3	30	544	-3.06
	6	40	544	-0.74
	3	30	545	-4.96
	6	40	545	-0.64
	3	30	546	-4.07
	6	40	546	0.64
4,6 70 mgd	4	40	542	-0.90
	6	30	542	-0.28
	4	40	543	-0.80
	6	30	543	-0.55
	4	40	544	-1.00
	6	30	544	-0.64
	4	40	545	-2.79
	6	30	545	-0.92
	4	40	546	-2.94
	6	30	546	-0.18
4,5 70 mgd	4	40	542	-0.10
	5	30	542	0.40
	4	40	543	-0.50
	5	30	543	0.71
	4	40	544	-0.25
	5	30	544	0.61
	4	40	545	-0.85
	5	30	545	0.81
	4	40	546	-1.94
	5	30	546	1.11

Note: negative sign denotes counterclockwise rotation when looking down on model, positive sign denotes clockwise rotation.

Table 8. Pump combinations resulting in swirl angles greater than 5 degrees.

Pump Combination	Pump #	Existing Configuration Water Level (ft)	Original Configuration Water Level (ft)
3	3		542
30 mgd			
6	6	543, 546	
50 mgd			
3,4	3	544	542-546
70 mgd	4	545	
2,6	6	544-546	
70 mgd			
3,5,6	3	546	
130 mgd			
2,3,4,5	5	543, 544, 546	543,544
140 mgd			
2,3,5,6	5, 6	543	
150 mgd	6	546	

Inlet Flow Variations

The tests discussed above were all performed for inlet flow conditions in which the inflow through the west inlet to the junction chamber was only slightly greater than that from the east inlet. Additional tests were performed to examine the effects of increasing the contribution to the total station flow from the west inlet. The flow through the influent sewers was adjusted to provide the west inlet with approximately 70 percent of the influent to observe the impact on vortex formation and swirl angles. Pump combinations associated with unacceptable flow conditions in the "existing" wet well configuration were then tested and the following results were observed:

- **Vortices and Other Flow Conditions:** The unequal flow between the two influent sewers caused vortices that formed previously with a nearly equal flow split to shift location and generally reduce in magnitude. Particularly, the large type 6 vortex associated with pump #5 was now not a stable vortex, even at low wet well water elevations. What was observed during the tests was that when the flow on the right hand side (looking downstream) of the wet well was increased, the location of the air entraining vortex was shifted towards the left side of the wet well. Eventually, the displacement created a sufficiently large travel distance down to the pump #5 inlet and the vortex was no longer capable of entraining air.

- **Swirl Angles:** Splitting the flow between the two inlets appears to have no significant impact on swirl. For all tested cases, no major change of swirl angles were observed except in the case of pump #4, for which it decreased. Table 9 summarizes the results of swirl testing with the larger flow from the west inlet. It is concluded that the effect of the flow distribution between the two inlets on swirl is only minor.

Table 9. Swirl angle for various pump combinations

Pump Combination	Pump #	Flow Rate (MGD)	Water Level (ft)	Swirl Angle (Equal Flow)	Swirl Angle (Unequal Flow)
2,6	2	20	546.5	0.00	0.00
70 mgd	6	50	546.5	-6.14	-6.77
3,4	3	30	545	5.59	6.10
70 mgd	4	40	545	2.04	0.00
2,3,4,5	2	20	545	0.06	0.00
140 mgd	3	30	545	1.40	2.04
	4	40	545	-0.80	0.75
	5	50	545	4.34	3.33

Note: negative sign denotes counterclockwise rotation when looking down on model, positive sign denotes clockwise rotation.

DISCUSSION

Comparing the findings from the tests of both the "existing" and "original" configurations, it is observed that the number of unacceptable flow conditions occurs more frequently under the "existing" pump station configuration. The effects of the modifications made in the late 1990's to the pump station are as follows:

- An increase in both surface and sub surface vortices. Specifically, air entraining vortices now occur in association with pumps #4, #5, and #6, where as only #5 exhibited air entraining vortices in the "original" pump station design.
- A general increase in pre-rotation of flow entering the pump intakes. Almost all swirl angles observed in testing the "existing" configuration were greater than those observed in testing the "original" configuration. Pump #5 appeared to be the most severely impacted by the modifications.

In the "original" configuration, a type 6 vortex was only observed when pump #5 operated individually. In the "existing" configuration, type 6 vortices were seen not only while pump #5 operated individually, but in many instances in which pump #5 was in operation in combination with other pumps. The strength of small or intermittent vortices observed in the "existing" configuration appear to be stronger than in the "original" design configuration.

As for swirl, the "original" design configuration only had two pumps (#3 and #5) exhibiting excessive swirl. Pump #5, in the "existing" configuration, had swirl angles of up to ten degrees. Table 10 summarizes the change of swirl angle for the pump combinations in which #5 had the greatest degree of swirl, Figure 15 graphically represents the comparison for one flow configuration for which the performance of pump #5 was particularly poor for the "existing" configuration. In general, it was observed that the excessive swirl decreases as water levels increase. Pump #5 exhibits larger swirl angles at low water levels for both "original" and "existing" configurations but the change in performance is greater at the lower water levels. In general, we find that the swirl angle for nearly all cases is greater for the "existing" compared to the "original" configuration, although only marginally. There are a few instances in which the "original" configuration produced greater swirl angles. For example, pump #3 (operation at low water levels) had larger swirl angles in the "original" configuration; this is represented graphically in figure 16. Figures 17 and 18 graphically depict other deviations in swirl between the two model designs where unacceptable swirl angles occurred. Figure 17 indicates the observation that Pump #6 demonstrated considerably higher swirl angles at high wet well elevations in the "existing" compared to the "original" wet well configuration. Figure 18 demonstrates the reduction in swirl angles at a high wet well elevation of 546 feet for almost all pump operation scenarios with the exception of the Pumps #3 and #4 combination discussed previously.

Table 10. Comparison of swirl for pump #2, 3, 4, and 5 combination.

Pump Combination	Pump #	Flow Rate (MGD)	Water Level (ft)	Swirl Angle (existing)	Swirl Angle (original)
2,3,4,5 140 mgd	2	20	543	0.00	0.30
	3	30	543	0.00	4.07
	4	40	543	-2.89	0.55
	5	50	543	10.01	5.84
	2	20	544	0.67	0.24
	3	30	544	0.25	2.67
	4	40	544	-2.89	0.75
	5	50	544	9.62	5.14
	2	20	545	0.61	0.30
	3	30	545	1.02	1.27
	4	40	545	1.30	-0.20
	5	50	545	4.84	4.84
	2	20	546	1.46	0.24
	3	30	546	3.06	2.17
	4	40	546	-3.98	-2.19
	5	50	546	6.04	3.43

Note: negative sign denotes counterclockwise rotation when looking down on model, positive sign denotes clockwise rotation.

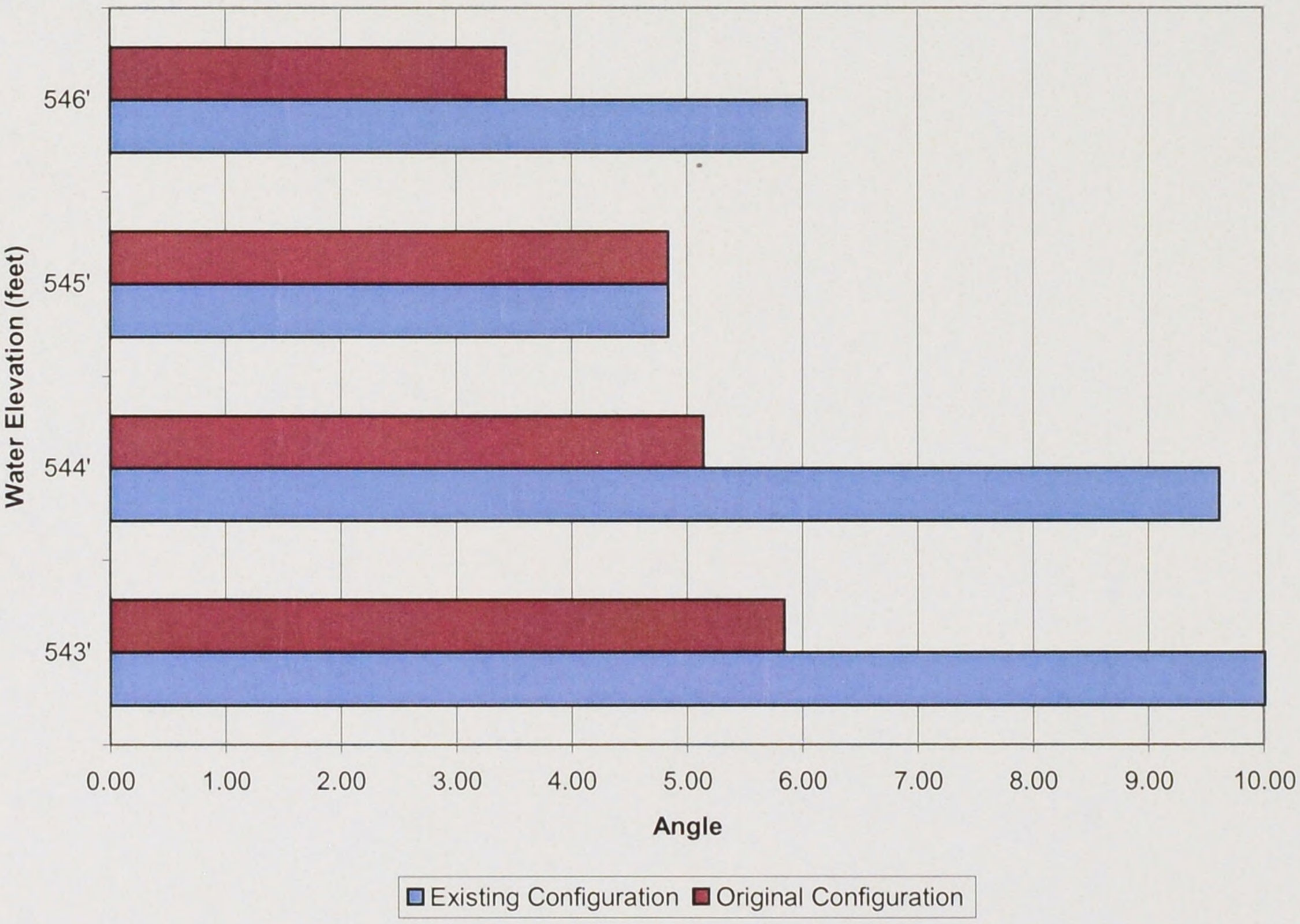

Figure 15. Swirl Angle Comparison: Pump #5 in combination with pumps #2, #3, and #4

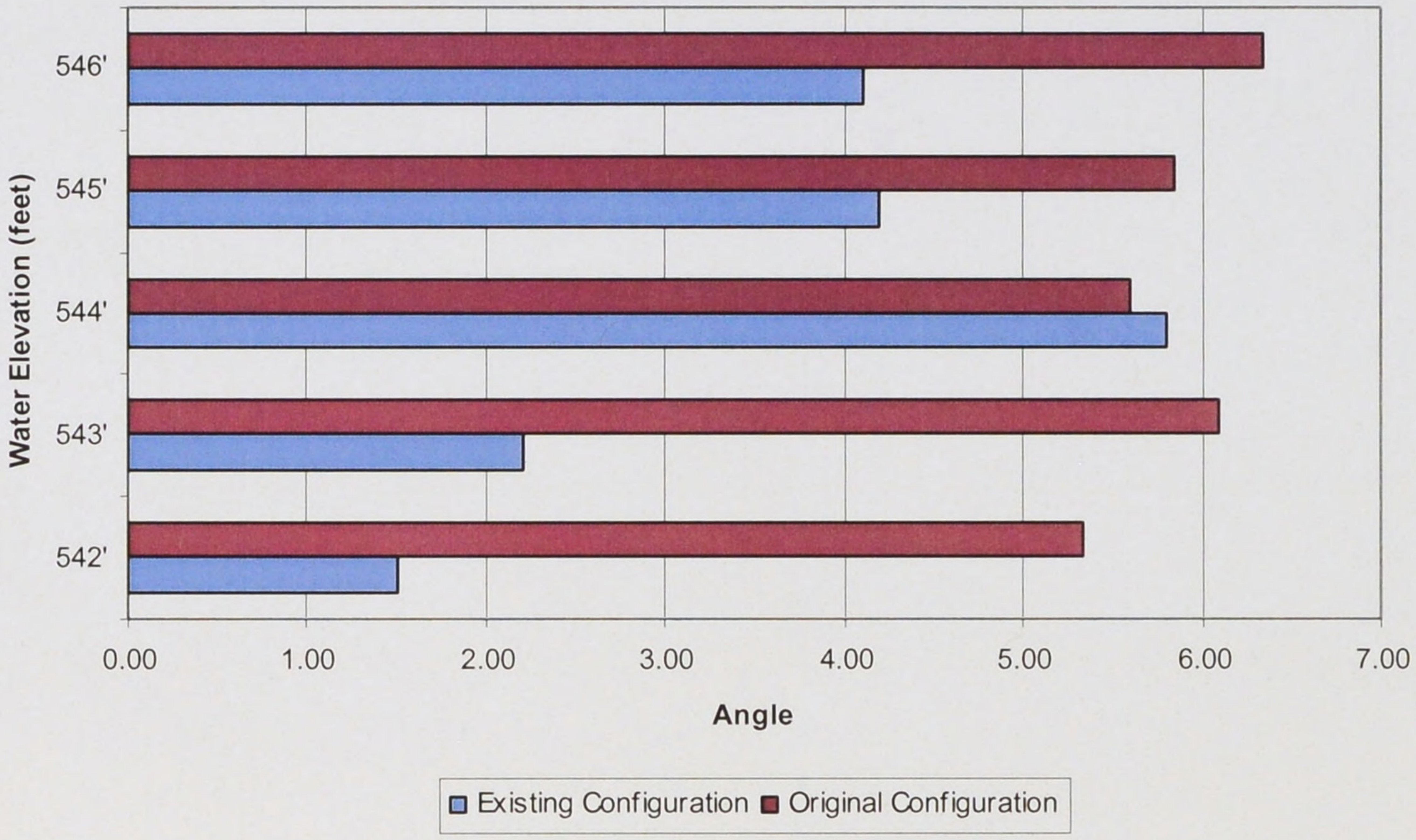

Figure 16. Swirl Comparison: Pump #3 in combination with pump #4.

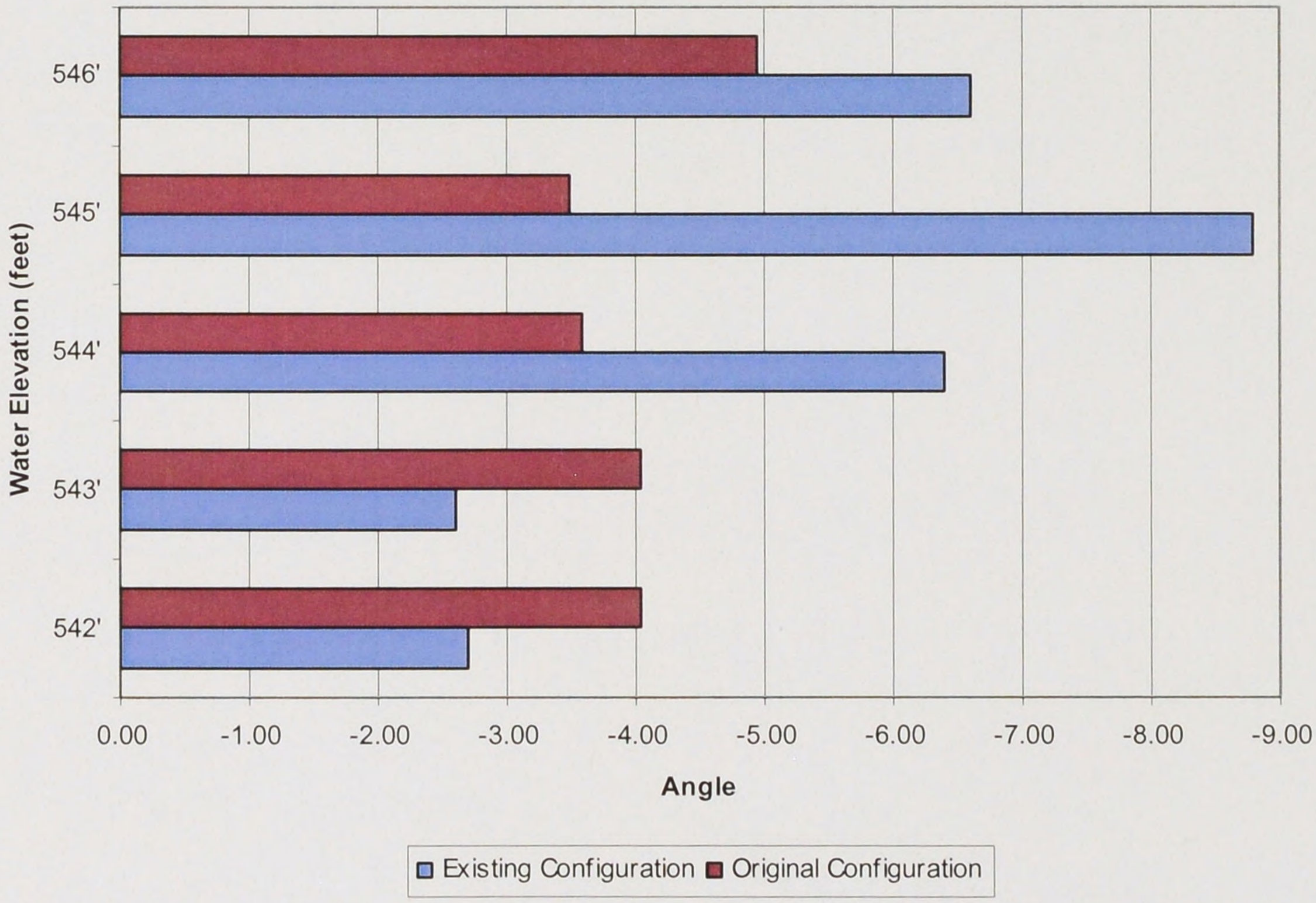

Figure 17. Swirl Comparison: Pump #6 in combination with pump #2.

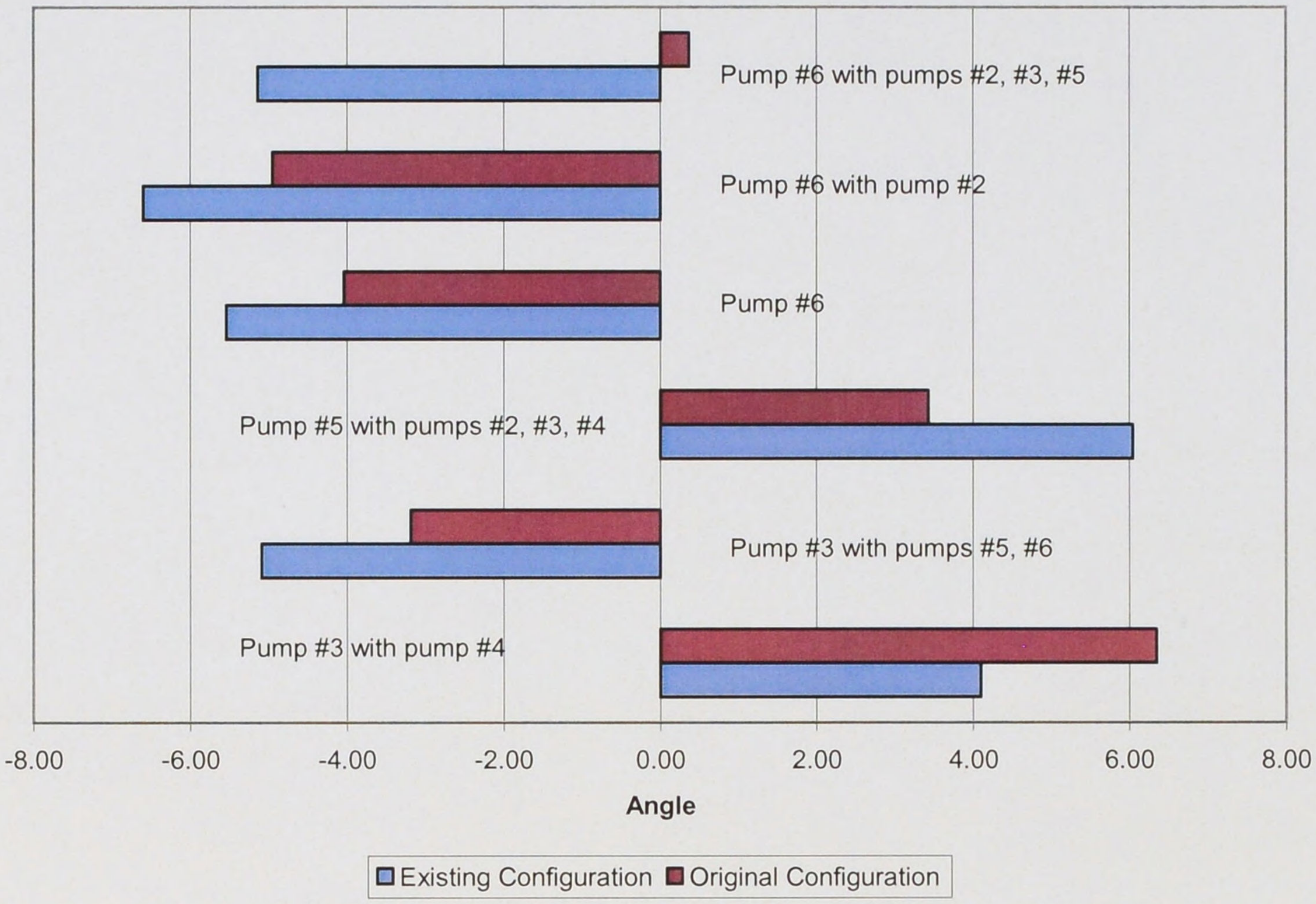

Figure 18. Swirl Angle Comparison: for Various Pumps at 546 ft Wet Well Elevation.

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AIIM SCANNER TEST CHART # 2

Spectra
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6 PT ABCDEFGHIJKLMNOPQRSTUVWXYZabcdefghijklmnopqrstuvwxyz;:",./?$0123456789
8 PT ABCDEFGHIJKLMNOPQRSTUVWXYZabcdefghijklmnopqrstuvwxyz;:",./?$0123456789
10 PT ABCDEFGHIJKLMNOPQRSTUVWXYZabcdefghijklmnopqrstuvwxyz;:",./?$0123456789

Times Roman
4 PT ABCDEFGHIJKLMNOPQRSTUVWXYZabcdefghijklmnopqrstuvwxyz;:",./?$0123456789
6 PT ABCDEFGHIJKLMNOPQRSTUVWXYZabcdefghijklmnopqrstuvwxyz;:",./?$0123456789
8 PT ABCDEFGHIJKLMNOPQRSTUVWXYZabcdefghijklmnopqrstuvwxyz;:",./?$0123456789
10 PT ABCDEFGHIJKLMNOPQRSTUVWXYZabcdefghijklmnopqrstuvwxyz;:",./?$0123456789

Century Schoolbook Bold
4 PT ABCDEFGHIJKLMNOPQRSTUVWXYZabcdefghijklmnopqrstuvwxyz;:",./?$0123456789
6 PT ABCDEFGHIJKLMNOPQRSTUVWXYZabcdefghijklmnopqrstuvwxyz;:",./?$0123456789
8 PT ABCDEFGHIJKLMNOPQRSTUVWXYZabcdefghijklmnopqrstuvwxyz;:",./?$0123456789
10 PT ABCDEFGHIJKLMNOPQRSTUVWXYZabcdefghijklmnopqrstuvwxyz;:",./?$0123456789

News Gothic Bold Reversed
4 PT ABCDEFGHIJKLMNOPQRSTUVWXYZabcdefghijklmnopqrstuvwxyz;:",./?$0123456789
6 PT ABCDEFGHIJKLMNOPQRSTUVWXYZabcdefghijklmnopqrstuvwxyz;:",./?$0123456789
8 PT ABCDEFGHIJKLMNOPQRSTUVWXYZabcdefghijklmnopqrstuvwxyz;:",./?$0123456789
10 PT ABCDEFGHIJKLMNOPQRSTUVWXYZabcdefghijklmnopqrstuvwxyz;:",./?$0123456789

Bodoni Italic
4 PT ABCDEFGHIJKLMNOPQRSTUVWXYZabcdefghijklmnopqrstuvwxyz;:",./?$0123456789
6 PT ABCDEFGHIJKLMNOPQRSTUVWXYZabcdefghijklmnopqrstuvwxyz;:",./?$0123456789
8 PT ABCDEFGHIJKLMNOPQRSTUVWXYZabcdefghijklmnopqrstuvwxyz;:",./?$0123456789
10 PT ABCDEFGHIJKLMNOPQRSTUVWXYZabcdefghijklmnopqrstuvwxyz;:",./?$0123456789

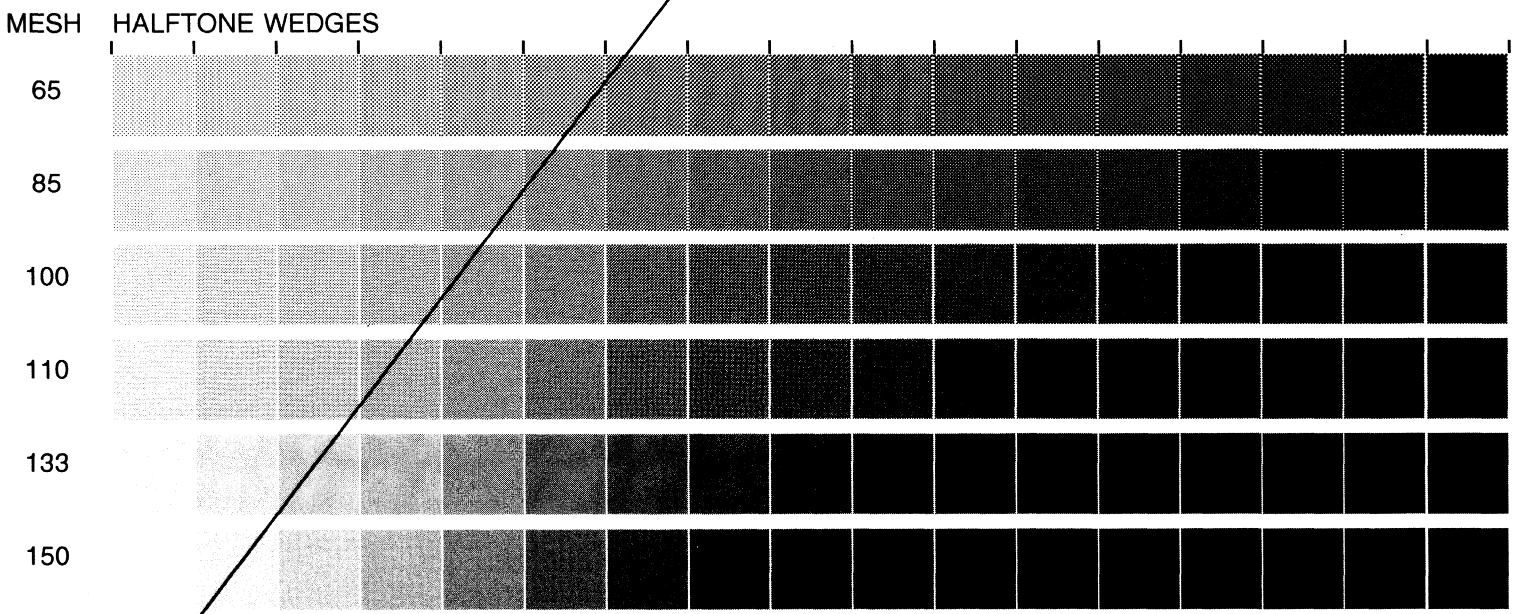
Greek and Math Symbols
4 PT ΑΒΓΔΕΞΘΗΙΚΛΜΝΟΠΦΡΣΤΥΩΧΨΖαβγδϵξθηικλμνοπφρστυωχψζ≧∓",./≦±=≠°><⊁⊀⩾⩽≡
6 PT ΑΒΓΔΕΞΘΗΙΚΛΜΝΟΠΦΡΣΤΥΩΧΨΖαβγδϵξθηικλμνοπφρστυωχψζ≧∓",./≦±=≠°><⊁⊀⩾⩽≡
8 PT ΑΒΓΔΕΞΘΗΙΚΛΜΝΟΠΦΡΣΤΥΩΧΨΖαβγδϵξθηικλμνοπφρστυωχψζ≧∓",./≦±=≠°><⊁⊀⩾⩽≡
10 PT ΑΒΓΔΕΞΘΗΙΚΛΜΝΟΠΦΡΣΤΥΩΧΨΖαβγδϵξθηικλμνοπφρστυωχψζ≧∓",./≦±=≠°><⊁⊀⩾⩽≡

White

Black

Isolated Characters

e	m	1	2	3	a
4	5	6	7	o	°
8	9	0	h	l	B



RIT ALPHANUMERIC RESOLUTION TEST OBJECT, RT-1-71

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