APPLICATION OF SUCTION SCOOPS TO IMPROVE PUMP-APPROACH FLOW DISTRIBUTIONS IN THREE-PUMP INTAKE BAYS: HYDRAULIC MODEL STUDIES OF ST. LOUIS COUNTY WATER COMPANY'S MERAMEC PLANT INTAKES 1 AND 2

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ABSTRACT

Two geometrically undistorted models of St. Louis Water Company's Meramec Plant Intakes 1 and 2 were constructed at a scale of 1:5 in order to solve chronic pump-vibration problems. Because of unconventional layouts of small, deep, rectangular pump pits with three pumps each, vertical-pump inverted drafttubes (VPIDs) were developed. Each intake chamber was divided into three individual bays using two vertical partition walls. Each VPD included a two-segment straight-line suction scoop, a floor splitter, a backwall splitter, two sidewall floor-corner fillets, two vertical backwall corner fillets, flow-turning vanes, and a vertical guidewall at the VPID entrance. This is the second VPID model designed by Iowa Institute of Hydraulic Research, The University of Iowa.

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I. INTRODUCTION

A. Background. St. Louis County Water Company's (SLCWC) Meramec Plant is located in St. Louis County, Missouri, along the left bank of the Meramec River, about 7 miles upstream from its confluence with the Mississippi River and immediately downstream from the I-55 bridge. The plant has two intakes, Unit 1 and Unit 2, both of which have three pumps each and withdraw water from the Meramec River for municipal water supplies. Each rectangular pump sump is 12 ft wide and 8 ft 7 in. long and river water enters each sump through a 9-ft wide and 4-ft high rectangular sluice, which is located 10 ft above the sump floor. The difficulty in delivering water to each pump in this particular case can be understood by imagining river water with cross flow entering the sump horizontally, changing its direction by 90 degrees downward, and reversing its flow direction by 180 degrees upward in a very short distance.

Intake 1, constructed in 1972, consists of three vertical pumps (Pumps 1, 2, and 3 counted from the downstream pump) manufactured by Johnston Pumps whose capacity is 15 MGD (23.2 cfs) each and their bell diameters are 36 in. The prototype intake forebay and pumps are shown in Photos 1 and 2, respectively. Intake 2, constructed in 1976, is located immediately upstream from Intake 1 and has three vertical pumps (Pumps 4, 5, and 6) manufactured by Ingersoll-Rand Pumps. The capacity of the Intake 2 pumps is 17 MGD (26.3 cfs) each and their bell diameters are 29.5 in. Photos 3 and 4 show the Intake 2 forebay and Pumps 5 and 6, respectively. The inside diameter of the pump column of these six pumps is 18 in. These pumps were installed in 1980s, replacing the original submersible pumps. However, the pumps have been experiencing chronic vibration problems, resulting in severe bearing wear, typically within approximately 300 hrs to 400 hrs of operation. No cavitation damage has been reported. As illustrated in figure 1 for Intake 2, each pump unit
was designed to be free of flood damage, therefore, it is extremely tall. The length of the pump including the bell is over 58 ft and the discharge elbow is located about 22 ft below the base plate of the motor.

Common to many pump-vibration problems are submerged, unstable, subsurface vortices known as floor-, backwall-, and sidewall-attached vortices which are produced by poor pump-approach-flow distributions and a poor geometrical layout of the pump sump. Unfortunately, these subsurface vortices cannot easily be detected in the prototype condition although air-entraining free-surface vortices are usually visible. Instead of removing the causes of subsurface vortices, it has been a common maintenance practice to simply replace bearings, seals, and impellers periodically and/or to resurface impeller blades if cavitation damages occur. The cost for these maintenance activities usually becomes quite high, not only because of the expense of the maintenance itself but also due to the shut down of municipal water supply and power generation during the maintenance. However, in recent years, it has become a rather routine practice to conduct small-scale laboratory model tests to find solutions. Conventional fixes to resolve these subsurface vortex problems include flow-straightening devices such as an array of deep vanes or baffle blocks and/or a perforated plate to improve sump-flow distributions, floor- and backwall-attached vortex splitters and various corner fillets to suppress formation of subsurface (Dicmas 1978; Bauer and Nakato 1997; Ettema and Nakato, 1990; Nakato 1984, 1988, 1989, and 1990; Nakato and Weinberger 1991; Nakato and Yoon 1992; Nakato et al. 1994 and 1996; Sweeney et al., 1982; Tullis 1979).

B. Scope of Study. The primary goal of the model study was to identify hydraulically objectionable features of the intakes, and to modify them so as to attain satisfactory operations of pumps under different pump combinations and hydraulic conditions. Some preliminary hydraulic concerns on the Meramec Plant intake layouts were nonuniform forebay velocity distributions and poor pump-approach flow conditions as intake flow enters through the rectangular sluice, flow circulation within each intake bay as flow moves downward toward the pump, formation of free-surface vortices, boundary-attached
subsurface vortices, and interaction between the three pumps. The ultimate goal was to devise simple and cost-effective corrective measures for some of the deficiencies which were found during the course of the study.

II. THE INTAKE MODEL

A. General. Although these two intakes are quite similar in geometry, the geometrical orientation of the pumps and the pump-bell diameters are quite different. Therefore, it was judged to be necessary to conduct hydraulic model studies for the two intakes separately. However, the intake sumps are practically identical in size for the two intakes, only one intake sump was built (see Photo 5 for the Intake 2 model) and two different forebay configurations were considered to be attached to it and tested separately. In this manner, the cost and time of model construction were reduced substantially. The Intake 1 model with diverging forebay sidewalls, as shown in figure 2 and 3, was fabricated first in a mirror image at an undistorted geometrical scale of 1:5 in the Institute's Model Annex and operated according to the Froude similitude. Photo 6 shows the model river basin and Photo 7 shows the Intake 1 model forebay. The model included a portion of the Meramec River (approximately 60 ft wide and 120 ft long in prototype dimensions), the intake forebay, the intake sump, and all pertinent intake structures. The plans and elevations of the Intake 2 model are shown in figures 4 and 5. It should be noted again that the actual Intake 1 and Intake 2 models were built in a mirror image; their actual plan model layouts can be visually seen from the back of figures 2 and 4, respectively.

The model basin was constructed primarily from fir timber and plywood, and the plywood surface was coated with fiberglass material for water-proof purposes. The detailed sump layout for each intake was reproduced in the model, including the pump-suction bell, a portion of the pump-suction line, and the pump-column support system. Figure 6 shows the detailed layout of the modeled pump-column support system which was used in both Intake 1 and Intake 2. Figures 7 and 8 show the prototype pump-bell sections of the Intake 1 and Intake 2 pumps, respectively. It should be noted that the Intake 2 bellmouth and pump-throat
diameters are smaller than those of Intake 1. Each model pump bell was machine-formed to scale from transparent lucite, and was connected to the lucite suction line. The model pump bells were fitted at their suction lines with vortimeters (four-blade, zero-pitch propeller supported by low-friction pivoted shafts) for prerotation measurements. The model pump sump was provided with a lucite window in each of two side walls and the sump backwall. These windows facilitated flow visualization and lighting.

Flow to the model was supplied through a 12-in. pipe connected to the 30-hp pump which pumped water from the underground sump. The model water-supply line was connected to a 12-in. diffuser pipe perforated with 1/2-in. orifices. The lateral distribution of flows in the river was adjusted by altering the pattern of open orifices by means of rubber plugs. Immediately downstream from the diffuser, a baffle wall with a horse-hair screen stapled to it was installed to reduce flow turbulence. The three intake-pump flows were withdrawn from the model intake by means of 3.5-in. siphon lines, and discharged into the laboratory’s pump sump. A calibrated orifice meter placed in the 12-in. supply line measured the total discharge into the model basin, and three calibrated elbow meters measured the flow rates through the model suction lines. Flows into the model and through the model suction lines were regulated by means of standard butterfly valves installed in the water-supply pipe and the individual suction lines.

**B. Equipment and Test Procedure.** The instrumentation which was used in the present pump-intake study was as follows:

1. A conventional orifice meter whose diameter was 10 in. was used to measure the discharge through the 12-in. diameter main model water-supply pipe. The meter was calibrated in the line in which it was installed using the IIHR’s weighing tank. Differential heads across the orifice plate were measured by means of precision two-tube manometers with a resolution of 0.001 ft.
(2) Three elbow meters were used to measure flow rates passing through the model suction pipes. The meters were calibrated using the Institute's calibration facility. The calibration curve for the elbow meter is shown in figure 9.

(3) A 1/2-in. wide, four-blade, zero-pitch vortimeter, which was supported by low-friction pivoted shafts, was installed in each suction pipe to measure prerotation of pumpapproach flow, which served as a measure of the strength of prerotation in the pump-column flow.

(4) Flow visualization was achieved by means of food dye injected through a wand tipped with a hypodermic needle and placed at desired locations in the flow field. This technique was used extensively to locate the origin of submerged vortices and to identify objectionable pump-approach flow patterns. Flow patterns were photographed and videotaped, and selected color photos are included herein. An unedited narrated videotape was also submitted to the client.

The test procedure involved, first, slowly filling the model river basin slightly above the low water level by adjusting the valve in the 12-in. main water-supply line, and purging off air from the three model pump-suction lines by means of a shop vacuum attached to each air vent in the suction pipes. Once the suction line was activated, the model pump discharge was set by adjusting the butterfly valve. Second, the river model tailgate was adjusted to maintain the proper river water level. Fine adjustments of the pump-intake discharge, the discharge into the river section, and the water level in the river section were repeatedly made to ensure proper model-operating conditions. It required approximately half an hour to obtain stable model-operating conditions.

**C. Model Similitude and Scale Ratios.** The model was operated in accordance with the Froude-similarity law. Undistorted geometric similarity requires that the ratio of all corresponding dimensions in model and prototype be equal. Thus, all geometric length ratios are given by
\[ L_r = \frac{L_m}{L_p} \]  

(1)

where \( L_r \), \( L_m \), and \( L_p \) are the length ratio, model length, and corresponding prototype length, respectively. Subscripts, \( r \), \( m \), and \( p \) hereinafter will be used to denote the ratio, model, and prototype, respectively. Flow processes involving a free surface, as is the case in this study, are controlled predominantly by gravitational and inertial forces. Therefore, it is important that the prototype-model ratio of gravity forces to inertial forces be preserved. This requires that Froude number, \( F_r \), be the same in model and prototype:

\[ F_r = \frac{F_m}{F_p} = 1 \]  

(2)

where

\[ F = \frac{V}{(gL)^{1/2}} \]  

(3)

where \( V \) is a characteristic flow velocity; \( g \) is the gravitational constant; and \( L \) is a representative length. The scale ratios for velocity, discharge, and time resulting from (1), (2), and (3) for \( L_r = 1/5 \) in the present case are

\[ V_r = \frac{V_m}{V_p} = L_r^{1/2} = 1/2.24 \]  

(4)

\[ Q_r = L_r^{1/2} L_r^{1/2} = L_r^{2.5} = 1/55.90 \]  

(5)

and

\[ T_r = L_r^{1/2} = 1/2.24 \]  

(6)

The rotational flow indicator in the suction line is generally expressed in terms of the angular velocity of the vortimeter tip and the average axial velocity. The swirl angle, \( \theta \), is defined by
\[ \theta = \tan^{-1}\left( \frac{V_o}{V_z} \right) \] (7)

where \( V_o = 2\pi r \omega / 60 \) = tangential velocity at the tip of the vortimeter blade; \( r \) = radius of pump column; \( \omega \) = angular velocity of vortimeter in rpm; and \( V_z \) = average axial velocity of pump-column flow.

**D. Criteria for Satisfactory Pump Operations.** IIHR's experience with numerous studies of this type has led to the following model criteria for satisfactory operations of prototype pump installations:

1. No free-surface vortices stronger than type 2, as shown in figure 10 (a).

2. No detectable boundary-attached vortices extending into the pump bells, as shown in figure 10 (b).

3. No velocities measured at the pump suction line that vary by more than 10% from the average of all local velocities measured in the cross section (*no velocities were measured in this study*).

4. No depth-averaged pump-bay intake velocities, measured approximately one-bay width upstream from the pump bell, that deviate by more than 20% from the area-averaged pump-bay average velocity over the central 75% of the bay width (*no velocity measurements were taken in this study*).

5. Vortimeter-tip velocity angles (swirl angles) no greater than 5 degrees. According to Eq. (7), the critical model vortimeter speeds corresponding to a swirl angle of 5 degrees are 33 rpm and 37 rpm for Intake 1 and Intake 2, respectively.
(6) No detectable, large-scale, persistent "unsteadiness" or "waviness" in the pumpbell approach flows; no indication of persistent large-scale turbulence; no flow anomalies judged objectionable by investigators experienced with pump-intake model tests.

It should be again pointed out that in this particular model investigation, the criteria items (3) and (4) above were not applicable because of the small pumps involved and the unconventional sump layout without any horizontal pump-approach flow section.

III. TEST RESULTS

A. Tests of Intake 1 Under the As-Built Conditions. For the seven possible pumpoperating combinations listed in table 1, preliminary tests were conducted to identify the test case which produced the worst pump-bell inlet-flow conditions, judging from vortimeter speed and vortex formation as detected through flow visualization assisted by injection of food dye into the flow. They were examined at a low river water level (LWL) at EL 380.0' because previous IIHR experience has shown that vortex formation in the pump sump is more acute at lower water levels. River crossflow corresponding to one pump discharge (15 MGD) was passed through in front of the intake for all the tests. In each test, three 2-minute-long vortimeter readings were taken and averaged, and the swirl angles computed according to Eq. (7) are summarized in table 1. Clockwise motion of the vortimeter when viewed from above was defined as positive, and counterclockwise, negative. The maximum swirl angle was -16.4° which was recorded in Pump 3 (upstream pump) in Run 3A (two-pump operation). The second largest swirl angle was -12.4° which was recorded in Pump 1 (downstream pump) in Run 1A (three-pump operation). These values far exceeded the critical swirl angle of 5°.

As shown in table 1, all other test cases showed very small magnitudes in prerotation, typically with a swirl angle less than 5°. However, flow visualization tests revealed several hydraulically objectionable features in each bay which stemmed from the poor design of the intake bay. Concentrated subsurface vortices were found to form at the sump floor.
immediately beneath each pump bell, at the backwall behind each pump, and along the sidewalls next to Pumps 1 and 3. No organized, air-entraining, free-surface vortices appeared around any pumps during the tests with the river water level set at the LWL. However, weak surface swirls, types 1 and 2 shown in figure 10 (a), were found to appear occasionally. Flow separation occurred at the upstream end of the riverside intake forebay wall, and consequently, more flow was directed toward the downstream pump. Pump-approach-flow distributions within the deep rectangular sump were unstable and highly nonuniform both vertically and laterally, resulting from the withdrawal of water through the small rectangular sluice whose bottom elevation is at EL 375’ (see section A-A in figure 3). Due to river crossflow, each pump-intake flow had to enter the bay at an angle, producing laterally nonuniform flow distributions within the small sump. This nonuniform flow distribution produced a large swirl within the sump and unstable turbulent pump-approach flow was found to circulate freely within the pump sump.

B. Description of Developmental Tests for Intake 1. The next phase of the program involved testing of various fixes step by step. Modifications tested in this phase are listed in table 2 together with resulting hydraulic features and measured swirl angles. Every effort was made to devise a simple, economical, and yet practical scheme which would be easy to construct and maintain.

In order to suppress the large-scale swirl within the sump, two 7-ft and 6-in. tall vertical partition walls were first installed in the rectangular sump in Run 1, creating three separate pump bays. However, the swirl remained within each bay. In Run 2, three layers of 5-in. by 5-in. staggered baffle bars were added horizontally immediately below the sluice gate to rectify the nonuniform flow distributions, as depicted in Photo 8. Although this arrangement suppressed the swirling actions, pump-approach flow was found to concentrate toward the backwall of each isolated bay. Therefore, a 10-ft tall vertical wall was added across the entire bay just above the pump-column brackets against the pump columns in Run 3. However, this scheme did not yield any improvement in overall flow distributions. Use of perforated plates was considered at this stage. However, it was suggested by the client that
neither perforated plates nor baffle bars be used as part of solutions in fear of zebra mussels clogging the water path in the water intake, which left the model developer very limited choices to develop a practical solution.

Based on the modeler’s past experience (Nakato 1989; Nakato, Rosenberger, and Ettema 1996), it was decided to apply a suction-scoop (or vertical-pump inverted drafttube (VPID)) approach to the Meramec Plant intakes. The VPIDs developed in 1989 for Iowa Power’s Council Bluffs Unit-3 circulating-water intake have been functioning extremely well even under the extremely low water level in the Missouri River.

Conventional vertical pumps employ pump bells to withdraw water radially and accelerate flow toward pump impellers. If a pump is installed at the center of a sufficiently large body of water, the present technology may function properly. However, the space available for a real pump-intake structure is very limited. Furthermore, the normal pump-ump layout is a narrow rectangular shape, and the pump is installed near the backwall. Because flow in the pump sump approaches the bell from one direction, the pump-approach flow generally cannot be distributed uniformly around the pump bell. The VPID intends to accelerate the pump-approach flow gradually toward the pump bell and to distribute it evenly around the bell, thereby reducing head losses of the pump-approach flow. The VPID also suppresses formation of free-surface and subsurface vortices when combined with other vortex-suppression schemes. The VPID developed at IIHR comprises a combination of a top cover which is attached to the pump bell, a floor splitter, a backwall splitter, backwall fillets, floor and ceiling fillets, and an array of flow-straightening vanes, as illustrated in figure 11 which depicts a plan and sections of the VPID developed for Iowa Power (Nakato 1989). The top cover (or ceiling) extends horizontally about one bay width upstream from the backwall, and then extends further upstream for a distance of approximately one bay width at a mild slope. The top cover whose horizontal ceiling is attached to the pump bell, therefore, forms a scoop enclosed by the sump backwall, two sump sidewalls, and the ceiling. The turning vanes installed at the entrance of the VPID serve as a flow-straightening device to rectify nonuniform distributions of pump-ump flow. The sloping ceiling functions as a flow
accelerator because it reduces the cross-section area of the flow toward the pump bell, resulting in increasing flow velocity. The triangular-shape floor splitter suppresses formation of floor-attached vortices and helps flow turn smoothly from a horizontal direction to a vertical direction. The triangular-shape backwall splitter, whose apex is very close to the lip of the pump bell, also serves as a suppressor of backwall-attached vortices, and prevents circulation of pump-approach flow around the pump bell. The backwall fillets, installed on both the sump floor and the ceiling, forms an appropriate geometrical configuration to guide flow smoothly toward the pump bell. They also eliminate stagnant flow areas which tend to develop boundary-attached subsurface vortices. The floor and ceiling corner fillets along the sump sidewalls eliminate stagnant flow areas along the corners, and serve as a vortex suppressor of sidewall-attached vortices. The VPID works under extremely low sump-water level conditions because the ceiling not only suppresses formation of air-entraining free-surface vortices, but also reduces various head losses of the pump-approach flow. Because the VPID eliminates practically all the possible swirling activities of the pump-approach flow around the pump bell, it can lower the head losses significantly, resulting in the increased net positive suction head available. This, in turn, reduces the possibility of cavitation occurrence. It is extremely important to note that the VPID can be easily installed in existing pump sumps.

Because undesired hydraulic features were more or less the same in all the three pump bays which were separated by the two partition walls, it was decided to develop a VPID for the Pump 1 bay. Run 4 was run with a VPID comprising a 4 ft 10-in. long horizontal ceiling and a 2 ft 6-in. long sloping section, a floor splitter (see Photo 9), a vertical backwall corner fillet, and a vertical corner fillet immediately upstream from the VPID entrance, as described in table 2. A significant improvement in reducing the swirl angle was achieved with this scheme. The swirl angle in Pump 1 was reduced to only 1° from -12.4° which was measured under the as-built condition. However, unstable turbulent flow conditions were found within the VPD. This was caused by a reverse flow which was reflected from the sump backwall above the VPID. In order to stop this reverse flow entering the VPID, a 1 ft and 8-in. tall vertical guidewall was installed just above the VPID entrance in Run 6. This vertical wall
was very effective in reducing large-scale turbulent-flow conditions within the VPID. Further refinement of the VPID flow was achieved by means of flow-turning vanes installed at the VPID entrance (Runs 7 and 8 shown in table 2).

**C. Final Modifications Developed for Intake 1.** After having developed the VPID for Pump 1 bay, some minor geometrical adjustments were made in order to optimize the performance of the VPID. The final VPID configuration developed for Pumps 1, 2, and 3 are shown in figures 12 through 15. Figure 12 shows the plan layout of the VPID for Intake 1. This layout is shown in the model layout built in a mirror image. Therefore, the prototype layout should be viewed from the back side of the page by flipping figure 12. Figures 13 through 15 depict a plan and detailed sections of the VPID developed for Pump 1, Pump 2, and Pump 3, respectively. Detailed dimensions of the VPID will be presented later in the recommendation section. Photos 10 and 11 show two different views of the final VPID developed for Intake 1.

Under the final VPID configurations, seven tests were conducted to determine swirl angles. The results shown in table 3 indicate that the swirl angle in each case was confined below the acceptable level of $5^\circ$. Dye tests also confirmed smooth pump-approach flow conditions within the VPID for all the test cases.

**D. Tests of Intake 2 Under the As-Built Conditions.** It was recognized during the Intake 1 model tests that the major hydraulic problems come from redirecting the river intake flow issuing as a horizontal jet through the small rectangular sluice toward each pump bell which is located down a short distance within the rectangular pump sump. This means that the forebay flow distribution is rather secondary to the pump approach-flow distributions. Therefore, in order to save time and cost, the converging, Intake-1 forebay layout shown in figures 2 and 3 was used for the Intake 2 study, instead of replacing it with straight forebay walls shown in figures 4 and 5.
Seven tests (Run 1A through Run 7A) were run under the as-built conditions with a river water level set at EL 380' (LWL). One intake discharge (17 MGD) was passed in front of the intake as a river crossflow. Because the Ingersoll-Rand pumps with a smaller bellmouth diameter of 29.5 in. for Intake 2 carry a higher discharge (17 MGD) than the Johnston pumps with a bellmouth diameter of 36 in. for Intake 1 (15 MGD) and the floor clearance for Intake 2 pumps (13 in.) is smaller than that (18 in.) of Intake 1 pumps, the intensity of floor vortices was much stronger than that observed in Intake 1. Floor vortices as strong as Type 3 shown in figure 10 (b) were occasionally observed under Pumps 4, 5, and 6. Minor surface swirls (types 1 and 2 in figure 10 (a)) were occasionally observed. Swirl angles determined are shown in table 4. The largest swirl angle was -12.8° which was observed in Pump 4 in Run 1A (three-pump operation). Pump 4 also registered a high swirl angle of -9.2° in Run 4A (Pumps 4 and 5 were on). The primary pump-approach flow features described previously for Intake 1 also apply for Intake 2. Unstable large-scale swirls within the pump sump dominated in Intake 2. For example, flow passing through laterally along the backwall under Pump 5 bellmouth was found to be entrained into Pump 4 in Run 1A.

**E. Description of Developmental Tests for Intake 2.** The basic approach taken for Intake 1 using the VPID was generally followed for Intake 2. All three bays were primarily used to develop modifications necessary to rectify unstable nonuniform pump-approach flow distributions. The sequence of the development is summarized in table 5. Run 1 was tested with two vertical partition walls with a floor splitter, a backwall corner fillet, and a vertical corner fillet applied to the upstream end of the pump bay. No suction scoop was installed. As expected for the pump with an extremely small bellmouth diameter, this arrangement which functioned well for Intake 1 did not work too well. Unstable turbulent flow with strong swirl was present and the swirl angle was quite large (-10.1° in Pump 5, for example). Runs 2 through 8 were tested with different pump combinations under the same bay modifications. Although pump-approach flows appeared steady, swirl angles larger than 3° were detected in Runs 2, 3, 5, and 7.
In order to reduce the swirl angle, a backwall splitter was employed in each bay. Furthermore, the vertical partition wall between pump bays 5 and 6 had to be extended to 5 ft 10 in. (the height of the partition wall between pump bays 4 and 5 was 4 ft 7 in.) This extension was needed to suppress lateral flow movement from the area near the Pump 6 column to Pump 4 which occurred in the unconfined area above the VPIDs. This approach helped reduce higher pump-approach flow velocities along the left (looking downstream) sidewall of the VPID for Pump 4. Prior to this wall extension, angles of several flow-turning vanes near the left side wall were altered (from 4° to 8°) to direct the VPID flow for Pump 4 toward the right sidewalls; however, it did not work due to the short bay length. Eventually, the primary source of the strong current along the left VPID sidewall was identified as originating from the area near the Pump 6 column above the VPID, and the problem was resolved by means of a taller partition wall.

**F. Final Modifications Developed for Intake 2.** The final configurations developed for Intake 2 are presented in figures 16 through 19. A plan view shown in figure 16 is again drawn in a mirror image; therefore, the prototype layout should be viewed in a mirror image also (flip the page and look at the drawing from the back side). Figure 16 shows the plan view of Intake 2 and a downstream section viewed just upstream from the VPID entrance. The detailed plan and sections for Pumps 4, 5, and 6 are shown in figures 17, 18, and 19 respectively. The VPID for each pump bay comprises a suction scoop, eight flow-turning vanes, a floor splitter, two horizontal sidewall floor-corner fillets, one horizontal backwall floor-corner fillet, a backwall splitter, one (Pumps 4 and 6) or two (Pump 5) vertical sidewall-backwall corner fillet(s), and one (Pumps 4 and 6) or two (Pump 5) vertical sidewall corner fillet(s) at the upstream end of the pump bay. Detailed dimensions of these VPID components are presented in the following chapter. Dye-injection tests revealed no objectionable hydraulic features within the VPID's developed for Intake 2. Photo 12 depicts the final VPID layout developed for the Pump 4 bay in Intake 2.

Similarly to the Intake 1 test cases, seven tests were run for different pump-operating combinations for the Intake 2 model under the final VPID configurations. Swirl angles
measured for these tests are summarized in table 6. The maximum swirl angle was only 2.1° which was detected in Pump 6 in Run 3F (Pumps 4 and 6 were on). All the other cases had swirl angles less than 1.8°.

IV. RECOMMENDATIONS

The final recommendations for Intake 1 and Intake 2 which were derived from the present model investigations are summarized in this chapter.

Intake 1

1. Install two 9-ft long and 7-ft 6-in. tall vertical walls which separate the single bay into three pump bays, as shown in figures 12 through 15.

2. Install a suction scoop in each pump bay. The scoop consists of a 4-ft wide, 4-ft 10-in. long horizontal segment attached to the pump bell and a 2-ft 6-7/16-in. long sloping (at 10°) segment (horizontal distance = 2 ft 6 in.), as shown in Section F-F of figures 13, 14, and 15.

3. Install in each bay a 1-ft 8-in. tall vertical guidewall above the suction-scoop entrance (see figures 13, 14, and 15).

4. Install seven 15-in. long flow-turning vanes, 6-in. on centers, in each suction scoop (see figures 12 through 15).

5. Install 7-ft 6-in. tall 12-in. by 12-in. triangular vertical sidewall corner fillets in each pump bay: two fillets for Pump 1 bay, four fillets for Pump 2 bay, and two fillets for Pump 3 bay (see figures 12 through 15).

6. Install in each bay a 7-13/16-in. tall and 5-ft long triangular floor splitter to suppress formation of floor vortices (see Section B-B in figures 13, 14, and 15).

7. Install in each bay two 7-13/16-in. tall and 3-ft 8-3/8-in. long triangular sidewall floor corner fillets to suppress formation of sidewall-attached vortices (see Sections A-A and C-C in figures 13, 14, and 15).
8. Install in each bay one 7-13/16-in. tall triangular backwall floor corner fillet to suppress formation of backwall-attached vortices (see Section D-D in figures 13, 14, and 15).

**Intake 2**

1. Install a 9-ft long and 4-ft 7-in. tall vertical wall between Pump 4 and 5 and a 9-ft long and 5-ft 10-in. tall vertical wall between Pumps 5 and 6; thus separating the existing single bay into three pump bays (see figures 16 through 19).

2. Install a suction scoop in each pump bay. The scoop consists of a 4-ft wide, 4-ft 7 1/2-in. long horizontal segment attached to the pump bell and a 2-ft 3 15/16-in. long sloping (at 10°) segment (horizontal distance = 2 ft 3-1/2 in.), as shown in Section F-F of figures 17, 18, and 19.

3. Install in each bay a 1-ft 8-in. tall vertical guidewall above the suction-scoop entrance (see Section F-F in figures 17, 18, and 19).

4. Install eight 15-in. long flow-turning vanes, 5 5/16-in. on centers, in each suction scoop.

5. Install 4-ft 7-in. tall 12-in. by 12-in. triangular vertical sidewall corner fillets in each pump bay: two fillets for Pump 4 bay, four fillets for Pump 5 bay, and two fillets for Pump 6 bay (see figures 16 through 19).

6. Install in each bay a 9 11/16-in. tall, 15 5/8-in wide, and 4-ft 7 15/16-in. long triangular floor splitter to suppress formation of floor vortices (see Section B-B in figures 17, 18, and 19).

7. Install in each bay two 9 11/16-in. tall, 7 13/16-in. wide, and 3-ft 8 3/8-in. long triangular sidewall floor corner fillets along the sidewalls to suppress formation of sidewall-attached vortices (see Sections A-A and C-C in figures 17, 18, and 19).

8. Install in each bay one 9 11/16-in. tall and 7 13/16-in. wide triangular backwall floor corner fillet to suppress formation of backwall-attached vortices (see Section D-D in figures 17, 18, and 19).

9. Install in each bay one 13-in. tall, 15 5/8-in. wide, and 4 1/16-in. deep triangular backwall splitter (see Sections E-E and F-F, and Detail 1 in figures 17, 18, and 19).
LIST OF REFERENCES


<table>
<thead>
<tr>
<th>Run No.</th>
<th>Intake 1 Pump Identification</th>
<th>Operating Mode (As-Built)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NO. 1 (Downstream)</td>
<td>NO. 2 (Middle)</td>
</tr>
<tr>
<td>1A*</td>
<td>-12.4°</td>
<td>-1.5°</td>
</tr>
<tr>
<td>2A</td>
<td>-6.6°</td>
<td>-4.5°</td>
</tr>
<tr>
<td>3A</td>
<td>-3.4°</td>
<td>-16.4°</td>
</tr>
<tr>
<td>4A</td>
<td>-0.2°</td>
<td>-5.1°</td>
</tr>
<tr>
<td>5A</td>
<td></td>
<td>-2.9°</td>
</tr>
<tr>
<td>6A</td>
<td></td>
<td>+1.1°</td>
</tr>
<tr>
<td>7A</td>
<td>-4.4°</td>
<td></td>
</tr>
</tbody>
</table>

NOTE:

1. Values shown above are swirl angles (= arctangent of tangential velocity/axial velocity). The maximum allowable swirl angle is about 5°.

2. Direction of vortimeter movement: clockwise positive and counterclockwise negative (viewed from the above)

3. * Suffix "A" in Run No. denotes "As-built."

4. All measurements were taken under the low river water elevation (EL 380’)

Table 1 Summary of measured swirl angles under the as-built intake conditions for Intake 1
<table>
<thead>
<tr>
<th>Run No.</th>
<th>Intake 1 Pump Identification</th>
<th>Operating Mode: 3-Pump Operation Modifications</th>
<th>Hydraulic Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-13.6° NO. 1, -6.3° NO. 2, -0.5° NO. 3</td>
<td>A (3 bays)</td>
<td>Floor Vortices, Swirling, Unsteady Flows</td>
</tr>
<tr>
<td>2</td>
<td>-13.2° NO. 1, -7.2° NO. 2, -1.6° NO. 3</td>
<td>A+B (3 bays)</td>
<td>Floor Vortices, Unsteady Flows</td>
</tr>
<tr>
<td>3</td>
<td>-11.1° NO. 1, -0.7° NO. 2, -3.1° NO. 3</td>
<td>A+B+C (3 bays)</td>
<td>Floor Vortices, Swirling, Unsteady Flows</td>
</tr>
<tr>
<td>4</td>
<td>1.0° NO. 1, Not Meas’d NO. 2, Not Meas’d NO. 3</td>
<td>A+D+E (Bay 1 only)</td>
<td>No Vortices, Large-Scale Turbulence</td>
</tr>
<tr>
<td>5</td>
<td>-0.3° NO. 1, Not Meas’d NO. 2, Not Meas’d NO. 3</td>
<td>A+D+E+F (Bay 1 only)</td>
<td>No Vortices, Better than Run 4</td>
</tr>
<tr>
<td>6</td>
<td>1.3° NO. 1, Not Meas’d NO. 2, Not Meas’d NO. 3</td>
<td>A+D+E+F+G (Bay 1 only)</td>
<td>No Vortices, Steady Flow</td>
</tr>
<tr>
<td>7</td>
<td>1.6° NO. 1, Not Meas’d NO. 2, Not Meas’d NO. 3</td>
<td>A+D+E+F+H (Bay 1 only)</td>
<td>No Vortices, Steady Flow</td>
</tr>
<tr>
<td>8</td>
<td>1.5° NO. 1, Not Meas’d NO. 2, Not Meas’d NO. 3</td>
<td>A+D+E+F+I (Bay 1 only)</td>
<td>No Vortices, Steady Flow</td>
</tr>
</tbody>
</table>

**NOTE:**

**Modification A:** Two 7 ft 6 in. tall vertical walls separating three pump bays

**Modification B:** Three layers of staggered baffle bars placed horizontally just below the sluice gate to straighten vertical pump-approach flows

**Modification C:** One 10 ft tall vertical wall placed across the entire bay above the pump-column brackets against the pump columns to stop pump-approach flows going toward the backwall

**Modification D:** A 7-13/16 in. tall and 5 ft long floor splitter, one 18 in. tall vertical backwall corner fillet, and one 7 ft 6 in. tall vertical corner fillet (applied for Pump 1 sump)

**Modification E:** A suction scoop consisting of 2 ft 6 in. long sloping and 4 ft 10 in. long horizontal sections applied for Pump 1 sump

**Modification F:** A 1 ft 8 in. tall vertical guidewall installed above the sloping scoop ceiling at the entrance

**Modification G:** Three equally-spaced 1 ft 8 in. long flow-turning vanes installed at the scoop entrance under the sloping ceiling

**Modification H:** Seven equally spaced 6 in. long flow turning vanes installed at the scoop entrance under the sloping ceiling

**Modification I:** Fifteen equally spaced 7.5 in. long flow-turning vanes installed at the scoop entrance under the sloping ceiling

Table 2 Summary of measured swirl angles under modified intake conditions for Intake 1
<table>
<thead>
<tr>
<th>Run No.</th>
<th>Intake 1 Pump Identification</th>
<th>Operating Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NO. 1 (Downstream)</td>
<td>NO. 2 (Middle)</td>
</tr>
<tr>
<td>1F*</td>
<td>+0.2°</td>
<td>-1.5°</td>
</tr>
<tr>
<td>2F</td>
<td>-1.5°</td>
<td>+1.5°</td>
</tr>
<tr>
<td>3F</td>
<td>+0.6°</td>
<td></td>
</tr>
<tr>
<td>4F</td>
<td>+0.3°</td>
<td>-1.8°</td>
</tr>
<tr>
<td>5F</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6F</td>
<td></td>
<td>-1.7°</td>
</tr>
<tr>
<td>7F</td>
<td>-1.4°</td>
<td></td>
</tr>
</tbody>
</table>

NOTE:

1. Values shown above are swirl angles (= arctangent of tangential velocity/axial velocity). The maximum allowable swirl angle is about 5°.

2. Direction of vortimeter movement: clockwise positive and counterclockwise negative (viewed from the above)

3. * Suffix "F" in Run No. denotes "Final Configuration"

4. All measurements were taken under the low river water elevation (EL 380’)

Table 3 Summary of measured swirl angles under the recommended intake conditions for Intake 1
<table>
<thead>
<tr>
<th>Run No.</th>
<th>Intake 2 Pump Identification</th>
<th>Operating Mode (As-Designed)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NO. 4 (Downstream)</td>
<td>NO. 5 (Middle)</td>
</tr>
<tr>
<td>1A*</td>
<td>-12.8°</td>
<td>-1.1°</td>
</tr>
<tr>
<td>2A</td>
<td></td>
<td>-6.7°</td>
</tr>
<tr>
<td>3A</td>
<td>-7.1°</td>
<td></td>
</tr>
<tr>
<td>4A</td>
<td>-9.2°</td>
<td>+2.9°</td>
</tr>
<tr>
<td>5A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7A</td>
<td>-0.4°</td>
<td></td>
</tr>
</tbody>
</table>

NOTE:

1. Values shown above are swirl angles (= arctangent of tangential velocity/axial velocity). The maximum allowable swirl angle is about 5°.

2. Direction of vortimeter movement: clockwise positive and counterclockwise negative (viewed from the above)

3. * Suffix "A" in Run No. denotes "As-built."

4. All measurements were taken under the low river water elevation (EL 380')

Table 4 Summary of measured swirl angles under the as-built intake conditions for Intake 2
<table>
<thead>
<tr>
<th>Run No.</th>
<th>Intake 2 Pump Identification</th>
<th>Operating Mode: 3-Pump Operation Modifications</th>
<th>Hydraulic Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>2*</td>
<td>0.8°</td>
<td>4.7°</td>
<td>N/A</td>
</tr>
<tr>
<td>8*</td>
<td>N/A</td>
<td>N/A</td>
<td>-1.1°</td>
</tr>
</tbody>
</table>

NOTE:

* Modifications applied for all three pump bays

**Modification A:** Two 4 ft 7 in. tall vertical walls separating three pump bays

**Modification B:** A 7-13/16 in. tall and 5 ft long floor splitter, one 18 in. tall vertical backwall corner fillet, two 5 ft long sidewall floor fillets, and one 7 ft 6 in. tall vertical corner fillet (applied for Pump 4 bay only)

**Modification C:** A suction scoop consisting of 2 ft 3-1/2 in. long sloping and 4 ft 7-1/2 in. long horizontal sections applied for Pump 4 bay only

**Modification D:** Eight equally-spaced 12 in. long flow-turning vanes installed at the scoop entrance under the sloping ceiling

**Modification E:** A 1 ft 8 in. tall vertical guidewall installed above the sloping scoop ceiling at the entrance

Table 5  Summary of measured swirl angles under modified intake conditions for Intake 2
<table>
<thead>
<tr>
<th>Run No.</th>
<th>Intake 1 Pump Identification</th>
<th>Operating Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NO. 4 (Downstream) NO. 5 (Middle) NO. 6 (Upstream)</td>
<td>(Final Configuration)</td>
</tr>
<tr>
<td>1F*</td>
<td>+0.1° +1.4° +1.8°</td>
<td>3-Pump Operation</td>
</tr>
<tr>
<td>2F</td>
<td>+1.6° +1.5°</td>
<td>2-Pump Operation</td>
</tr>
<tr>
<td>3F</td>
<td>+0.4° +2.1°</td>
<td>2-Pump Operation</td>
</tr>
<tr>
<td>4F</td>
<td>+0.3° +1.5°</td>
<td>2-Pump Operation</td>
</tr>
<tr>
<td>5F</td>
<td></td>
<td>1-Pump Operation</td>
</tr>
<tr>
<td>6F</td>
<td>+1.6°</td>
<td>1-Pump Operation</td>
</tr>
<tr>
<td>7F</td>
<td>+0.3°</td>
<td>1-Pump Operation</td>
</tr>
</tbody>
</table>

NOTE:

1. Values shown above are swirl angles (= arctangent of tangential velocity/axial velocity). The maximum allowable swirl angle is about 5°.

2. Direction of vortimeter movement: clockwise positive and counterclockwise negative (viewed from the above)

3. * Suffix "F" in Run No. denotes "Final Configuration"

4. All measurements were taken under the low river water elevation (EL 380')

Table 6 Summary of measured swirl angles under the recommended intake modifications for Intake 2
Photo 1  Meramec Plant Intake 1 forebay

Photo 2  Meramec Plant Intake 1 pumps
Photo 3  Meramec Plant Intake 2 forebay

Photo 4  Meramec Plant Intake 2 pumps (Pump 4 out of service)
Photo 5 A general view of the intake model (Intake 2)

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Photo 7 A view of the model forebay for Intake 1

Photo 8 Three-layer staggered horizontal baffle bars tested for Intake 1
Photo 9  A view of the model floor splitter and sidewall corner fillets tested for Intake 1

Photo 10  A sidewall view of the final VPID layout developed for Intake 1
Photo 11 A backwall view of the final VPID layout developed for Intake 1

Photo 12 A sidewall view of the final VPID layout developed for Intake 2
Figure 1  An elevation view of Ingersoll-Rand pump in Intake 2
Figure 2 A plan and sections of the Intake 1 model
Figure 3 A detailed plan and sections of the Intake 1 model
Figure 6 A sketch showing the pump-column support system
SECTION THROUGH PUMP BELL FOR INTAKE NO. 1 (PUMPS 1, 2, AND 3) (Johnston Pumps - prototype dimensions)

Figure 7: A section of the intake 1 pump bell
Figure 8 A section of the intake 2 pump bell

SECTION THROUGH PUMP BELL FOR INTAKE NO. 2 (PUMPS 4, 5, AND 6)
(ingersoll-Rand - prototype dimensions)
Elbowmeter Calibration

- Calibration Points
- Regression Line

\[ Q = 0.440 \cdot \text{SQRT}(\Delta h) \quad r^2 = 0.999 \]

(10-11-96 for St. Louis Water Company's Meramec Plant Model)

Figure 9 Calibration curve for the elbow meter
(a) Classification of free-surface vortices

(b) Classification of boundary-attached sub-surface vortices

Figure 10 Classification of free-surface and subsurface intake vortices
Figure 11  A plan and sections of the VPID developed for Iowa Power
Figure 13  Detailed plan and sections of the bay modifications developed for Intake 1 Pump 1 bay
Figure 14 Detailed plan and sections of the bay modifications developed for Intake 1 Pump 2 bay
Figure 15 Detailed plan and sections of the bay modifications developed for Intake 1 Pump 3 bay
Figure 16. A plan of the bay modifications recommended for Intake 1.
Figure 17 Detailed plan and sections of the bay modifications developed for Intake 2 Pump 4 bay
Figure 18 Detailed plan and sections of the bay modifications developed for Intake 2 Pump 5 bay
Figure 19 Detailed plan and sections of the bay modifications developed for Intake 2 Pump 6 bay