SUBSURFACE VORTEX SUPPRESSION
IN WATER INTAKES
WITH MULTIPLE-PUMP SUMPS

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ABSTRACT

This report describes laboratory development of a means for enhancing the flow performance of pumps in a rectangular multiple-pump bay without cross flows in front of the pump sump. Detailed two-dimensional velocity measurements within the pump bay revealed interesting vortical structures which coincided with visual observations of the flows using food dye. The study focused on suppression of boundary-attached subsurface vortices. Using triangular-shaped horizontal floor splitters, triangular-shaped vertical backwall splitters, and corner fillets, subsurface vortices present in the four-pump sump were eliminated for all the combinations of pump operation. No vertical walls separating individual pumps were needed with these flow enhancement devices.

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NOMENCLATURE

A: Area corresponding to specified discharge;
A_r: Area ratio between model and prototype;
b: Width of the multiple-pump sump;
B: Backwall clearance;
C: Floor clearance;
D: Pump column inner diameter;
Fr: Froude number;
Fr_r: Froude number ratio between model and prototype;
g: Acceleration due to gravity;
h: Water depth;
L: Length of the multiple-pump sump;
L_r: Length ratio between model and prototype;
L_m: Characteristic model length;
L_p: Characteristic prototype length;
n: Number of revolutions per unit time for the swirl meter;
Q: Discharge;
Q_r: Discharge ratio between model and prototype;
Re: Reynolds number;
u: Velocity in the x-direction;
U_av: Calculated average approach flow velocity;
v: Velocity in the y-direction;
V: Approach flow velocity/Characteristic velocity;
\vec{V}: Velocity vector;
$V_a$: Axial velocity in the intake;
$V_r$: Velocity ratio between model and prototype;
$V_t$: Tangential velocity in the intake;
$w$: Velocity in the z-direction;
$W_s$: Weber number;
$\Delta H$: Pressure head differential;
$\alpha$: Swirl angle;
$\zeta$: Vorticity;
$\nu$: Kinematic viscosity;
$\vec{\omega}$: Vorticity vector;
$\rho$: Fluid density; and,
$\sigma$: Surface tension;
INTRODUCTION

Overview

Many thermal power plants encounter flow problems in their cooling-water intakes. One of the principal flow problems encountered by cooling-water intakes is swirling-flow problems in the pump sump. If swirling-flow problems are not resolved, the effectiveness of the intake is reduced and operating costs for the power plant may increase. A particularly difficult and quite common problem for intakes is obtaining satisfactory performance of sumps fitted with multiple vertical pumps. For reasons of construction economy, a common sump is often used for a row of sumps. The present study set out to determine the sources of swirling-flow problems and solutions to them in multiple-pump intake sumps. The approach taken was to carry out a laboratory investigation of flow in a four-pump sump. It was assumed, quite reasonably, that flow in a four-pump sump is representative of flows in sumps with multiple pumps generally. Laboratory studies, using principles of hydraulic modeling, are frequently performed to locate and suppress or avoid flow problems in existing water intakes. For example, Larsen and Padmanabhan (1986) recommend model studies for the following water intakes:

1) Intakes with asymmetric approach flow (e.g., an offset in the approach channel);
2) Intakes with multiple-pump sumps with a common approach channel and a variety of pump-operating combinations;
3) Intakes with pumps of capacities greater than 40,000 gpm (2.5m³/s) per pump;
4) Intakes with an expanding approach channel; and,
5) Intakes with possibilities of screen blockages and/or obstructions close to the suction-pipe entrance.

There is a considerable amount of information on the prevention of vortices at intake structures. However, most of the previous investigators have focused on free-surface vortices that form in single-pump intakes. Little is known about the prevention of vortices in multiple-pump intakes in a single sump. The multiple-pump sump condition investigated in the present study corresponds to item 2 of Larsen and Padmanabhan's list. However, there were no offsets in the sump, no expanding approach channel, and no screen blockages or obstructions in the suction pipe entrance.

A hydraulic intake structure, such as the multiple-pump sump, consists of an open channel (pump sump or diversion channel) and a pipe or conduit. The flow in the intake...
involves the transition from a free-surface flow in the open channel to a closed-conduit flow in the pipe. Various types of intake structures exist. Figure 1 shows the different types of intake structures. The vertically downwards intake consists of a pipe or conduit located just above (or near) the floor of the pump sump. Other intake structures include a horizontal intake, inclined downward and upward intakes, and vertically upward intakes in free-surface flow. If the flow is not driven by gravity, as in the vertically and inclined downward intakes, a pump is needed to withdraw water from the pump sump to its final destination. Therefore, a pump is required in the horizontal, the vertically upward, and the vertically inclined intakes. The intakes that require pumps are commonly referred to as pump intakes.

A number of flow problems may be encountered in a hydraulic intake if swirl occurs in the pump sump or in a pump's suction pipe. Swirl is defined as any flow condition where a tangential velocity component exists in addition to the axial velocity component. An example of swirl, similar to the circulation in a pump sump, is flow in a draining basin. The water does not simply flow radially into the drain, but swirls around the basin as it enters the drain. Sometimes a vortex may form from the water surface to the drain. The swirl continues into the drain pipe beyond the basin's drain. When swirl enters the suction line of a pump (suction pipe), the phenomenon is called prerotation. For multiple-pump intakes, as investigated, prerotation would occur if swirl existed upstream of any of the pumps.

Swirling flow in the pump sump and/or intake is linked to intake structures susceptible to vortex formation. Swirling flow and the formation of vortices at the intakes have negative effects on pumps in the intake structure. Tullis (1979) summarizes various negative effects of nonuniform pump-approach flow distributions, vortices, and swirls:

1) Free-surface vortices which, if strong enough, draw air from the free surface into the pump, causing unbalanced loading of its impeller, periodic vibration, and reduction in pump capacity;

2) Subsurface vortices, which originate from the floor, backwall, or sidewalls, and in the case of a pressurized sump from a ceiling, entering the pump and causing vibration and cavitation;

3) Prerotation of the flow entering the pump which alters the angle of attack of the impeller blades, thereby, potentially affecting pump efficiency and causing cavitation;

4) An uneven distribution of flow at the pump throat which results in unbalanced loading of the pump impeller;
5) Significant unsteadiness of flow at the pump throat which causes vibration and cavititation; and,

6) Flow separation at the pump-suction bell, which causes nonuniform flow at the impeller and possible cavititation.

Jain et al. (1978) also report that air-entraining vortices, known also as free-surface vortices, draw air into the intake from the water surface and thereby cause considerable loss of pump efficiency and produce vibrations and noise. Free-surface vortices are most damaging to the pump when they draw air or trash into the intake.

A subsurface or submerged vortex is a vortex that forms beneath the water surface and usually attaches itself to the wall or floor of a pump sump. Vorticity generated in separation zones close to the pump entrance or below the suction bell produces submerged vortices (Larsen and Padmanabhan, 1986).

When the velocity of a flow is increased, the pressure of the flow decreases. Cavitation, the formation and collapse of vapor bubbles in a fluid, occurs when the fluid velocity increases to the point where the pressure has decreased to the vapor pressure of the liquid. The implosion of vapor bubbles produces very large pressure transients, which can cause considerable damage to any surfaces near the implosions, such as the pump's impellers. When pressure is reduced in the vortex core or air is drawn into the intake, a fluctuating load on the impeller may occur along with vibration and noise, higher inlet losses, and decreased pump efficiency (Larsen and Padmanabhan, 1986). Since the formation of vortices in an intake structure can lead to considerable damage to the pumps, prevention of the vortices is a main concern when designing intake structures. If the formation of vortices is not prevented, the pump may need to be replaced frequently. Frequent replacement of a pump is costly, while modifications to the intake structure also increase the costs of maintaining and operating the intake. Prosser (1977) lists five sources of extra costs if the existing intake structure is modified or if the intake structure is left in its existing condition:

1) Delay in commissioning the pumping station, when modifications to the intake structure are being made or when the pumps are being replaced;

2) Increased maintenance during the life of the pumping station, if the intake structure is not modified;

3) Changes in performance or restrictions in the operating range of the pumps, to avoid damaging the pumps;

4) Structural alterations in the sump to improve flow conditions; and,

5) Retrospective model tests to determine the necessary alterations.
These costs involve improvements to existing intake structures. Not mentioned is the continuing cost of replacing pumps worn out by adverse flow conditions.

**Approach and Scope of the Study**

The primary objective of the study was to experimentally develop a means to reduce interference between pumps in a multiple-pump sump by eliminating vortex formation. The approach taken entailed analysis of velocity distributions and vorticity in the sump, and most importantly, detecting and locating vortex formation using food dye while varying pump-operating conditions. The study did not include analysis of cross-flow effects on sump flows. Time-averaged velocity measurements were taken in the streamwise and lateral directions of the sump using an electromagnetic flow meter. Also measured was swirl flow inside each pump-suction pipe. The experimental results were analyzed and used as a basis for establishing sump modifications for eliminating vortices. A preliminary set of modifications was studied for varying pump-operating conditions so that an optimal design of the sump could be established.

**FUNDAMENTALS OF VORTEX FLOWS IN SUMPS**

**Sources of Swirl**

Eccentricities, or deviations in the pump-approach flow distribution, are the most common source of swirl and vortex formation. Durgin and Hecker (1978) categorize the sources of vortex formation into three types:

1) Nonuniform approach flow to the sump due to the geometric orientation of sump or approach channel or due to streaming flow patterns generated by obstructions such as intake piers;

2) Existence of shear layers of high velocity gradients, including separated boundary layers which are inherently rotational; and,

3) Rotational wakes generated by objects or obstructions in the way of the approach flow to the sump.

Padmanabhan (1987) reports that items 1 and 2 listed above are major sources of vorticity in free-surface and submerged vortices in pump sumps, respectively. The multiple-pump sump described herein did not have any objects or obstructions in the approach flow, so item 3 listed above would not be a source of vorticity in the sump. Item 1 applies to this model study because a symmetric approach flow was expected to flow into the sump only when all pumps were operating or when some pumps were operating in a symmetric manner such that uniform pump-approach flow conditions would be expected. Flow...
separation was expected at the entrance of the sump as the flow passed the corners of the entrance for any discharge or pump operating conditions.

Chang (1977) summarizes the flow processes that generate vortices in a pump sump as follow:

1) **Asymmetric approach flow** - the approach flow has an inherent swirl which can be magnified as the flow converges into the intake, due to the conservation of angular momentum;

2) **Boundary discontinuities** - changes in channel cross-section, diffusers, false baffles, etc., can cause small eddies to shed, thus adding to the total vorticity. The importance of this effect depends on how close the discontinuity is to the intake and the strength of the eddy it creates. The presence of the intake in the flow itself can also be a source of shed eddies;

3) **Boundary-layer development** - since the velocity at any solid boundary must be zero because of viscosity, velocity gradients will be present in the boundary layer which generate vorticity, \( \zeta \);

4) **Stagnation-point flow** - Swainston (1976) considered the flow at a plane surface near a gas-turbine intake and showed the existence of a stagnation point towards which the boundary layer, containing vorticity, flowed and was, subsequently, drawn into the intake. Using a combined boundary-layer and potential flow analyses, he argued that a concentrating stagnation point in the free-surface is associated with vortex formation at hydraulic intakes; and,

5) **Secondary flow** - Gessner and Jones (1965) have shown the presence of secondary flow currents in a plane perpendicular to the main flow direction in straight rectangular channels. These secondary flow velocities are only about 1% of the main velocity, but may be of sufficient strength to contribute to the instability of vortices. Figure 2 illustrates the secondary flow currents in a rectangular channel.

All five of the processes listed by Chang pertain to the present model study except for item 2, boundary discontinuities. There were no boundary discontinuities (such as an abrupt change in floor elevation) within the sump, although the corners at the entrance could be considered boundary discontinuities where vortex shedding may occur.

The formation of vortices is governed by two major factors mentioned by Anwar (1968): the submergence depth or distance from the water surface to the entrance of the suction pipe, and the swirl in the approach flow. He also stated that a reduction in the swirl or an increase in submergence depth can prevent the formation of vortices. In most situations, it is difficult to maintain a level of submergence where vortices do not form at the intake. For instance, if an intake structure is located at the ocean, the water elevation
would continuously be altered by the tide. It is likely that another structure such as a dike might have to be constructed to control the water level. Since the multiple-pump sump considered herein was connected to a large body of water where changes in water level are fairly small, large fluctuations of the water level were not a concern. There are different methods of reducing swirl in an intake structure, primarily by making changes in geometry of the pump sump. The different methods of reducing swirl will be described later.

**Classification of Vortex Strength**

Hecker (1987) describes the visual classification system of the strength of vortices developed by the Alden Research Laboratory (ARL), as shown in figures 3 and 4. There are six classifications of free-surface vortices:

- **Type 1:** Coherent surface swirl;
- **Type 2:** Surface dimple (coherent swirl at surface);
- **Type 3:** Dye core into intake (coherent swirl throughout water column);
- **Type 4:** Vortex pulling floating trash, but not air;
- **Type 5:** Vortex pulling air bubbles into intake; and,
- **Type 6:** Full air core to intake.

There are three classifications of subsurface vortexes:

- **Type 1:** Presence of swirl visible with dye (but not coherent core);
- **Type 2:** A coherent core visible with dye; and,
- **Type 3:** Coherent core with air bubbles coming out of solution (air-bubbles or air-core visible).

This information is valuable in determining whether the design or performance of an intake structure is acceptable. As mentioned before, vortex formation can be detrimental to the pump. If an air-entraining vortex or even surface dimples are observed in the model study, it is likely that air-entraining vortices at the free-surface will occur in the prototype. Submerged vortices are not easily seen in laboratory models unless an air core has developed or dye is injected into the flow. Therefore, it is very unlikely that a submerged vortex would be observed in the prototype or model without dye or air injection. Photos 1 and 2 show examples of a free-surface vortex pulling air bubbles into the intake (ARL's free-surface type 5) and a subsurface vortex attached to the floor with an air core visible (ARL's subsurface type 3). If an intake structure were experiencing flow problems during pump operation, it would be difficult to determine whether the problem is due to submerged vortices unless a laboratory model study is carried out. The possibility of a submerged vortex forming in an intake makes such studies necessary. A
model study of an intake prior to the construction of the prototype should be done to locate submerged or free-surface vortices, to suppress the vortex formation, and to avoid subsequent problems. An acceptance standard, pertaining to vortex formation at vertical intakes, from the Ingersoll-Rand Company (1991) specifies that no organized free-surface or submerged vortex activity is permitted and that no vortex activity greater than surface dimples and/or subsurface rotation (type 2 of ARL’s classification) is acceptable. Other related acceptance standards from the Ingersoll-Rand Company are that a surface disturbance should be less than 0.3 feet (prototype) and that the level of prerotation of flow approaching the pump impeller location measured by a vortimeter should be steady and less than 5 revolutions per minute (rpm). If the direction of rotation changes or if the rotation is intermittent, additional testing must be performed to achieve a rotation that is steady. Acceptance standards from previous research and from pump manufacturers, like Ingersoll-Rand, determine whether a laboratory model is satisfactory to achieve efficient prototype pump operation.

A set of design criteria has been developed by the Iowa Institute of Hydraulic Research (IIHR) based on IIHR’s vast experience with model studies of pump sumps. Nakato and Yoon (1992) summarize them as follows:

1) No detectable boundary-attached vortices extending into the pump bells;
2) No free-surface vortices stronger than type 2 (ARL’s classification);
3) No velocities measured at the pump throat that vary by more than 10% from the average of all local velocities measured in the cross section;
4) Vortimeter-tip velocity angles (swirl angles) no greater than 5 degrees; and,
5) No detectable, large-scale, persistent "unsteadiness" or "waviness" in the pump-bell approach flows; no indication of persistent large-scale turbulence; no flow anomalies judged objectionable by investigators experienced with pump-intake model tests.

The guidelines listed above help the researcher determine whether conditions for the existing intake structure are acceptable. If the conditions are not acceptable, modification to the intake structure must be made until the standards above are satisfied.

There are many guidelines or basic designs that have been developed to improve the reliability and performance of pump sumps. The pump-sump guidelines recommended by the Hydraulic Institute Standards (1983), and the British Hydromechanics Research Association (Prosser, 1977) appear to be the most popular. Both the Hydraulic Institute Standards and the BHRA have guidelines for multiple-pumps in open sumps. These guidelines are illustrated in figures 5 and 6. Padmanabhan (1987) has also formulated guidelines for single-sump and multiple-sump intakes, which are
illustrated in figures 7 and 8. Ingersoll-Rand (1991) developed a basic single-pump sump design as shown in figure 9. The guidelines and basic sump designs mentioned above were considered in this study in determining methods to minimize the vorticity in the multiple-pump sump.

As Padmanabhan (1987) states, the guidelines given previously are helpful for the preliminary design of pump sumps, but model studies should be performed for more complex intake structures and for the evaluation of preliminary designs. Therefore, it is recommended that model studies of an intake structure be carried out before the prototype is constructed in order to minimize costs of operating and maintaining the intake structure.

EXPERIMENTAL SETUP AND PROCEDURES

The Laboratory Sump

The layout of the laboratory sump is shown in figure 10. Photos 3, 4, and 5 show the layout of the multiple-pump and suction-scoop sumps. The multiple-pump sump was the focus of the present study. Photos 6 and 7 display the multiple-pump sump. The multiple-pump sump consisted of four 4-in. (10.2 cm) diameter vertical pump columns equally spaced at 12-in. (30.5 cm) intervals in a 4-ft (1.22 m) by 5-ft (1.52 m) sump (see figure 11). The multiple-pump sump was connected to a model basin which produced fairly uniform conditions with no cross-flow. The model pump bell used in the multiple-pump sump study is shown in figure 12. To relate the test setup to full-scale pumps and pump sumps, the pump-suction bell used is normally a 1:10 to 1:20 scale geometrically undistorted model of typical pumps used in water intakes for power plants. In this case, a 1:16-scale geometrically undistorted model of the Circulating-Water (CW) pump bell manufactured by Byron-Jackson Pumps for Union Electric's Labadie Plant CW pump intake on the Missouri River was used. The prototype pump has a rating discharge of 107,000 gpm (6.7 m³/s). The prototype dimensions are as follows:

- Bell Diameter: 98-in. (2.48 m)
- Bell Height: 54-3/8-in. (1.38 m)
- Floor Clearance (C): 32-in. (81.3 cm)
- Backwall Clearance (B): 4-in. (10.2 cm)
- Pump Column Inner Diameter (D): 68-in. (1.73 m)
In the test setup, the floor clearance (the distance between the bottom of the pump bell and the floor level) was set as \(1/2D = 3-1/16\)-in. (7.8 cm). The backwall clearance, \(B\), the distance between the pump column and backwall, was set to \(1/4D = 1-9/16\)-in. (3.9 cm), following Hydraulic Institute Standards (1983).

**Operating Conditions**

The water level in the test setup was kept at a low water level (LWL) because previous research (Anwar, 1968) has shown that vortex formation is more acute in lower water depths in pump sumps. The flow depth in the model was equal to 0.979 ft (29.8 cm) corresponding to the LWL for the pump bell in Union Electric's Labadie Plant CW pump intake. Water was supplied to the model from a constant head tank located on the third floor of the building. The water flowed through a horse-hair screen and a perforated plate as it discharged through a diffuser pipe into the model to keep the flow as uniform and steady as possible. As the water level reached the model’s LWL, water was siphoned through each of the suction pipes by the use of a vacuum. Then, the water was discharged into a drain culvert connected to an underground sump. The discharge in each intake was kept constant and equal to 0.232 cfs (6.6 l/s) following the Froude-similarity law, which will be defined subsequently. The flow through each intake was regulated by two valves. One valve was used to control the discharge through the intake, while the other valve was used as a shut-off valve. During the experiments, a small amount of water constantly leaked out of the tailgate (see figure 10), so that the total discharge supplied to the model was slightly greater than the total discharge through the operating intakes. Therefore, the total discharge in the supply line was adjusted until a constant depth was obtained. Approximately thirty minutes to an hour was needed to obtain steady-state test conditions.

**Similitude Requirements**

The model was operated according to the Froude-similarity law, because the flow in the model was a free-surface flow. Free-surface flows are governed by gravitational and inertial forces. In this case, the Froude number, the ratio of inertial forces to gravitational forces, was the dominant parameter. Therefore, in addition to the geometric similarity (same length-scale ratios between the model and the prototype), the Froude numbers of both the prototype and the model must be equal. The multiple-pump sump model was undistorted, hence the ratios of all corresponding dimensions between the model and the prototype were equal. The geometric length ratio, \(L_n\), is given by:
where $L_r$ is the length ratio, $L_m$ is the model length, and $L_p$ is the prototype length.

With the Froude number, $Fr$, the same in both model and prototype the Froude number ratio, $Fr_r$, must be equal to unity:

$$Fr_r = Fr_m/Fr_p = 1 \tag{2}$$

where

$$Fr = V/(gL)^{1/2} \tag{3}$$

where $V$ is a characteristic velocity, $g$ is the gravitational acceleration, and $L$ is a characteristic length. From these relationships, scaling rules for velocity, $V$, and discharge, $Q$, can be formulated. For example, if $L_r = 1/16$, as:

$$V_r = (g_r L_r)^{1/2} = L_r^{1/2} = 1/4 \tag{4}$$

where $g_r = 1$, since the gravitational acceleration, $g$, was the same in both the prototype and the model, and

$$Q_r = V_r A_r = (L_r)^{2.5} = 1/1,024 \tag{5}$$

where $A_r$ is the ratio of the cross-sectional area in the model to that in the prototype.

From the scaling laws formulated above, the velocity and discharge used for the test setup can be related to full-scale pump-sump flows. Table 1 summarizes the velocities and discharges used for the test setup.

Because the test setup is a Froude-scale reduced-size intake, the viscous and surface tension forces may not be exactly simulated. There has been a number of studies to determine viscous and surface tension scale effects on the formation of vortices at hydraulic intakes. For example, Dagget and Keulegan (1974) state that viscous effects on free-surface vortices are negligible when the inlet Reynolds number, $Re > 3 \times 10^4$ ($Re = Vd/\nu$, where $V$ is the inlet velocity, $d$ is the diameter of the intake, and $\nu$ is the kinematic viscosity of water). Padmanabhan and Hecker (1984) did not find any significant scale effects on free-surface vortices for tests with inlet Reynolds number greater than $7 \times 10^4$. The Reynolds number for the pump intakes in the present study was approximately $8.2 \times 10^4$. 

\begin{equation}
L_r = L_m/L_p \tag{1}
\end{equation}
Therefore, it can be assumed that scale effects on free-surface vortices would not be a concern based on the findings mentioned above.

There is not much information available about the influence of scale effects on submerged vortices. Padmanabhan and Hecker (1984) state that no significant scale effects on the subsurface vortices existed in a pump sump when the approach-flow Reynolds number was greater than 3 \times 10^4 (Re = \frac{V_a s_a}{\nu} > 3 \times 10^4, \text{ where } V_a \text{ is the approach-flow velocity and } s_a \text{ is the depth of the approach flow}). Additional research on the influence of scale effects on subsurface vortices is needed to improve the hydraulic modeling of pump sumps with subsurface vortices.

**Instrumentation**

Two-dimensional velocity measurements were taken using an electromagnetic velocity meter manufactured by Delft Hydraulics Laboratory. The velocity meter was attached to a point gauge equipped with a vernier scale that measured vertical distances with a precision of 0.001 ft (0.3 mm) so that the position of the electromagnetic meter in the vertical direction was accurately known. Velocity measurements were taken in both x (streamwise direction parallel to the sump sidewall) and y (lateral direction normal to the sump sidewall) directions at specified vertical locations (z-direction). Figure 13 defines the x and y coordinates as well as the z coordinates for the multiple-pump sump model. The meter was connected to a personal computer where voltage outputs were recorded. From the recorded voltage outputs, the corresponding velocities were calculated using a calibration curve for the meter. Velocity measurements were taken for two different operating cases. In Case I, all four intakes were in operation. In Case II, only intakes 1, 2, and 3 were in operation. There were several different operating conditions for this model, as shown in Table 2.

For Cases I and II, velocity measurements in the streamwise and lateral directions were taken at 315 points. The velocity-measurement locations consisted of nine equally spaced points in the x-direction, seven equally spaced points in the y-direction, and five equally spaced points in the vertical direction. Figure 13 illustrates the locations of velocity measurement. Measurements were taken every 6-5/16-in. (16.0 cm) in the streamwise direction (x-direction), every 6-in. (15.2 cm) in the lateral direction (y-direction), and every 1-15/16-in. (4.9 cm) in the vertical direction (z-direction). The flow meter/gauge rested on an aluminum beam, which was placed across the sump at the specified streamwise position for velocity measurement. The lateral positions of the flow meter/gauge were marked on the beam. Using the gauge connected to the velocity meter,
the water depth was measured and the positions of the velocity measurement points were
determined.

A four-blade vortimeter or swirl meter was installed in each pump column as seen
in photo 7. The blades of the swirl meter had a diameter approximately 90% of that of
the pump column and were approximately 0.5-in. (1.27 cm) in height in the axial
direction of the pump column. By noting the number of revolutions per unit time, n, of
the swirl meter, the average tangential velocity could be estimated. From the tangential
velocity, the swirl angle could be calculated. The formulation for the swirl angle, $\alpha$, is:

$$\alpha = \arctan \left( \frac{V_t}{V_a} \right)$$  \hspace{1cm} (6)

where $V_t$ is the tangential velocity and $V_a$ is the axial velocity.
The tangential velocity, $V_t$, is given by:

$$V_t = \pi dn$$  \hspace{1cm} (7)

where $n$ is the number of revolutions per unit time and $d$ is the diameter of the intake.
The axial velocity, $V_a$, is given by:

$$V_a = \frac{4Q}{\pi d^2}$$  \hspace{1cm} (8)

where $Q$ is the flow rate.

A swirl angle is a flow parameter used to determine whether the amount of swirl
existing in the intake is acceptable for operation. As mentioned previously, IIHR
specifies that the vortimeter-tip velocity angles (swirl angles) should be no greater than 5
degrees for the flow conditions to be acceptable in the suction pipe (Nakato and Yoon,
1992). Ingersoll-Rand (1991) also indicates that the level of prerotation of flow
approaching the pump impeller location measured by the vortimeter should be less than 5
rpm. The swirl angle measured in the multiple-pump sump model will be compared to
the standards mentioned above to determine if the amount of swirl in the intake is
acceptable.

The total discharge in the model and the discharge for each intake were measured
by a calibrated orifice meter and elbow meters, respectively, which were connected to a
two-tube manometer. The pressure head differential corresponding to a given discharge
could be measured to 0.001 ft (0.3 mm) using the two-tube manometer. The flow meter
equation for the total discharge, which consisted of an 8-in. (20.3 cm) inner diameter pipe with a 6.25-in. (15.9 cm) orifice plate was

\[ Q = 1.395(\Delta H)^{1/2} \]  \hspace{1cm} (9)

where \( Q \) is the total discharge for the model in cfs and \( \Delta H \) is the pressure head differential in feet. The flow equation for each of the four 4-in. (10.2 cm) diameter pipe elbow meters was

\[ Q = 0.506(\Delta H)^{1/2} = 0.232 \text{ cfs (6.6 l/s)} \]  \hspace{1cm} (10)

where \( Q \) is the discharge through the pump column and \( \Delta H \) is as defined above. The pressure head differential, \( \Delta H \), for the constant discharge of 0.232 cfs (6.6 l/s) for each intake was 0.211 ft (6.4 cm).

Visual observations of the flow were achieved through the use of food dye injected through a wand connected to a hypodermic syringe. Dye was injected in the flow throughout the sump and near the intakes to observe velocity profiles and to locate any vortex activities.

**Experimental Procedure**

Flow observations or velocity measurements were made after each operating intake attained a pressure head differential of approximately 0.211 ft (6.4 cm) and the water depth had stabilized at 0.979 ft (29.8 cm). In Cases I and II, the flow visualization was carried out by the injection of food dye to note the formation of any vortices. As stated before, all intakes were in operation for Case I and intakes 1, 2, and 3 were operating for Case II. The directions of rotation for each vortex and the vortimeter were recorded. The number of revolutions per minute of the vortimeter was also recorded. Velocity measurements were taken at the locations specified earlier in figure 13. With these measurements, vector and contour plots of velocity and vorticity were obtained.

For Cases III through IX, only flow observations for the modified sump, consisting of vortex suppressors, were carried out. This included locating any vortices and noting the directions of rotation of the vortices and of the vortimeter. Photographs were taken of the model which included the original and modified sump, vortices, flow profiles, and other important flow phenomena seen in the flow. A video of the flow characteristics in the modified sump was also recorded.
EXPERIMENTAL RESULTS

Formation of Vortices

Case I

In Case I, all four pumps were operated with an equal model discharge of 0.232 cfs (6.6 l/s). Therefore, the total discharge through the sump was 0.928 cfs (26.3 l/s). The water depth was kept at the LWL (h = 0.979 ft = 29.8 cm) for all model tests. The average velocity in the sump was 0.237 fps (7.2 cm/s), as shown in table 1.

At the free-surface, dye was injected to reveal any surface vortices. There were no surface dimples (type 2) observed near the pump columns. The flow visualization revealed no free-surface vortex formation stronger than type 1 (ARL's classification) in the vicinity of the four pump columns. Dye was also injected near the sidewall and/or backwall of each pump-suction bell. A strong subsurface vortex attached to each backwall of pumps 2 and 3 appeared. Behind pumps 1 and 2, weaker, intermittent subsurface vortices were found to form on the backwall. There was also a weak, intermittent submerged vortex attached to each sidewall of pumps 1 and 4. The submerged vortices attached to a sidewall or backwall were classified as type 1. When dye was injected underneath the pump bell near the floor, a strong floor-attached vortex was seen underneath each of the four pump bells. There was a coherent dye core for each of the vortices attached to the floor, which is shown in photos 8 and 9. Therefore, the floor-attached vortices can be classified as type 2 subsurface vortices. Figure 14 shows a qualitative velocity distribution at the sump entrance and locations of subsurface vortex formation around the pump columns.

Case II

In Case II, when pumps 1, 2, and 3 were in operation, the total discharge into the sump was 0.696 cfs (19.7 l/s). With the water depth set at 0.979 ft (29.8 cm), the average velocity in the sump was 0.178 fps (5.4 cm/s). When dye was injected near the pump-suction pipes, the flow characteristics were quite different from those seen in Case I. Case I did not produce any free-surface vortex formation, while free-surface vortices did occur in Case II. A free-surface vortex formed at the surface and extended into the pump-suction pipe from the right side of each pump column as shown in figure 15. The vortex strength of the free-surface vortices was approximately type 3 of ARL's free-surface vortex classification (see figure 3). The free-surface vortex at pump 3 was the strongest, while those at pumps 1 and 2 were about equal in strength. Photos 10 and 11 display two of the free-surface vortices formed in the multiple-pump sump for Case II. As dye was
injected near the pump-suction bells, a backwall-attached submerged vortex was found to form for each of the operating pumps. The backwall-attached vortices appeared to have about the same vortex strength. Based on ARL's subsurface classification, they can be classified as type 2 (see figure 4). As in Case I, a type 2, floor-attached subsurface vortex developed underneath each operating pump.

**Velocity Profiles**

**Case I**

**Dye visualization**

By injecting a streak of dye across the entrance of the sump, it was possible to observe general qualitative velocity profiles. In Case I, it was found that the velocity profile was nearly uniform (except near the walls) and practically symmetrical about \( y/b = 0.5 \) or the middle of the sump, where \( b \) is the width of the sump. Photographs were taken when dye was released across the sump floor, at mid-depth, and at the water surface. The flow visualizations were carried out at these depths at the entrance and the middle of the sump. Photos 12 through 14 show the velocity profile at the sump floor halfway into the pump sump. Figure 14 shows the velocity profile near the entrance of the sump. The lack of dye movement near the walls seen in the photos was caused by flow separation at the entrance and boundary-layer development at the sidewalls. The reverse flow observed near the right sidewall (in photo 14) may be caused by nonuniform flow distributions in the model basin and flow separation at the sump's entrance.

Vortex shedding occurred at the corners of the entrance of the sump, as can be seen in photos 15 and 16, and in figure 16. This phenomenon is referred to as vortex shedding because the vortices seem to shed at the upstream edge of the sidewalls. The vortices were shed at regular intervals of time. The corners of the entrance were boundary discontinuities in the flow causing vortex shedding and contributing to the overall vorticity in the sump. As previously stated, Chang (1977) reported processes that generate vorticity in a pump sump. Vortex shedding and boundary-layer development were included in Chang's list of vorticity generators. Secondary-flow currents in rectangular channels were also included in Chang's list and may have increased the amount of vorticity in the multiple-pump sump, although this process was difficult to observe with dye injections. The corners at the entrance (boundary discontinuities in the flow), vortex shedding, boundary-layer development, and secondary-flow currents contributed to the overall vorticity in the sump which consequently caused the formation of vortices in the sump.
Velocity profiles

The velocity measurements were taken in the sump using the electromagnetic flow meter at specific locations, as shown in figure 13. The velocities in the streamwise direction (x-direction) were depth-averaged so the velocity profile could be plotted on the x-y plane. Figure 17 shows the lateral distributions of the depth-averaged velocity in the streamwise direction (x-direction) at nine different sections. The same velocity profiles are re-plotted in figure 18 with three profiles in each plot. Since the points were equally-spaced, depth-averaging was accomplished by simply taking the arithmetic mean of the measurements along each vertical. The velocity data were normalized for a more general use of the results. The transverse distances, y, were normalized by the width, b, of the sump (b = 4 ft = 1.22 m). The streamwise distances were normalized by the length of the sump, L (= 5 ft = 1.52 m). The velocities were normalized with $U_{av}$, where $U_{av}$ is the calculated average approach flow velocity ($U_{av} = Q/A$) in the streamwise direction and had a value of 0.237 fps (7.2 cm/s) for Case I.

The depth-averaged velocity profiles show a good agreement with the velocity profiles observed from dye visualizations. Figures 17 and 18 clearly show how the velocity profile developed within the sump. Because of the no-slip condition at the walls, a parabolic velocity profile was expected in the multiple-pump sump. A parabolic velocity profile fully developed at section $x/L = 0.632$ or shortly after halfway into the sump. These figures also show that the mean of the normalized average streamwise velocity at each section was approximately equal to unity except for the last section at $x/L = 0.843$. The reason for the decrease in velocity in the x-direction at this section was because it was the closest section to the pump-suction pipes. Dye tests clearly indicated that there were substantial downward velocity components near this section because the pump-approach flow was directed toward the individual pump columns. Due to this increase in the vertical velocity component, the streamwise velocity decreased at this section.

Velocity-contour plots

The velocity-contour plots were generated using TECPLOT. Contour plots of the normalized streamwise velocities for Case I are shown in figure 19. The plot consists of velocity-contours for nine equally spaced lateral planes. On this figure, all the variables were normalized as before. The streamwise velocities were normalized by $U_{av}$. The contour plot illustrates better how the flow profile developed in the sump. At the entrance of the sump ($x/L = 0.0$), the streamwise velocities were higher near the upper left
and right corners of the cross section. The higher velocities were caused by the contraction in the flow as water entered the sump from the model basin.

The lower velocities near the sump floor were caused by boundary-layer development and ultimately the no-slip condition at the solid boundary. The no-slip condition also applied to the walls of the sump, which is illustrated in figure 19 by the lower streamwise velocities near the walls for sections \( x/L = 0.211 \) through \( x/L = 0.737 \). The velocity contours for the section at \( x/L = 0.105 \) were somewhat erratic and asymmetric unlike the section at \( x/L = 0.0 \). The velocity distribution for the section at \( x/L = 0.211 \) was quite similar to that for the section at \( x/L = 0.105 \) because the flow was still conforming to the new boundaries in the sump. The lower velocities at each wall, evident at \( x/L = 0.211 \), was caused by flow separation at the entrance and the development of boundary layers at the sidewalls. The lower velocities near the sidewalls did not change much for the sections at \( x/L = 0.316 \) to \( x/L = 0.527 \). At section \( x/L = 0.316 \), the velocity contours were almost symmetrical, but had not attained the parabolic velocity profile. The velocity contours for the section at \( x/L = 0.421 \) were fairly symmetrical and had attained higher velocities near the center of the cross section signifying the development of a nearly parabolic velocity profile in the flow (see figure 17). Toward the section at \( x/L = 0.632 \), a parabolic velocity profile had developed. A similar velocity profile was observed at \( x/L = 0.737 \). The final measurement section at \( x/L = 0.843 \) showed very high velocities near the floor underneath each of the suction pipes and very low velocities everywhere else. Since the section at \( x/L = 0.843 \) was located immediately upstream from the suction pipes, the water had nowhere else to flow except into the pump-suction pipes. The low streamwise velocities in the area above the bellmouths of the pumps were caused by an increase in velocity in the downward direction.

**Velocity-vector plots**

Vector plots of two-dimensional velocity components were obtained on horizontal planes at approximately every 0.16 ft (4.9 cm) along the depth. The vector plots were developed using TECPLLOT. Figure 20 shows the vector plot for Case I. The vertical distances, \( z \), were normalized by the flow depth, \( h \). The resultant velocity vector on the plots was calculated by summing the normalized velocity vectors in the \( x \)- and \( y \)-directions.

The velocity vectors in the sump show that the pump-approach flow was very symmetric. At \( z/h = 0.167 \), the lowest depth at which the velocities were measured, the flow converged toward the centerline of the sump as it entered the sump. This
"convergence" tendency due to the flow separation at the corners of the entrance of the sump was not as strong at other elevations. The reason that the convergence of the flow was more evident at the lowest depth was because the flow near the bottom was influenced more by the flow separation at the entrance and the boundary-layer development on the sump floor. The vector plots also show that velocities near the walls decreased as the elevation increases. The smaller velocities along the right sidewall compared with those along the left sidewall were believed to be caused by nonuniform flow distributions within the model basin. Photos 12 through 14 support this assumption.

As can be seen in figure 20, the velocities near the pump-suction pipes were very small except at section \( z/h = 0.167 \), which was approximately an inch (2.5 cm) below the bell mouth. Below the bell mouth, the main direction of flow remained in the \( x \)-direction. Above \( z/h = 0.167 \), the small planar velocity vectors near the pump columns corresponded to the larger velocity components in the \( z \)-direction. The velocity vectors surrounding the pump column were not influenced by the swirl in the pump-suction pipe or free-surface vortices because no free-surface vortices formed in this case.

Case II

Dye visualization

A streak of dye was injected across the width of the sump while pumps 1, 2, and 3 were operating. Figure 15 shows the velocity profile near the entrance of the sump. Photos 17 and 18 show the velocity profile near the middle of the sump for Case II. The flow profile for Case II was different from that for Case I, as expected. Photo 17 clearly shows the uniformity in the flow upstream of pumps 1, 2, and 3. Photo 18 shows the stagnation in the flow upstream from and near pump 4 (left side of sump in photo). Photo 19 from Case I shows water moving upstream towards the entrance of the sump only near \( y/b = 0.0 \), but photo 17 from Case II shows significant reverse flows near both walls moving upstream towards the entrance of the sump. The difference in reverse flow between Cases I and II was obviously because pump 4 was not in operation. The reverse flows were ultimately caused by flow separation at the corners of the entrance.

Near the entrance, the flow separation at \( y/b = 1.0 \) was larger than that at \( y/b = 0.0 \) (see figure 15). The flow separation near \( y/b = 1.0 \) in Case II resulted from the difference in the direction of flow towards the pump-suction pipes. In Case I, the maximum velocity in the flow occurred between pumps 2 and 3 (or at \( y/b = 0.5 \)) causing an equal amount of flow separation. In Case II, the maximum velocity in the flow occurred at \( y/b = 0.375 \) closer to the right sidewall, resulting in a larger flow separation near \( y/b = 1.0 \). The
velocity-vector plots illustrate better the direction of the flow and flow separation for Case II.

**Velocity profiles**

The locations of velocity measurements were the same for both Cases I and II, as shown in figure 13. Figures 22 and 23 show the depth-averaged velocity profiles in the streamwise direction (x-direction) at nine different sections or at approximately every 0.53 ft (16.2 cm) in the streamwise direction. Depth-averaging was accomplished in the same fashion as Case I. The velocities were normalized by $U_{av}$, the calculated average approach flow velocity which had a value of 0.178 fps (5.4 cm/s) for Case II.

As in Case I, the velocity profiles shown in figures 22 and 23 for Case II agreed well with the results from the dye visualization. At every section the streamwise velocities near $y/b = 1.0$ were noticeably smaller than the streamwise velocities near $y/b = 0.0$. Since pump 4 was not operating, larger flow separation occurred in the flow near $y/b = 1.0$, as described in the dye visualizations for Case II. The reverse flows occurring near both walls in photos 17 and 18 were not observed in the velocity profiles in figures 22 and 23 because the velocity measurements were taken a distance 0.5 ft (15.2 cm) away from the sidewalls where the reverse flows existed.

Figure 23 illustrates how a velocity profile went through a transition before the profile became fully developed. At each section except at $x/L = 0.843$, the average depth-averaged streamwise velocity across the sump was approximately equal to $U_{av} (= 0.178$ fps = 5.4 cm/s for Case II), which is the calculated average approach flow velocity in the streamwise direction. The streamwise velocity profiles for sections at $x/L = 0.0$ and $x/L = 0.105$ were practically identical. At $x/L = 0.211$, the streamwise velocities near pumps 1 and 2 increased while velocities near pump 4 ($y/b = 1.0$) decreased to almost 35% of $U_{av}$ (see figure 23). There was a profound difference between the velocity profiles at $x/L = 0.105$ and $x/L = 0.211$. This difference led to some concern over the validity of the data at section $x/L = 0.211$, but similarities between streamwise velocity profiles at $x/L = 0.211$ and $x/L = 0.316$ subdued any concern.

The sections at $x/L = 0.316$, $x/L = 0.421$, and $x/L = 0.527$ produced almost identical velocity profiles (see figure 23). Near $y/b = 0.0$, the streamwise velocity increased only slightly from about 79% of $U_{av}$ at $x/L = 0.211$ to 85% of $U_{av}$ at $x/L = 0.527$. Near $y/b = 1.0$, the streamwise velocity increased from 35% of $U_{av}$ at $x/L = 0.211$ to approximately 55% of $U_{av}$ at $x/L = 0.527$. The streamwise velocity profiles at sections $x/L = 0.632$ and $x/L = 0.737$ were approximately the same and were parabolic in shape as expected. For the fully-developed profile at $x/L = 0.737$, the streamwise velocity near $y/b$
= 0.0 reached approximately 92% of Uav, while that near y/b = 1.0 reached only 68% of Uav. The lower velocities near the sidewalls demonstrate the impact flow separation and boundary discontinuities (corners at entrance) in the flow had on the streamwise velocity in the sump.

From the dye visualization tests for Case II, the location of maximum streamwise velocity was found to occur approximately at y/b = 0.375 or near pump 2 (see figures 22 and 23). Figure 23 shows that the maximum velocity occurred at y/b = 0.375 and x/L = 0.737 with a value of 1.3 times Uav.

As mentioned above, the average depth-averaged streamwise velocity across the sump at the section at x/L = 0.843 was much less than Uav. The average depth-averaged velocity at x/L = 0.843 was approximately 60% of Uav. The reason for lower streamwise velocities at x/L = 0.843 was because this section was the closest to the pump-suction pipes, as was stated for Case I.

**Velocity-contour plots**

Figure 24 shows the normalized streamwise velocity contours for Case II. As mentioned previously, the velocities were normalized by Uav which had a value of 0.178 fps (5.4 cm/s) for Case II. The velocity contours for Case II were similar to those for Case I, especially at the entrance where velocity contours were practically symmetrical, about y/b = 0.5. The velocity contours at the entrance for Case II were less symmetrical, about y/b = 0.5 than Case I and had lower values of streamwise velocity near the sidewalls. Because pump 4 was not operating, areas of low normalized streamwise velocities existed from y/b = 0.5 to y/b = 1.0 in sections at x/L = 0.105 and x/L = 0.211.

The development of the streamwise velocity profile was fairly similar to that for Case I. For both cases, irregular contours existed for sections at x/L = 0.316 through x/L = 0.527, and the parabolic velocity profile was attained by x/L = 0.632. Dark blue regions at x/L = 0.843 indicate very low velocities near pump 4 and near each pump column above the bell mouth (see figure 24). The flow near pump 4 was practically stagnant, except for flow in the lateral direction towards pumps 1, 2, and 3.

**Velocity-vector plots**

As with Case I, vector plots of two-dimensional velocity components were obtained on horizontal planes at approximately every 0.16 ft (4.9 cm) along the flow depth. Figure 25 shows the normalized velocity vectors for Case II. The velocities were again normalized by Uav.
At $z/h = 0.167$, the lowest depth at which the velocities were measured, the flow converged as it entered the sump. This "convergence" tendency also occurred for Case I. The convergence at the entrance of the sump was practically identical at each elevation. Flow separation at the corners of the entrance of the sump created this convergence in the flow. The normalized velocity vectors were not symmetrical about $y/b = 0.5$ except at the entrance of the sump. By comparing the vector-velocity plots for Cases I and II, the following differences can be seen (see figures 20 and 25): in Case I, the velocity vectors were practically symmetrical about $y/b = 0.5$ in every plane, while those in Case II were not. Besides the "convergence" near the entrance of the sump, the velocity vectors in Case I were directed straight toward the suction pipes, while those in Case II were directed slightly towards the right sidewall. The directions of the velocity vectors in Case II explain why the flow separation near $y/b = 1.0$ for Case II was larger than that for Case I as illustrated in dye tests.

The velocity vectors near $y/b = 1.0$ were smaller than those near $y/b = 0.0$ in every horizontal plane, because pump 4 was not operating. Near $y/b = 1.0$ and $y/b = 0.0$, the vectors in the horizontal plane at $z/h = 0.334$ were smaller than those at $z/h = 0.167$. The velocity vectors near each sidewall had approximately the same magnitude and direction as those at $z/h = 0.334$ for the remaining horizontal planes. Velocity vectors immediately upstream from the suction pipes for Case II behaved similarly to those in Case I (see figures 20 and 25). At $z/h = 0.167$, the velocity vector directly upstream from each suction pipe was larger than those between suction pipes. For the remaining horizontal planes, the velocity vector directly upstream from each pump column was smaller than those between pump columns. The velocity vectors directly upstream from the suction pipes were much larger at $z/h = 0.167$ because the measurements at $z/h = 0.167$ were 0.16 ft (4.9 cm) below the pump bell of the suction pipe. At higher elevations ($z/h = 0.334$ to $z/h = 0.668$), the velocity vector directly upstream from each pump column was smaller because the main direction of flow was in the $z$-direction, flowing downward and into the pump bell.

**Vorticity-Contour Plots**

To depict sump locations prone to swirl, contour plots of the vertical component of the mean vorticity were generated using TECPLOT. The contours were constructed on five equally-spaced horizontal planes, using the velocity measurements and the definition of vorticity, $\zeta$:

$$\zeta = 2\vec{\omega} = \nabla \times \vec{V}$$  \hspace{1cm} (11)
where $\vec{V}$ is the velocity vector and $\vec{\omega}$ is the rotation vector where,

$$\vec{\omega} = \frac{1}{2} \nabla \times \vec{V} = \frac{1}{2} \left[ \left( \frac{\partial w}{\partial y} - \frac{\partial v}{\partial z} \right) \hat{i} + \left( \frac{\partial u}{\partial z} - \frac{\partial w}{\partial x} \right) \hat{j} + \left( \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \right) \hat{k} \right]. \tag{12}$$

Only the z-component of vorticity,

$$\omega_z = \frac{1}{2} \left( \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \right) \tag{13}$$

was plotted since velocity measurements consisted of x- and y-directions. The vorticity was normalized by multiplying $\zeta$ by $L/U_{av}$. Positive values of vorticity indicate a counterclockwise (looking down) circulation, while negative values indicate a clockwise circulation.

Case I

Figure 21 shows the vorticity-contour plots for Case I. Levels of high vorticity existed near both sidewalls of the multiple-pump sump, while the vorticity near the center of the sump was practically zero. Positive (a counterclockwise circulation) and negative (a clockwise circulation) vorticities existed near $y/b = 1.0$ and $y/b = 0.0$, respectively. The contours were practically symmetrical about $y/b = 0.5$ on each plane, although the vorticity near $y/b = 0.0$ extended more toward the suction pipes. The strong vorticity observed just beyond the entrance near the sidewalls in figure 21 was caused by flow separation and vortex shedding, as photos 15 and 16 show.

The vorticity intensity was fairly small near the pump-suction pipes, although at $z/h = 0.835$ and $z/h = 0.668$, stronger vorticity stretched towards the suction pipes. At $z/h = 0.501$, the stronger vorticity still existed at the corner of $y/b = 0.0$ and $x/L = 0.843$. The vorticity remained fairly weak near the corner of $y/b = 1.0$ and $x/L = 0.843$ at every elevation.

Strong vorticities along the sidewalls occurred near the surface. At lower depths, the vorticity intensity was lower and isolated in smaller areas near the sidewalls and closer to the entrance. The regions of higher vorticity near the sidewalls were practically symmetrical about $y/b = 0.5$ on each plane, as expected. Larger portions of intense vorticity near the free-surface indicated that the free-surface was more susceptible to vortex formation.
Case II

Figure 26 displays the vorticity-contours for Case II, which were quite different from those in Case I. They were not symmetrical around y/b = 0.5 as those in Case I, because pump 4 was not in operation. A large region of strong vorticity existed near y/b = 1.0, while a smaller region existed near y/b = 0.0. The vorticity was positive near y/b = 1.0 and negative near y/b = 0.0, which was the same as for Case I. The higher vorticity near y/b = 1.0 was caused by the large flow separation at the entrance occurring near y/b = 1.0 since pump 4 was not in operation.

The vorticity intensity near the pumps was fairly small. Negative vorticity extended toward the suction pipes near the wall at y/b = 0.0 causing negative vorticity at the corner of y/b = 0.0 and x/L = 0.843. The negative vorticity in this corner existed at every elevation. At the opposite corner, y/b = 1.0 and x/L = 0.843, the vorticity was practically zero in every plane except at z/h = 0.167, where the practically equal vorticity extended almost to the suction pipes from the entrance of the sump.

The vorticity contours for the horizontal planes at z/h = 0.334 through z/h = 0.835 were very similar. As in Case I, the strongest vorticity existed near the free-surface (z/h = 0.835) and its strength decreased toward the horizontal plane at z/h = 0.167. The vorticity intensity at z/h = 0.167 was much weaker than that in z/h = 0.334.

Swirl Angle

The swirl angle is a flow parameter used to determine whether the swirl or prerotation in a suction pipe is acceptable for satisfactory pump performance. The criterion set by the Iowa Institute of Hydraulic Research (IIHR) involving the swirl angle states that the vortimeter-tip velocity angles (swirl angles) should be no greater than 5 degrees (Nakato and Yoon, 1992). By using a vortimeter installed in each suction pipe, the prerotation was measured.

Case I

Table 3 summarizes the results concerning the amount of swirl for each suction pipe in Case I. Because the total discharge in the sump was 0.930 cfs (26.3 l/s), the discharge in each suction pipe was 0.232 cfs (6.6 l/s) corresponding to a mean axial velocity of 2.66 fps (0.81 m/s) in each suction pipe. The vortimeters rotated clockwise in suction pipes 1 and 2 and counterclockwise in suction pipes 3 and 4. The directions of rotation were consistent with the general flow pattern which was observed during the test. The pump-approach flow was fairly uniform across the sump. As it reached the backwall,
the flow split to the right (towards pump 1) and left (towards pump 4), creating a clockwise swirl around pumps 1 and 2 and a counterclockwise swirl around pumps 3 and 4.

The estimated swirl angles in suction pipes 1 and 4 were higher than those in suction pipes 2 and 3. Suction pipes 1 and 4 had swirl angles of 5.4 degrees and 6.4 degrees, respectively. These swirl angles exceeded the limit of 5 degrees set by IIHR. Suction pipes 2 and 3 had estimated swirl angles of only 1.2 and 3.4 degrees, respectively.

Table 5 summarizes the estimated swirl angles for Case II. The discharge and axial velocity in each suction pipe was the same as in Case I, 0.232 cfs (6.6 l/s) and 2.66 fps (0.81 m/s), respectively. The swirl meter rotated in the clockwise direction in suction pipe 1, in both directions in suction pipe 2, and counterclockwise in suction pipe 3. The directions of rotation of the flow in the suction pipes for Case II were similar to those in Case I. The swirl meter in suction pipe 2 did not have a consistent direction of rotation most likely because the pump-approach flow split in two directions at suction pipe 2. The estimated swirl angles for suction pipes 1 and 3 were 3.4 degrees and 3.0 degrees, respectively, which were smaller than the limit set by IIHR.

SUPPRESSION OF VORTICES

There are various methods of suppressing free-surface and subsurface vortices. The study herein concentrated on the suppression of subsurface vortices, which were influenced more by the circulation of flow around the pump columns rather than the circulation upstream of the suction pipes. Therefore, devices to prevent subsurface vortex formation were placed very close to the suction pipe for the primary purpose of reducing flow circulation near the suction pipe. Padmanabhan (1987) lists some techniques or devices which can be used to control subsurface vortices:

1) Altering wall and floor clearances;
2) Vertical flow splitters placed on the backwall behind the pump column;
3) A horizontal floor splitter placed on the axis of longitudinal symmetry;
4) A floor cone placed beneath the pump bell;
5) Installing fillets in the corners of the sump or floor to fill regions of flow separation and/or stagnation in the flow; and,
6) Turning vanes placed on the floor upstream of the pump column to improve flow alignment into the pump bell. The wall and floor clearances were not altered in this study. The devices used to suppress submerged vortices consisted of vertical backwall splitters, horizontal floor splitters, and fillets for the corners of the sump.

**Subsurface Vortex-Suppression Devices**

*Location*

Figure 27 displays the devices used to prevent the formation of vortices and their locations in the multiple-pump sump. Triangular-shaped horizontal floor splitters were placed beneath each pump bell along the axis of longitudinal symmetry, and between neighboring suction pipes to control the flow near the pump-suction bell. A vertical, triangular-shaped backwall splitter was installed on the backwall behind each pump column. Corner fillets were placed in all the corners near the pump columns, including the sidewall-backwall corners, the backwall-floor corner, and sidewall-floor corners. Photos 19 and 20 depict the model vortex-suppression devices installed in the multiple-pump sump.

*Dimensions*

The dimensions of the splitters and fillets were determined by evaluating devices used and recommendations made for previous model studies, especially those reviewed by Melville, Ettema, and Nakato (1993). The dimensions of the splitters and fillets are shown in figures 27 and 28. The sidewall-backwall corner fillets and backwall splitters extended to the water surface (h = 11-3/4-in. = 29.8 cm). The apex angle of each of the splitters and fillets was 90 degrees. The height of the floor splitters was 1-7/8-in. (4.8 cm) or about 61% of the floor clearance, C. The height of the floor corner fillets was the same as the height of the floor splitters beneath the pump bells. The length of the floor splitters and sidewall-floor corner fillets was 10-3/8-in. (26.4 cm), which was about 1.7 times the bell diameter. The backwall-floor corner fillet extended along the entire length of the backwall. The backwall splitter placed behind each pump bell had a depth of 1-3/16-in. (3.0 cm) or about 76% of the backwall clearance, B.

*Results*

The effectiveness of the splitters and fillets to suppress subsurface vortices was determined using dye visualization and estimating the swirl angle in each suction pipe. Dye visualization was performed for nine different operating conditions. Table 2
summarizes the operating conditions for each case. Figures 29 through 37 display the vortex activity for Cases I through IX. The swirl angle was estimated for only Cases I and II, so the swirl angles estimated for the existing sump could be compared with those for the modified sump. Tables 4 and 6 summarize the estimated swirl angles for Cases I and II, respectively.

Dye Visualization

Subsurface vortices

For each case, no subsurface vortices were detected in the modified sump. The splitters and fillets successfully prevented the formation of subsurface vortices. Figures 29 through 37 depict the vortex activities for Cases I through IX with the vortex suppressors in place. In Cases III through IX, an extremely weak subsurface swirl was observed. The swirl was attached to the floor splitters between pump columns (see figures 31 through 37). According to ARL’s subsurface vortex classification, the very weak swirl observed in Cases III through IX was weaker than that of Type 1. Therefore, the weak swirl would not likely be detrimental to the pump.

The floor splitter beneath each pump bell prevented the floor-attached vortex from forming. Photo 21 displays the flow around the floor splitter and into the suction pipe. The backwall splitter behind each pump column prevented any formation of backwall-attached vortices. The corner fillets eliminated the regions of flow stagnation near the suction pipes. Floor splitters placed between neighboring suction pipes were able to direct the flow smoothly towards the pump-suction bells. Photos 22 and 23 show the flow being directed by the floor splitters for Case I where all pumps were in operation. Photos 24 and 25 show the dye visualization of flow characteristics near the suction pipes for Case II. Each splitter and fillet installed in the multiple-pump sump were able to suppress subsurface vortex formation by preventing circulation and swirl near the pump-suction bell.

Free-surface vortices

The splitters and fillets placed in the multiple-pump sump did not, and were not intended to, prevent the formation of free-surface vortices. For Case I, free-surface vortices were observed at every suction pipe in the modified sump, while no free-surface vortices were detected in the existing sump (see figure 29). The vortex suppressors influenced the free-surface vortices in Case II. Figure 30 displays the vortex activity in the modified sump for Case II. Without the vortex suppressors, a free-surface vortex was always observed on the right side of each of the three operating pumps (see figure 15).
With the splitters and fillets in place, free-surface vortices still existed at each suction pipe although their characteristics were not the same. The vortices at suction pipes 2 and 3 were not stable and would move to either side of the pump column. The vortex at suction pipe 1 was the strongest with the fillets and splitters in place, while in the unmodified sump the free-surface vortex at suction pipe 3 was the strongest of the three operating pumps. Photo 26 shows the free-surface vortex that developed at suction pipe 1.

Figures 31 through 37 show locations of free-surface vortices in the modified sump. The differences in free-surface vortex formation in the unmodified and modified sump for Cases I and II indicate that the splitters and fillets placed in the sump did impact free-surface vortex activity.

Because the primary focus of this study was to suppress subsurface vortex activity, methods of free-surface vortex suppression will be described. Free-surface vortices can be suppressed by increasing the minimum submergence or using vortex suppressors. Increasing the minimum submergence is usually not economical and vortex suppressors would usually be used. Some of the free-surface vortex suppressors presented by Padmanabhan (1987), include:

1) Horizontal grating placed approximately 4 to 6 in. (10.1 cm to 15.2 cm) below the water level at which strong free-surface vortices appear;
2) A grating cage placed just below the minimum water level;
3) Floating rafts placed in the vicinity of the pump column; and,
4) A curtain wall or surface beam protruding into the water surface and across the approach channel is used in situations where nonuniformity in the approach flow contributes to strong vortex formation.

The vortex suppressors listed above should prevent the formation of the free-surface vortices in the multiple-pump sump.

The multiple-pump sump did not involve any obstructions or offsets in its approach channel. For pump sumps with an expanding channel, an offset in the approach channel, or sumps with screen blockages, the following are suggested to reduce the amount of swirl and ultimately the vorticity in the sump:

1) Baffle bars placed upstream of the pumps;
2) A curtain wall placed upstream of the pumps to reduce swirl occurring near the surface; and,
3) Guide vanes to direct the flow toward the pumps.
Swirl Angle

The swirl angle was estimated in each suction pipe for Cases I and II. Since the operating conditions remained the same for the modified sump, the axial velocity was the same as that for the unmodified sump. Tables 4 and table 6 summarize the estimated swirl angles with the vortex suppressors installed for Cases I and II, respectively.

Case I

With the splitters and fillets in place, each of the vortimeters rotated in the counterclockwise direction for Case I. The swirl angle estimated for each suction pipe was less than the 5 degree limit set by IIHR mentioned previously (see table 4). The swirl angles ranged from 0.2 degrees to 1.9 degrees. Except for the swirl angle in suction pipe 2, the swirl angles estimated in the modified sump were less than those estimated in the unmodified sump. The subsurface vortex-suppression devices reduced the swirl angle and ultimately the swirl and prerotation in the suction pipe. The reduction in swirl angle caused by the splitters and fillets agrees with the findings of Padmanabhan (1987), who notes that swirl, prerotation, and uneven flow distribution to the impeller can be reduced by subsurface vortex suppressors.

Case II

The vortimeter in each of the suction pipes in Case II rotated in the counterclockwise direction. For both Cases I and II, each vortimeter rotated in the counterclockwise direction. Apparently, with improved flow conditions at the pump-suction bell, the vortimeter rotates in the counterclockwise direction. The swirl angles estimated for Case II were also less than the 5 degree limit. The swirl angle for suction pipe 1 had decreased after vortex suppressors were installed, while the swirl angle for suction pipes 2 and 3 had increased slightly (see table 6). The swirl angles ranged from 1.1 degrees to 3.4 degrees.

CONCLUSIONS

The main objective of the study was to determine means for enhancing the flow performance of pumps in a multiple-pump sump. To accomplish this objective meant establishing how swirling-flow problems occur in such sumps, then experimentally developing means to eliminate those problems, especially near the pump columns. Dye visualization tests were performed to detect undesirable swirl and vortex formation. Velocity measurements of sump flows were taken to diagnose how sump flow generates
vorticity. The diagnostic information was used to develop minor sump modifications to eliminate undesirable vortices at the pump bells. The experiments were conducted at varying pump-operating conditions to determine whether the modifications prevent subsurface vortex formation near the four pump columns. The swirl in each suction pipe was measured to ensure proper pump operation in the prototype.

Dye visualization tests revealed that subsurface or submerged vortices form when all four pumps were operating and when pumps 1, 2, and 3 were operating. When all four pumps were operating (Case I), floor-attached, sidewall-attached and backwall-attached vortices developed. When pumps 1, 2, and 3 were operating (Case II), floor-attached, backwall-attached, and free-surface vortices developed. Dye visualization also showed vortex shedding occurring at the entrance of the sump.

Velocity profiles obtained from the two-dimensional velocity measurements agreed qualitatively with those observed from dye visualizations. Velocity-vector, streamwise velocity-contour, and vorticity-contour plots were developed from the velocity measurements, which clearly showed flow separation at the entrance of the sump and boundary-layer development at the sidewalls and sump floor for both cases. The vorticity-contour plots showed strong vorticity near the sidewalls, caused by flow separation, the velocity gradients in the boundary layers, and vortex shedding at the corners of the entrance. The swirl angle estimated in suction pipes 1 and 4, when all pumps were operating, had values greater than the limit of 5 degrees.

The subsurface vortex suppressors in the multiple-pump sump consisted of triangular shaped horizontal floor splitters, backwall splitters, and corner fillets. With the splitters and fillets in place, the subsurface vortices in the multiple-pump sump were eliminated for all combinations of pump operation. Free-surface vortices did develop when all pumps were running, though they had not formed in the unmodified multiple-pump sump. Their formation was aggravated by the backwall splitters. The approach flow would divide between suction pipes 2 and 3, creating a flow near the backwall to the right and left of the sump and around the backwall splitters causing free-surface vortex formation. The free-surface vortices in Case II were not significantly affected by the vortex suppressors. The swirl angle estimated for each suction pipe in the modified sump was smaller than 5 degrees for both Cases I and II. The vortex suppressors placed in the multiple-pump sump greatly improved flow conditions near the pump columns by eliminating zones of stagnation and minimizing circulation near the pump-suction bells.

Additional research is recommended to prevent free-surface vortex formation in multiple-pump sumps. Analysis of the influence of cross-flow in front of multiple-pump sumps is also recommended. Hydraulic modeling of multiple-pump sumps is essential
for solving flow problems, because computational fluid dynamics can not yet effectively simulate the flow characteristics in a multiple-pump sump.

REFERENCES


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<th>2</th>
<th>3</th>
<th>4</th>
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<td>0.465</td>
<td>0.697</td>
<td>0.930</td>
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<td>0.119</td>
<td>0.178</td>
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Table 1. Discharges and velocities for multiple-pump sump.

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<th>Pump 2</th>
<th>Pump 3</th>
<th>Pump 4</th>
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<tr>
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<td>ON</td>
<td>ON</td>
<td>ON</td>
</tr>
<tr>
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<td>ON</td>
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<tr>
<td>Case III</td>
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<tr>
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<td>ON</td>
<td></td>
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<tr>
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<td></td>
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<td></td>
</tr>
<tr>
<td>Case VIII</td>
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<td></td>
</tr>
<tr>
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Table 2. Number of pumps operating for each case.
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<th>$V_s$, fps</th>
<th>Swirl angle, degrees</th>
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<td>0.16</td>
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Table 3. Swirl angles for unmodified sump with all pumps in operation.

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Table 4. Swirl angles for modified sump with all pumps in operation.

<table>
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<th>Direction</th>
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<th>$V_s$, fps</th>
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<td>2.66</td>
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Table 5. Swirl angles for unmodified sump with pumps 1, 2, and 3 in operation.

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<th>$V_t$, fps</th>
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<tr>
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<td>3</td>
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Table 6. Swirl angles for modified sump with pumps 1, 2, and 3 in operation.
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Figure 1. Types of intake structures (Knauss, 1987).
Figure 2. Typical secondary-flow streamline patterns in a square channel (Chang, 1977).
Classification of free-surface vortices

Figure 3. Free-surface vortex classification system according to Alden Research Laboratory (Nakato, 1995).
Classification of boundary-attached subsurface vortices

Figure 4. Subsurface vortex classification system according to Alden Research Laboratory (Nakato, 1995).
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<tr>
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- **V** = 1 fps
- **S** = 1D - 2D
- Add wall thickness to centerline distance
- Round or ogive wall ends
- Gap at rear of wall approximately 3/D

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<tr>
<td>W</td>
<td>S  Y</td>
</tr>
<tr>
<td>1</td>
<td>2 4 6 8</td>
</tr>
</tbody>
</table>

- Baffles, grating or strainer should be introduced across inlet channel at beginning of maximum width section
- Maximum angle = 15 deg.
- Preferred angle = 10 deg.

- **W** = 5D or more, or
- **V** = 0.2 fps or less and
- **Y** = same as chart left
- **S** = greater than 4D

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Figure 5. Hydraulic Institute Standards (1983) guidelines for multiple pump sumps.
Figure 6. Basic sump design for multiple pump sumps according to BHRA (Prosser, 1977): (a) open sump and (b) unitized sumps
Minimum Water Level

Select S using $S/D = a + b F_0$
With $a = 1 - 1.5$ and $b = 2 - 2.5$

S should also satisfy the required NPSH for the pump

$V_0 = Q/(\pi D^2/4)$  $F_0 = V_0/(gD)^{1/2}$  $C = 0.4D - 0.75D$

Figure 7. Basic design for a single bay sump with uniform approach flow, according to Padmanbhan (1987).
Select \( S \) using \( S/D = a + bF_c \)
With \( a = 1-1.5 \) and \( b = 2-2.5 \)
\( S \) should also satisfy the required NPSH for the pump

\[
V_o = \frac{Q}{(nD)^{1/4}} \quad F_c = \frac{V_o}{(gD)^{1/2}}
\]

\[ C = 0.4D - 0.75D \]

Figure 8. Basic design for multiple bay sump with uniform approach flow, according to Padmanbhan (1987).
As a design guide, I-R recommended that sump dimensions are indicated below (as a ratio of Pump Suction Bell diameter, D). Also included are the most frequently used fillets/splitter type modifications that appear in many cases as a part of the final design. The modifications are offered here as a "starting point" and do not preclude the need for a model sump test.

Figure 9. Basic sump design guide for a single bay sump according to Ingersoll-Rand (1991).
Figure 10. Entire layout of multiple-pump sump and suction-scoop sump.
Figure 11. Layout of multiple-pump sump in model scale.
Figure 12. Section through test pump bell.
Figure 13. Locations of velocity measurement.
Figure 14. Vortex activity and qualitative flow profile into multiple-pump sump for Case I.
Figure 15. Vortex activity and qualitative flow profile into multiple-pump sump for Case II.
Figure 16. Illustration of vortex shedding at entrance of multiple-pump sump.
Figure 17. Lateral distributions of depth-averaged streamwise velocities for Case I.
Figure 18. Lateral distributions of depth-averaged streamwise velocities for Case I.
Figure 19. Velocity-contour plots on the lateral planes for Case I.
Figure 20. Velocity-vector plots on the horizontal planes for Case I.
Figure 21. Vorticity-contour plots on the horizontal planes for Case I.
Figure 22. Lateral distributions of depth-averaged streamwise velocities for Case II.
Figure 23. Lateral distributions of depth-averaged streamwise velocities for Case II.
Figure 24. Velocity-contour plots on the lateral planes for Case II.
Figure 25. Velocity-vector plots on the horizontal planes for Case II.
Figure 26. Vorticity contour plots on the horizontal planes for Case II.
Figure 27. Preliminary design of modified multiple-pump sump.
Figure 28. Sections of backwall splitters, floor splitters, and corner fillets.
Figure 29. Vortex activity and qualitative flow profile into modified sump for Case I.
Figure 30. Vortex activity and qualitative flow profile into modified sump for Case II.
Figure 31. Vortex activity and qualitative flow profile into modified sump for Case III.
Figure 32. Vortex activity and qualitative flow profile into modified sump for Case IV.
Figure 33. Vortex activity and qualitative flow profile into modified sump for Case V.
CASE VI

FLOW DIRECTION

VELOCITY PROFILE

VORTEX STRENGTH AT 1 > 3

COUNTER CLOCKWISE

CLOCKWISE

PUMP IN OPERATION

DYE CORE FROM SURFACE

WEAK SWIRL

Figure 34. Vortex activity and qualitative flow profile into modified sump for Case VI.
Figure 35. Vortex activity and qualitative flow profile into modified sump for Case VII.
Figure 36. Vortex activity and qualitative flow profile into modified sump for Case VIII.
Figure 37. Vortex activity and qualitative flow profile into modified sump for Case IX.
Photo 1. Surface dimple and floor-attached vortex with air core.

Photo 2. Free-surface vortex drawing air bubbles into suction pipe and floor-attached sub-surface vortex with air core.
Photo 3. Suction-scoop and multiple-pump sumps.

Photo 4. Layout of multiple-pump sumps with model basin and tailgate.
Photo 5. Layout of single-pump suction scoop and multiple-pump sumps.

Photo 6. Multiple-pump sumps.
Photo 7. Side view of multiple-pump sumps.

Photo 8. Floor-attached subsurface vortex for Case I.

Photo 9. Floor-attached subsurface vortex with coherent dye core for Case I.
Photo 10. Free-surface vortex formation with visible dye core at pump 2 for Case II.

Photo 11. Free-surface vortex formation with visible dye core at pump 3 for Case II.
Photo 12. Dye visualization of velocity profile in sump for Case I at time 1.


Vortex Shedding

Photo 15. Shedding vortices at corner of multiple-pump sump entrance.

Vortex Shedding

Photo 16. Shedding vortices at corner of multiple-pump sump entrance.
Photo 17. Dye visualization of velocity profile in sump for Case II at time 1.

Photo 18. Dye visualization of velocity profile in sump for Case II at time 2.
Photo 19. Modified multiple-pump sump consisting of splitters and corner fillets.

Photo 20. Modified multiple-pump sump consisting of splitters and corner fillets.
Photo 21. Flow around splitter and into suction pipe with no signs of vortex formation near the sump floor.
Photo 22. Dye visualization of flow characteristics near suction pipes for Case I in modified sumps.

Photo 23. Dye visualization of flow characteristics near suction pipes for Case I in modified sumps.
Photo 24. Dye visualization of flow characteristics near suction pipes for Case II in modified sumps.

Photo 25. Dye visualization of flow characteristics near suction pipes for Case II in modified sumps.
Photo 26. Free-surface vortex with visible dye core into suction pipe in modified sump.