BONURA

PROPOSAL FOR
HYDRAULIC MODEL STUDY OF PUMPING STATION NO. 3
JEFFERSON PARISH, LOUISIANA

Submitted to
URS Greiner, Inc

February 1997

ALDEN RESEARCH LABORATORY, INC.
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ALDEN RESEARCH LABORATORY, INC.
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February 12, 1997

Mr. David Lapene
URS Greiner, Inc.
3500 North Causeway Boulevard, Suite 900
Metairie, LA 70002-3527

Proposal for Hydraulic Model Study of
Pumping Station No. 3
Jefferson Parish, Louisiana

Dear Mr. Lapene:

Enclosed please find three copies of our proposal for the subject study, including a separate model for the discharge basin. Having previously conducted a model study of the last Station No. 3 expansion, we are confident that a cost effective solution for the new expansion can be developed.

A copy of this letter is enclosed for your convenience in acknowledging receipt of this proposal. Please sign and date this copy and return it to ARL as soon as practicable. To help us in planning our work schedule, we would appreciate being notified of the disposition of the proposal at the earliest convenient date.

We look forward to possibly being of service. Should you have any questions, do not hesitate to contact me or Johannes Larsen.

Sincerely,

George E. Hecker
President

GEH/sjb

enclosures
Overnight Mail

30 SHREWSBURY STREET, HOLDEN, MASSACHUSETTS 01520-1843
TELEPHONE (508) 829-6000 • FAX (508) 829-5939

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ALDEN RESEARCH LABORATORY, INC.
30 Shrewsbury Street
Holden, MA 01520

PROPOSAL FOR
HYDRAULIC MODEL STUDY OF PUMPING STATION NO. 3
JEFFERSON PARISH, LOUISIANA

This proposal to construct and test two hydraulic models of Pumping Station No.3 is submitted to URS Greiner, Inc, in accordance with their January 20, 1997 request.

INTRODUCTION

URS Greiner is the design engineer for modifications to drainage pumping Station No. 3 located on Elmwood Canal in Jefferson Parish, Louisiana. As part of the modifications to increase station capacity, the best hydraulic performance of the sump is to be obtained at the least construction cost.

Pumping Station No. 3 presently includes eight pumps, trash screens, and an approach channel 140 ft wide, which rapidly expands to a width of 190 ft as it slopes down to the invert of the sump. The existing pumps are vertical shaft pumps, four with a bell diameter of 10 ft and a capacity of 550 ft^3/sec per pump, and four with bellmouth diameters of approximately 7.7 ft and a capacity of 300 ft^3/sec per pump. The station capacity expansion includes the addition of two horizontal 1,200 ft^3/sec pumps with cast inlet tunnels. The sump water level will vary between El. 7.0 to 11.5 ft (Cairo Datum). The number and combination of pumps operating will depend on the total capacity required.

To aid in the design of the station expansion, it is proposed to design and construct two physical models, one of the station approach canal and forebay, and one of the discharge bay and exit canal. The objectives of the upstream physical model would be to study the flow conditions in the pump sump, at the pump inlets, and in the approach channel to identify potential flow irregularities that could adversely affect the performance of the pumps. The occurrence of vortices, non-uniformities in approach velocities, and pump inlet swirl would be investigated. The downstream model would be used to determine the shape of the transition from the station to the discharge canal, and to determine local velocities in the transition for erosion protection design.

The hydraulic design of the present station was investigated in a 1:16.7 scale model [Pennino and Larsen, 1981].

MODEL SIMILITUDE AND SCALING CONSIDERATIONS

To properly simulate the kinematics and dynamics of the flow phenomena to be investigated, an undistorted geometric model is required. Since the model will have free surface flow, inertial and gravitational forces are dominant. A necessary condition of similitude is therefore that model and prototype Froude numbers are equal. In addition, consideration must also be given to the model Reynolds number, such that viscous forces would not significantly affect the model results.

The Froude number represents the ratio of fluid inertial to gravitational forces, and is given by

$$F = \frac{V}{(gy)^{0.5}} \tag{1}$$

where

V = characteristic velocity, ft/sec
y = characteristic flow depth, ft
g = gravitational constant, ft/sec

In a Froude model,

$$F_m = F_p \tag{2}$$

or

$$F_r = 1 \tag{3}$$

where

m = model parameter
p = prototype parameter
r = ratio of model to prototype

Defining the length scale ratio L_r as

$$y_p/y_m = L_r \tag{4}$$

and using Equations 3 and 4 provides scaling ratios for flow, velocity, time, etc.

In addition to the dominant inertial and gravitational forces, viscous forces and surface tension can affect the flow. These forces are not completely scaled in a Froude model, resulting in "scale effects" which must be evaluated relative to their possible effect on model results. In the prototype, viscous forces are small compared to inertial forces, i.e., the prototype has high Reynolds numbers. Scale effects due to viscous forces are minimized by selecting a model scale that produces Reynolds numbers well into the turbulent range. The Reynolds number (the ratio of inertial forces to viscous forces) is defined as:

$$R = \frac{VD}{\nu} \tag{5}$$

where

R = Reynolds number
ν = kinematic viscosity, ft^2/sec
V = average pipe velocity, ft/sec
D = 4 x the hydraulic radius A/P, ft

A = flow area, ft^2
P = wetted perimeter, ft

Turbulent flow occurs when the Reynolds number is above approximately 2,000 and model scale ratio should be selected accordingly.

Similarity of Vortices

The fluid motions involving vortex formation in pump sumps have been studied by several investigators. It can be shown by principles of dimensional analysis that the dynamic similarity of fluid motion that could cause vortices at an intake is governed by the following dimensionless parameters:

$$\frac{ud}{\Gamma}, \frac{u}{\sqrt{gd}}, \frac{d}{s}, \frac{ud}{\nu}, \text{and } \frac{u^2 d}{\sigma/\rho}$$

where

u = average axial velocity at the bell entrance
Γ = circulation contributing to vortexing
d = diameter of the bell entrance
s = submergence at the bell entrance
ν = kinematic viscosity of water
g = acceleration due to gravity
σ = surface tension of water air interface
ρ = water density

The influence of viscous effects is defined by the parameter $ud/\nu = R$, the Reynolds number, and surface tension effects are indicated by $u^2 d\rho/\sigma = W$, the Weber number. As strong air-core type vortices, if present in the model, would have to be eliminated by a modified sump design, the main concern for interpretation of model performance involves the similarity of weaker vortices. If the influence of viscous forces and surface tension on vortexing is negligible, dynamic similarity is obtained by equating the parameters ud/Γ, $u/\sqrt{gd}$, and d/s in model and prototype. A Froude model satisfies this condition, provided the approach flow pattern in the vicinity of the sump, which governs the circulation, Γ, is properly simulated.

ARL has conducted considerable research on scaling free surface and submerged vortices. From a study of horizontal outlets for a depressed sump [Padmanabhan and Hecker, 1984], it was determined that no scale effect on vortex strength, frequency or air withdrawal existed for pipe Reynolds numbers above 7×10^4.

A review of all available data on model versus prototype vortex intensity [Hecker, 1981] indicated negligible scale effects for weak vortices and small scale effects for air drawing vortices, and that this effect could be overcome by a relatively small increase in model flow rate. The model flow rate should only be increased by an amount such that sufficient Reynolds and Weber numbers result. Excessively increasing the model flow, particularly to prototype velocity, produces highly exaggerated vortices incompatible with prototype observations.

A generalized technique to evaluate scale effects of modeling vortices was developed by ARL [Durgin and Hecker, 1978]. Daggett and Keulegan [1974] indicated that an inlet Reynolds number of 3×10^4 is sufficient to obtain a good model to prototype correlation of vortices. Anwar et al. [1978], using a radial Reynolds number, indicated that viscous forces become negligible at values of 3×10^4.

INTAKE MODEL

MODEL DESCRIPTION

Based on the scaling criteria, it is proposed that the model be constructed to a scale of approximately 1:15. This ratio provides nondimensional parameters well above critical values and, thereby, assures minimal scale effects. Slight adjustments may be made to the scale ratio when details of the large horizontal pumps are provided to allow standard pipe sizes to be used for the pumps.

The model would extend from the back wall of the sump to approximately 500 ft upstream, including 200 ft of channel upstream of the present transition structure. Model limits are shown in Figure 1. The channel would be defined by templates backfilled with gravel, and topped with a thin layer of sand-cement mix to stabilize the geometry and reproduce the prototype roughness. The existing transition would be constructed in plastic coated plywood with all pertinent buttresses and pilings included. The pump sump concrete structure would also be fabricated from plastic coated plywood, and include all internal piers, walls, and sub-structures affecting the flow. Trash racks between the piers in the rack structure would be simulated to account for head loss and reduction in cross sectional areas.

The existing vertical shaft pumps would be modeled with plexiglass suction bells and clear transitions to the impeller location. Swirl meters will be included in each pump. The new pump suction inlets will be modeled in clear plastic to the section where the pump is to be attached. At this section, a straight length of lucite pipe will transition to the model syphon piping. The lucite pipe will contain provisions for velocity distribution and swirl measurments. It will thus be possible to estalish the flow conditions at the inlet to the pump, and to investigate how the sump geometry affects these conditions. Velocity distribution at the pump inlet section will be based on four 10 point velocity traverses located on diameters 45 degrees apart. Figure 2 illustrates a model to a scale of 1:16.8 used to design the present configuration of pumping station No. 3.

Model flow would be provided from a permanent flow supply system and withdrawn from the model by syphoning through each of the model pumps. Each pump syphon would contain an ASME orifice plate and a valve to measure and regulate the flow through each pump separately.

INSTRUMENTATION AND MEASURING TECHNIQUES

Flow

Flow will be measured with orifice meters constructed to ASME standards. Differential head from the meter will be measured using water manometers providing an estimated accuracy of the flow metering of ±2%.

Free Surface Vortices

In order to systematically evaluate the strength of vortices at pump intakes, ARL uses a vortex strength scale of Type 1 to Type 6, as shown in Figure 3a, where Type 1 is a surface swirl and Type 6 is an open air-core vortex to the inlet. Vortex types are identified in the model by visual observations aided by dye injection. Free surface vortices are usually unsteady and intermittent. Hence, in addition to noting the maximum strength, an indication of vortex type persistence is obtained through observations made every 30 seconds for 10 minutes. Such detailed vortex observations are undertaken only if coherent core vortices (of strength higher than a surface dimple, Type 2) exist for any test. For acceptance, vortex strengths should be reduced to values below Type 3.

Sub-Surface Vortices

Sub-surface vortices usually emanate from the sump floor and walls, and may be visible only when dye is injected. ARL uses the classification of sub-surface vortices given in Figure 3b. Type 1 sub-surface vortices are weak swirls while Types 2 and 3 have a coherent core. Type 3 vortices have a relatively strong core and may cause pressures low enough to release air bubbles out of solution.

Type 1 sub-surface vortices would be acceptable, with weak Type 2 sub-surface vortices allowed if they occur occasionally.

Swirl in the Suction Pipe at Impeller Location

Flow swirl intensity is measured at or a short distance downstream of the propeller location using a swirl meter. The swirl meter consists of four zero-pitch vanes oriented in the flow direction, and mounted on a shaft with low friction bearings. The vanes occupy a diameter of 75 to 80 percent of the pipe diameter and have a length equal to 0.6 pipe diameters. The rotation rate of the swirl meter is used to calculate a swirl angle, θ, which is indicative of the flow rotation.

$$\theta = \tan^{-1} \left(\frac{\pi n d}{u}\right)$$

where

u = average axial velocity at the swirl meter
d = diameter of the pipe at the swirl meter
n = revolutions/second of the swirl meter

Swirl induced by sub-surface and surface vortices is generally unsteady and intermittent. Typically, swirl meter readings are obtained over ten 1 minute intervals, covering a period of 10 minutes in the model. Thus, a 10 minute average swirl angle will be obtained. For acceptance, the average swirl angle should be less than 5 degrees.

Pump Column Velocity Traverse

Four 10 point velocity traverses will be made at the inlet section of the new pumps located on diameters 45 degrees apart. Each measuring station will be selected to represent equal areas of the cross section and will be monitored using a three hole pitot tube connected to two differential pressure cells. The cells are monitored by a computer and the axial velocity computed and plotted at the measuring location. The acceptance criteria will require all individual points to be within 10 percent of the mean velocity.

TEST PLAN

The test plan would include four phases:

1. Evaluation of new pumps east of present station, with recomended channel configuration
2. Testing of remedial designs with new pumps
3. Testing of remedial designs with present pumps
4. Detailed testing of final design

Testing in Phase 1 would be aimed at developing base line data to understand the impact of the new pumps on the flow distribution to, and performance of, all the pumps in the station.

Phase 2 testing would address changes to the forebay alignment and the intake bays for the new pumps to achieve aceptable values of the flow parameters, as detailed above. For cost estimating purposes, it is envisioned that two major channel re-alignments (i.e., right bank transitions) would be tested, each with three minor internal geometry changes incorporating guide walls and changes to the trash rack structure.

Phase 3 testing would entail developing remedial devices for the existing pumps, should the addition of the new pumps adversely affect the old pumps. As a guide, the existing pumps would be made to operate at the level of refinement documented in the 1981 ARL model study. Changes, if nessesary, would be confined to the immediate intake geometry by the addition of splitters, cones, and corner fillets, or to the near forebay by the addition of guide walls.

Phase 4 testing would entail final documentation of all pumps, with the final geometry, for a range of operating conditions. The actual test conditions will be determined based on expected field operation, and the cost has been estimated based on testing twelve pump operating combinations, each at two water levels.

COST AND SCHEDULE

Design and construction of the model could start immediately upon authorization and would require seven weeks to complete, including shakedown testing of the model. Testing is estimated to require eight weeks, and a draft report could be issued two weeks after completion of testing. Test results would be transmitted regularly, and at the end of testing all pertinent information affecting design would be available. A schedule with an assumed starting date of March 3 is shown in Figure 4, and indicates that testing would be completed in the second week of June.

Design and construction of the model is estimated at $32,600. Testing is estimated at $4,500 per week, for a total of $36,000. Reporting costs include two, one day model demonstrations for clients and their guests, and this effort is estimated at $6,000. Two visits by ARL personel to the site would be recomended to provide the modeler with detailed familiarity with the existing layout, and present and discuss modeling results to the engineers. These visits are estimated to cost $1,600 per visit.

Included in the cost are instrumentation, data retrieval software and hardware, and photographic and video equipment, as needed, for data and documentation purposes. The total cost of the upstream model study is, thus, estimated at $77,800. A summary of cost and time is provided in Table 1.

TABLE 1

COST AND TIME SUMMARY, INTAKE MODEL

	Activity	Duration (Weeks)	Cost ($)
1.	Model Design and Construction	7	32,600
2.	Testing		
	Phase 1 - Evaluation of New Pumps	1	4,500
	Phase 2 - Remedial Designs of New Pumps	3	13,500
	Phase 3 - Remedial Designs of Present Pumps	2	9,000
	Phase 4 - Details Testing of Final Design	2	9,000
	Field visits (2)		3,200
3.	Report (incl. Meetings/Visits)	2	6,000
	Total	17	77,800

DISCHARGE BASIN MODEL

INTRODUCTION

To accommodate the new pumps, it is necessary to widen the discharge basin, and a physical model of the basin is proposed to aid in the design of the new basin layout. The proposed model will be free surface and Froude scaled according to the section on similitude. Because vortex formation is not an issue in this model, a smaller scale can be used and still satisfy the scaling criteria; therefore, a scale ratio of approximatly 1:20 is proposed to ensure that the model will be sufficiently large to allow accurate measurments to be made.

MODEL DESCRIPTION

A 1:20 scale model will be constructed of the discharge basin from the downstream face of the pumping station to a section 500 feet downstream. The downstream end of the model will thus be

2 3.91
7.4
16.54

the exit of the discharge canal at Lake Pontchartrain. Figure 5 shows the model boundaries. Canal topography will be reproduced in a weak sand cement mix screeded over templates placed approximatly 50 feet apart. This construction technique allows topography changes to be made with little effort. Concrete structures will be reproduced in plastic coated plywood. Pump discharges will be individually modeled and supplied flow to allow any combination of pumps to be operated. Initially, the model will reproduce the present canal to allow baseline data to be collected, and subsequently the new discharge will be excavated and designed to channel the water into the canal.

TEST PROGRAM

The test program would be executed in three steps:

1. Testing of present geometry,
2. Adding new pumps, and
3. Documentation of final geometry.

In Step 1, flow patterns would be documented for the present design and velocity distributions obtained in several sections along the discharge canal to establish baseline data for the design of the expansion. These data would be obtained at full station capacity (8 pumps).

In Step 2, the new pumps would be installed and transitions from the pumps to the canal tested to provide a separation free discharge to the canal without excessive bank velocities.

In Step 3, the selected design would be documented for the following range of operating conditions:

a) Full station capacity (all 10 pumps),

b) All vertical pumps (8 pumps),

c) New horizontal pumps (2 pumps), and

d) Four 550cfs pumps and new horizontal pumps (6 pumps).

Each operating condition would be documented with the following data:

i. Flow patterns througout the model,

ii. Velocities in four cross sections, and

iii. Head loss through the transition.

COST AND SCHEDULE

Design and construction of the model could start immediately upon authorization and would require five weeks to complete, including shakedown testing of the model. Testing is estimated to require four weeks, and a draft report could be issued two weeks after completion of testing. Test results would be transmitted regularly, and at the end of testing all pertinent information affecting design would be available. A schedule with an assumed starting date of March 3 is shown in Figure 6, and indicates that testing would be completed in the first week of May.

Design and construction of the model is estimated at $18,000. Testing cost is estimated at $4,000 per week for a total of $16,000. Data evaluation and reporting costs are estimated at $4,000. The report would be part of a single volume report for both models. Model demonstrations for clients and their guests and field visits have been combined with the intake model and are, therefore, included in the cost for that model.

Included in the cost is instrumentation, data retrieval software and hardware, and photographic and video equipment, as needed, for data and documentation purposes. The total cost of the discharge basin model study is, thus, estimated at $38,000. A summary of cost and time is provided in Table 2.

TABLE 2

COST AND TIME SUMMARY, DISCHARGE BASIN MODEL

	Activity	Duration (Weeks)	Cost ($)
1.	Model Design and Construction	5	18,000
2.	Testing		
	Phase 1 - Present Geometry	1	4,000
	Phase 2 - New Pumps	2	8,000
	Phase 3 - Final Design	1	4,000
3.	Report	2	4,000
	Total	9+2	38,000

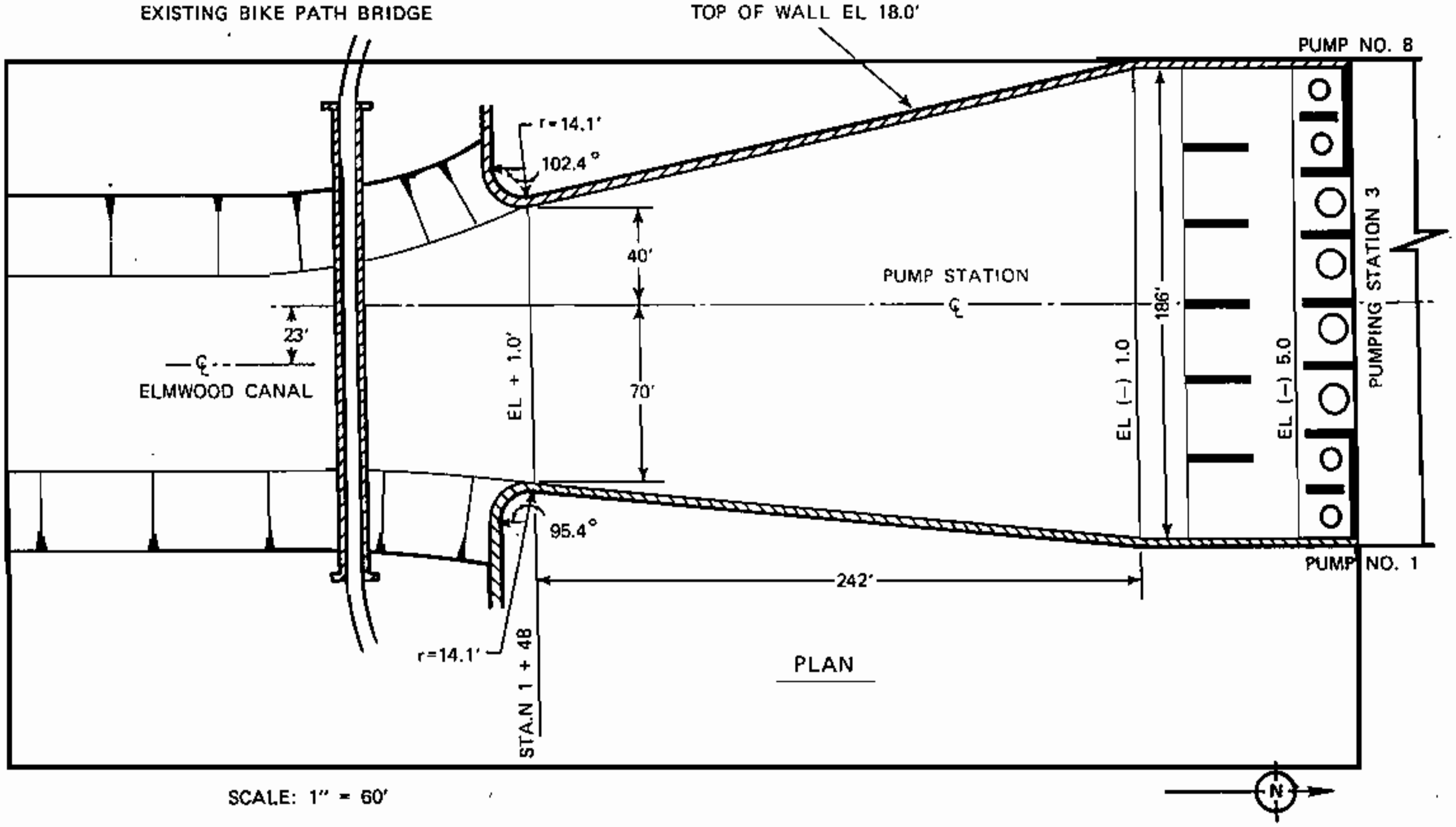


FIGURE 1 INTAKE MODEL BOUNDARIES

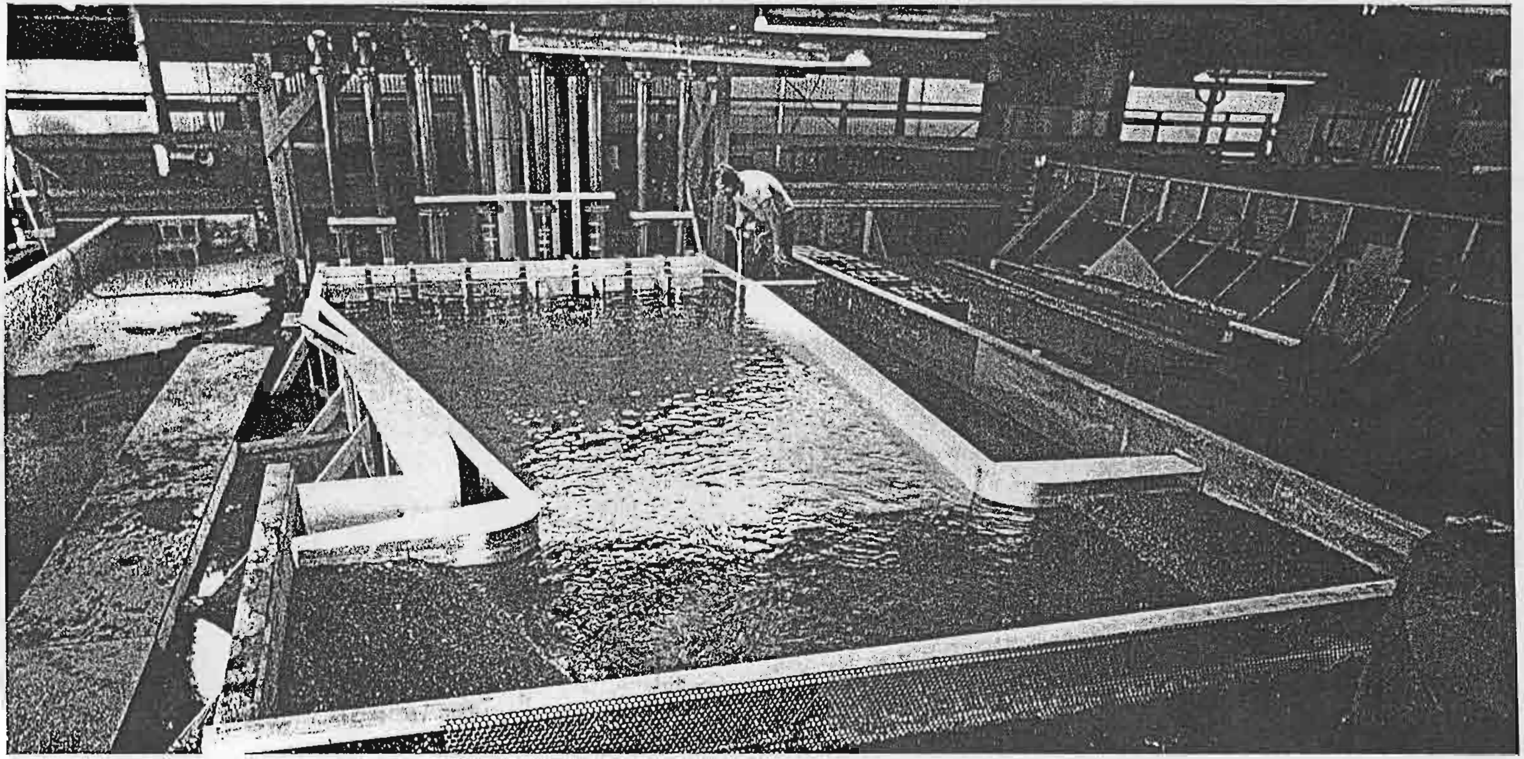
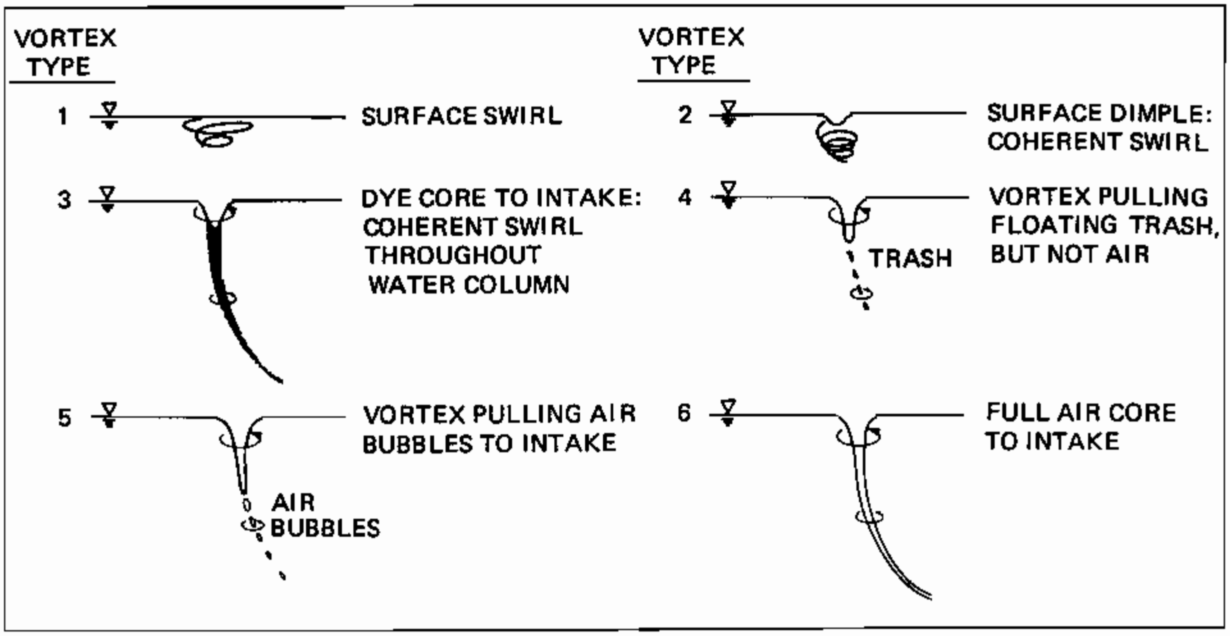
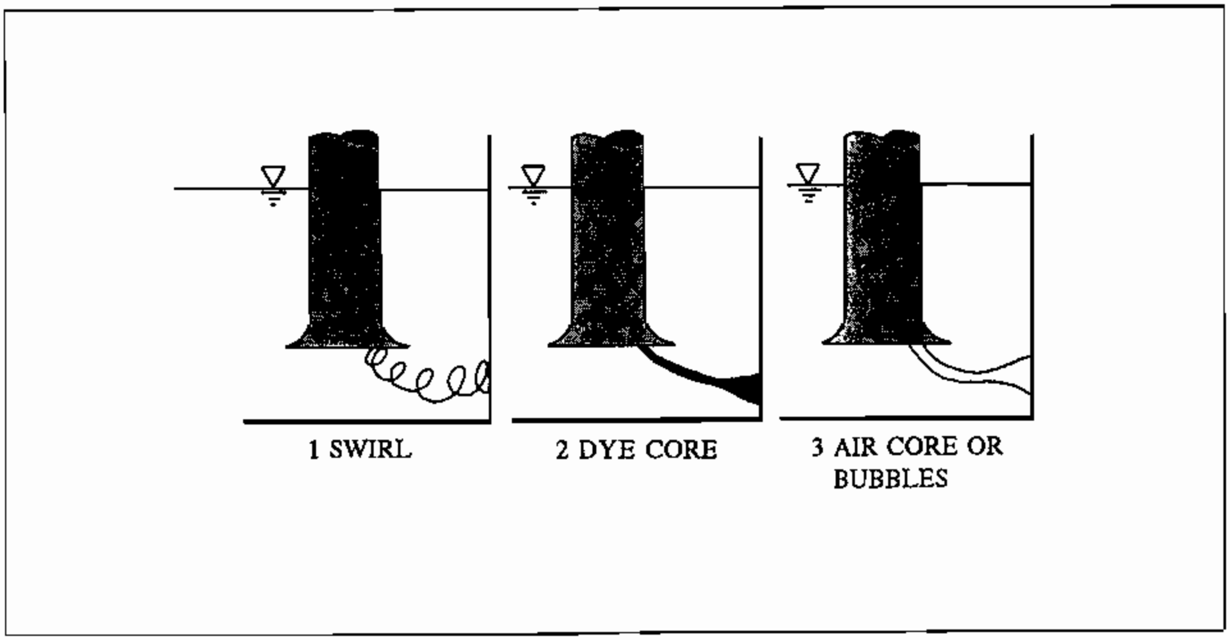


FIGURE 2 MODEL OF EXISTING STATION NO. 3



a. FREE-SURFACE VORTICES



b. SUBSURFACE VORTICES

FIGURE 3 VORTEX SCALE

SCHEDULE
INTAKE MODEL
Jefferson Parish Pumping station # 3

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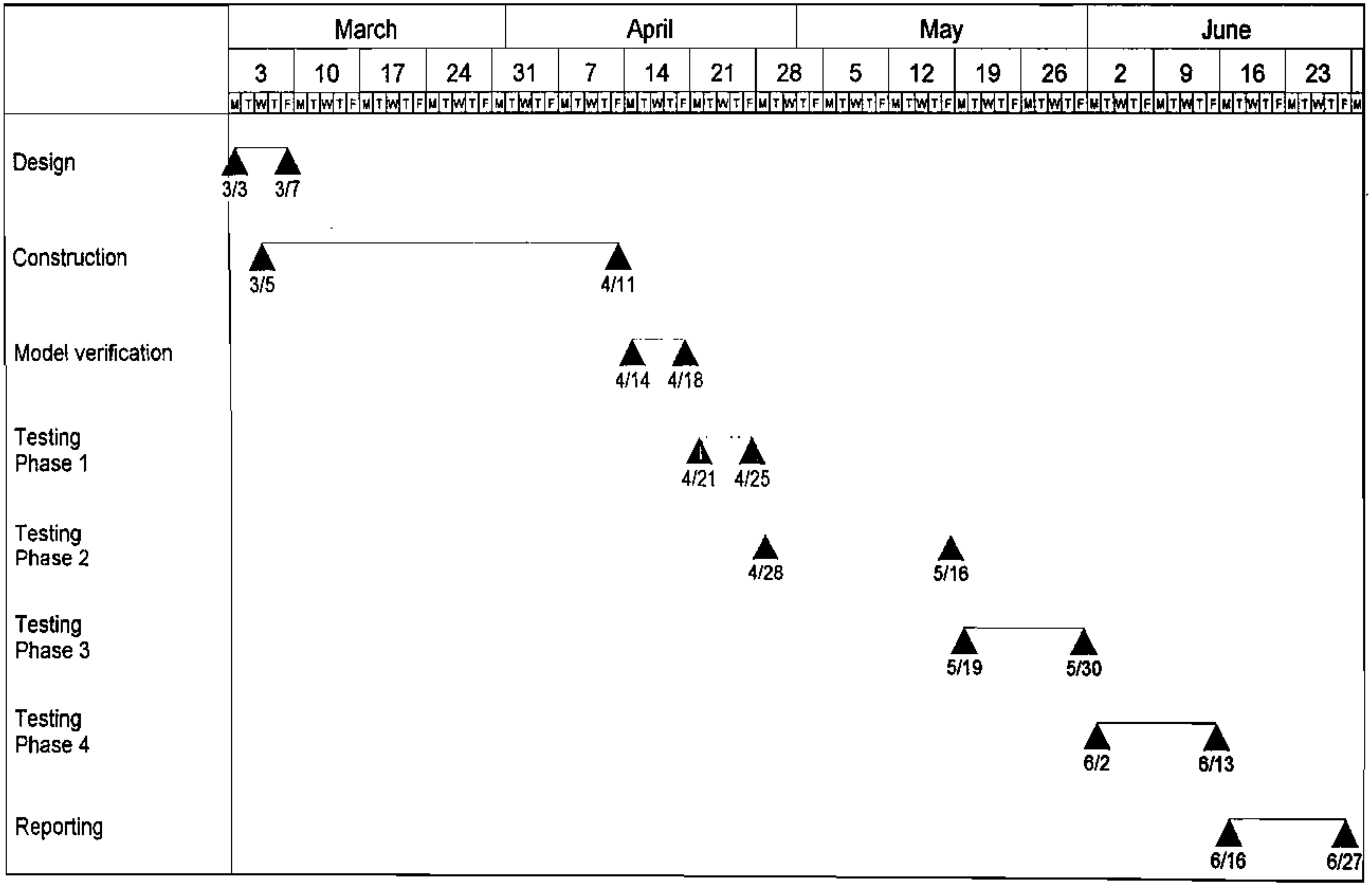

FIGURE 4 SCHEDULE FOR INTAKE MODEL

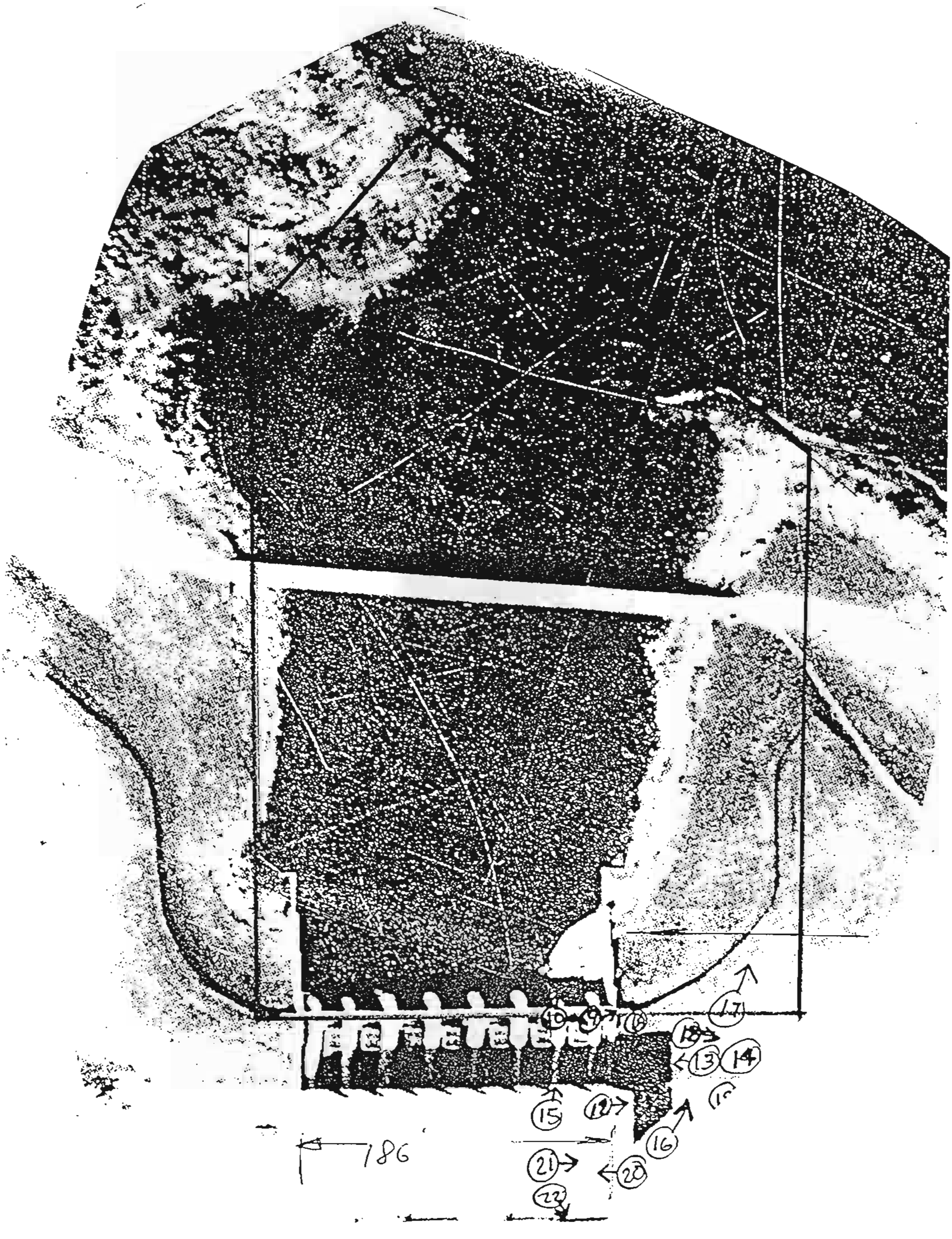

FIGURE 5 DISCHARGE BASIN MODEL BOUNDARIES

SCHEDULE
DISCHARGE BASIN MODEL
JEFFERSON PARISH PUMPING STATION 3

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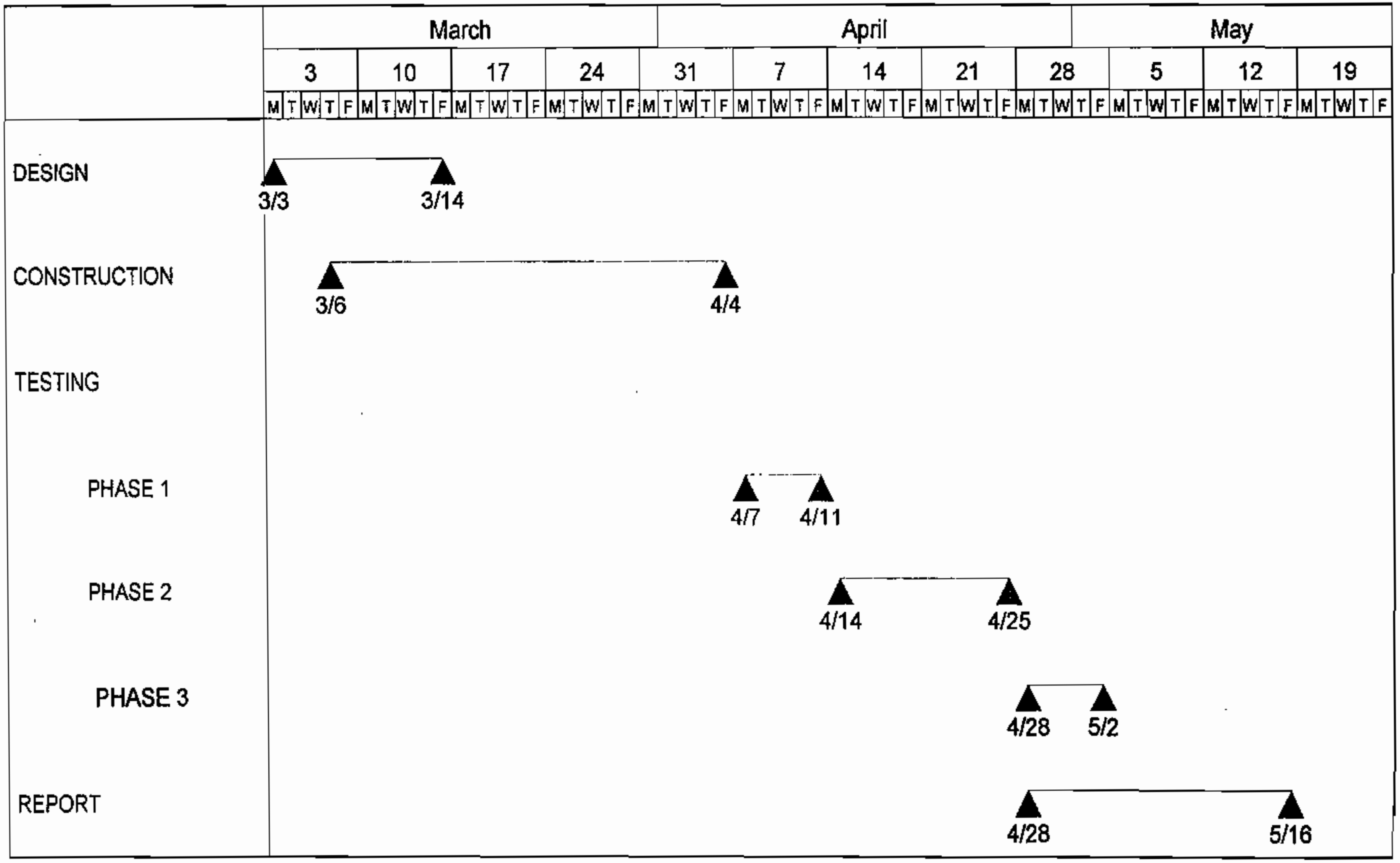


FIGURE 6 SCHEDULE FOR DISCHARGE BASIN MODEL

REFERENCES

1. Anwar, H.O., Wellen, J.A., and Amplett, M.B.," Similitude of Free-Surface Vortex at Horizontal Intake," Journal of Hydraulic Research, IAHR, Vol. 16, No. 2, 1978.

2. Daggett, L. and Keulegan, G.H., "Similitude in Free-Surface Vortex Formations," Journal of the Hydraulic Division, ASCE, November 1974.

3. Durgin, W.W. and Hecker, G.E., "The Modeling of Vortices at Intake Structures," Proceedings, Joint Symposium on Design and Operation of Fluid Machinery, ASCE-IAHR/IAHR-ASME, June 1978.

4. Hecker, G.E., "Model-Prototype Comparison of Free Surface Vortices," Journal of the Hydraulics Division, ASCE, October 1981.

5. Padmanabhan, M. and Hecker, G.E., "Scale Effects in Pump Sump Models," Journal of Hydraulic Engineering, ASCE, Vol. 110, No. 11, November 1984.

6. Pennino, B.J. and Larsen, J., "Hydraulic Model Study of Jefferson Parish Drainage Pump Station No. 3," ARL Report No. 68-81/M429F, July 1981.

PROJECT PERSONNEL

The study would be executed under the technical direction of Mr. Johannes Larsen, Vice President of ARL, whereas general guidance will be provided by Mr. George E. Hecker, President. Resumes of engineers who would likely be involved with the study are included at the end of this proposal.

George E. Hecker, President

George E. Hecker, President of ARL, has almost 30 years of experience in hydraulic modeling, field studies, and mathematical models covering a wide variety of hydraulic phenomena. He has conducted and supervised more than 150 studies on hydraulic structures, open and closed flow systems, pump intakes and sumps, convection and dispersion of effluents, and fluid-mechanic equipment.

Prior to joining ARL, G.E. Hecker worked for the Tennessee Valley Authority (TVA) as a Hydraulic Research Engineer. In this capacity, he was responsible for numerous model and field studies concerning spillways, energy dissipation and scour, inlets and outlets, major hydraulic structures related to hydro-power projects, hydraulic forces on control gates, navigation locks, and flow diversion. Field inspections and measurements provided an important practical background to complement laboratory model studies. Numerous technical reports were prepared for the TVA Division of Design. During this time period, G.E. Hecker served on the ASCE Task Committee on Outlet Works and published several papers on flow induced forces on control structures.

While at Stone and Webster Engineering Corporation, G.E. Hecker worked on the hydraulics of cooling water systems for steam-electric power stations and helped develop one of the first diffusers for thermal discharge.

During 20 years at ARL, George Hecker supervised a variety of model, analytic, and field studies relating to hydraulic structures and hydro-electric power. Particular contributions and publications were made in the areas of manifold flow, scale effects of modelling vortices at intakes, hydroturbine vibration and field efficiency measurements, and pump intakes. A close association with the EEI Hydraulic Power Committee was developed, and national recognition of G.E. Heckers contributions is indicated by his selection to the ASCE Hydraulic Structures Committee and chairing the ASCE Task Committee on Intake Vortices. He also served as Chairman of the ASCE Hydraulics Division Executive Committee, and is presently Chairman of the ASCE Task Committee on Standards in Hydraulics. Internationally, G.E. Hecker is the founding chairman of the Committee on Experimental Methods and Physical Modeling, a Section of the International Association for Hydraulic Research, and is currently serving as Chairman of their Working Group on Scale Effects.

Johannes Larsen, Vice President

As Vice President of the Hydraulic Structures Section, Mr. Larsen is responsible for the technical direction of several scale model studies every year for evaluation of flow conditions at hydroelectric plants and other hydraulic facilities. J. Larsen has directed numerous studies designed to improve station performance, facilitate construction, and evaluate field performance. These studies have encompassed evaluation of design concepts, physical and analytic studies of project layouts, and field studies. He has also provided technical guidance in studies of related structures such as spillways, gates, energy dissipators, and fish ladders. With 25 years experience in hydraulic modeling covering many aspects of hydraulics and fluid mechanics, Mr. Larsen has developed main interests in scale effects in modeling of free surface vortices and in the effect of pumpwell geometry on pump performance. Mr. Larsen has contributed significantly to the development of intake concepts to alleviate fish entrapment at water intakes. He co-authored a section on pump intake modeling for a pump handbook published by McGraw-Hill. Mr. Larsens extensive experience in modeling and supervising similar projects will provide the expertise needed to rapidly and efficiently conduct the study. J. Larsen has published several technical papers and over 150 reports on research projects.

Dean K. White, Project Engineer

Mr. White has worked at the ARL as a Research Engineer for 20 years and has conducted a large number of hydraulic model studies specializing in free surface flow. These models include small and large hydroelectric projects, pump intakes, fish ladders, and associated structures. Mr. White has been involved in a number of other free surface flow models for evaluating flow patterns approaching intake structures and has authored a number of reports and publications. Mr. White has worked as a consulting engineer and served as contracting officer at various naval facilities. Including his graduate work in hydraulics, Mr. White has over 23 years experience in hydraulic engineering.

ARL EXPERIENCE WITH INTAKES FOR PUMPS AND TURBINES

ARL has conducted numerous hydraulic model studies of cooling water intakes, reactor containment sumps, pump storage intake structures, and other pump intakes, all of which have required observations of approach flow patterns, formation and types of vortices, swirling flow in the suction pipes, and inlet losses. Studies have also been conducted for cooling tower intakes, flood control pumping stations, sewerage pumping plants, fresh water intakes, and other facilities. Brief descriptions of some studies conducted at ARL in the above areas are given below so as to provide definite examples of ARL's experience in modeling intake structures.

ARL has also conducted considerable research in the area of vortex formation and suppressors, and scale effects on vortices in Froude models, both as part of contract research and graduate theses. Papers on scale effects on vortex flows and other topics related to intakes are regularly presented at various national and international meetings, and published particularly in ASCE journals and proceedings. Generic testing to determine flow characteristics in containment pump sumps was conducted at ARL, and these tests results led to revised NRC regulatory guidelines. The President of ARL is past Chairman of the ASCE Task Committee on Intake Vortices and the Task Committee for Standards in Hydraulics. He is currently serving on the HI Intake Design Standards Committee for pump sumps. Reprints of published papers are available upon request. In addition, ARL staff have written chapters for various handbooks and manuals on pump intakes and swirling flow. Copies of ARL reports on most of the studies listed below are available upon request.

A. Cooling Water Intake Sumps

Model studies of cooling water intake sumps, both once through and cooling towers, are conducted to investigate flow patterns in the approach region, pump bays, and at the pump bell, and to derive suitable devices to achieve uniform flow pattern and to suppress vortex formation, if any. Often, the flow patterns resulting from a few of the pumps operating in a system with many adjacent bays are of importance. Velocity measurements in the sump and pump throat, swirl in the pump column, determination of pre-rotation under the bell, and flow visualization and photography to identify vortexing are commonly included in the model study. The following are some of the cooling water intake model studies conducted at ARL.

Anclote Plant, Auxiliary Cooling Water Pumps: Operational problems with four wet pit pumps prompted a 1:10 scale model study to find the cause of the pump problems. The model tests showed that both surface and submerged vortices were produced, and that pre-rotation was excessive. Various remedial devices were developed to achieve acceptable hydraulic conditions. After field modifications, proper pump operation was achieved. ARL Report No. 87-83/M468F. Sponsored by Black and Veatch Consulting Engineers and Florida Power Corporation.

B.L. England Generating Station, Units 1 and 2, Cooling Water Pump Intake: A 1:12 scale model was used to investigate flow problems at the sump for various operating conditions. Modifications involving curtain walls, splitters, and fillets were recommended. ARL Report No. 1-88/M628F. Sponsored by Atlantic City Electric Company.

Brayton Point Power Station, Unit 4, Circulating Water Pump Intake: To insure proper flow to the pumps with a revised approach canal, a 1:12 scale model study was conducted. The reasons for some of the existing pump operating problems were determined, and improvements for the new conditions were developed. ARL Report No. 160-85/M14F. Sponsored by New England Power Company.

Bridgeport Harbor Steam Electric Station: A 1:8 scale model of the water intake structure was used to observe eddies and vortexing. Baffling was suggested to improve flow patterns. ARL Report No. 30-72/M270F. Sponsored by United Illuminating Company.

Brooklyn Navy Yard Cogeneration Facility, Circulating Water Pumps: Using a 1:6 scale model, flow patterns approaching three pumps in a circulating water pumping sump were investigated to insure acceptable conditions. The tests considered two water levels and different pump operating combinations for the unusually confined intake with relatively high flow pumps. Unacceptably high vortex activity and swirl angles were measured with the original design. Within the space constraints, modifications were developed such that acceptable swirl and flow patterns resulted. Sponsored by Parsons Main of New York, Inc.

Calvert Cliffs Nuclear Power Project, Units 1 and 2, Circulating Water Pump Intake With Dual Flow Screens: The potential impact of dual flow screens on the hydraulic performance was investigated using a 1:10 geometric scale model. No significant flow problems were observed. A comparison of different dual flow screen designs was made. Sponsored by Bechtel Power Corporation.

Charles Poletti Power Project Intake Study: A 1:10 model was used to investigate flow conditions for proposed variable speed pumps. Free and sub-surface vortexing and potential silt deposition were investigated. ARL Report No. 48-93/M360F. Sponsored by New York Power Authority.

Cross Unit One Cooling Tower Intake: Excessive noise and vibration of a new pump undergoing startup testing were investigated in a 1:10 scale model. Tests indicated a non-uniform approach flow and unacceptable swirl angles. No vortex activity was observed. A flow distributor in the gate slot improved the flow distribution and reduced the swirl to acceptable levels. ARL Report No. 1-95/M711F. Sponsored by Santee Cooper.

Indian Point Nuclear Power Station, Unit 2, Service Water Intake: Pump failures after installation of additional once-through travelling screens were investigated in a 1:6 scale model. Results showed severe sub-surface vortices to be the problem. Several modifications were tested, and the most effective solution involved rearranging a few pumps within the intake and adding wall splitters. ARL Report No. 132-94/M118F. Sponsored by Consolidated Edison Company of New York.

Indian Point Nuclear Power Station, Unit 2, Service Water Pump Intake with Dual Flow Screens: A 1:6 scale model was used to investigate flow conditions in the pump bay due to the installation of dual flow screens. Modifications involving flow straighteners and vortex suppressors were recommended. ARL Report No. 74-87/M118F. Sponsored by Consolidated Edison Company of New York.

Indian Point Nuclear Power Station, Unit 2, Service Water Pump Intake: A 1:6 scale model of the service water intake indicated hydraulic problems in terms of subsurface vortices and swirl. A modified design was developed. ARL Report No. 63-84/M118F. Sponsored by Consolidated Edison Company of New York.

Indian Point Nuclear Power Station, Unit 3, Cooling Water Intake: A 1:13 scale model of the intake with cross flow effects modeled indicated unacceptable vortexing and swirl. A final design was developed which included splitters, fillets, curtain wall, and floor changes; ARL Report No. 45-85/M360F. Sponsored by New York Power Authority.

Indiantown Cogeneration Power Project: Modifications to improve the hydraulic conditions in the original design of the circulating water intake were developed using a 1:7 scale model. Swirl, vortexing, and velocity distributions at the pump entrance were evaluated. ARL Report No. 128-93/M124F. Sponsored by Bechtel Corporation.

Mitsui/Egat Khanom Combined Cycle Plant, Thailand, Intake Structure: Using a 1:10 scale model, the poor flow patterns of the original intake design are being corrected. The model includes one bay from and including the skimmer wall upstream of the bar screens, the hot water recirculation line, the dual flow screen, and the pump bell up to the throat. Sponsored by Ingersoll-Dresser Pump Company.

Killen Generating Station: Flow patterns were investigated using a 1:10 scale model of the pump intake located at a cooling tower. Modifications made to the original design resulted in increased flow capacity and improved flow distribution to two vertical shaft pumps. ARL Report No. 18-80/M7JF. Sponsored by Ebasco Services, Inc.

Martin Combined Cycle Power Plant, Units 3 and 4, Circulating Water Intake: Flow conditions were evaluated in a 1:9 scale model for various level and crossflow conditions. No objectionable free surface vortices were present. Intermittent sub-surface vortices were eliminated with back and side wall fillets. Sponsored by Bechtel Corporation.

McGuire Nuclear Power Station: A 1:15 scale model was used for optimizing four vertical suction inlets and their pumpwell. ARL Report No. 129-72/M208GR. Sponsored by Duke Power Company.

Mitchell Power Plant Intake: Horizontal pump intakes were simulated in a 1:10 scale model. Vortex activity was noted, and a vortex suppressing device recommended. ARL Report No. 119-77/M292AF. Sponsored by Worthington Pump Corporation.

Muara Tawar Combined Cycle Power Plant, Pakistan: Testing on the 1:10 scale model intake was conducted to evaluate the original design and develop remediations, as necessary. Testing indicated that the dual flow screen produced non-uniform flow, unacceptably high swirl angles, and severe submerged vortex activity. Modifications were developed to meet acceptance criteria. Sponsored by Ingersoll-Dresser Pump Company.

Northport Dilution Pumps: A pump intake structure with two 247,000 gpm vertical shaft pumps was modeled at a 1:9 scale. The existing design was modified to reduce surface and subsurface vortex activity which greatly decreased pump maintenance. ARL Report No. 22-79/M71. Sponsored by Ebasco Services, Inc.

Perry Nuclear Power Plant Cooling Tower Intake: The original design of a three bay pump was modeled at a 1:16 scale model. The original design was modified to reduce vorticity and improve approach flow distribution. ARL Report No. 153-77/M294EF. Sponsored by Cleveland Electric Illuminating Company.

Perry Nuclear Power Plant Offshore Intake Structure: A 1:25 scale model was used to evaluate three submerged intakes. Velocity distribution at intake ports and head losses were measured. The objective was to minimize fish entrapment. ARL Report No. 93-75/M294BF. Sponsored by Cleveland Electric Illuminating Company.

Seabrook Condenser Circulating Water Pump Intake: Vortices, swirl, and flow patterns were evaluated in a 1:12 scale model. Modifications to improve performance were recommended. ARL Report No. 131-76/M296DF. Sponsored by Public Service Company of New Hampshire.

Somerset Power Plant Intake: A 1:10 scale model of an intake pumphouse with three vertical shaft circulating water pumps was tested. The original design was modified to improve flow patterns approaching the traveling screens. Vortex activity, persistence, and pre-rotation were investigated over the range of water levels and combinations of pump operation. Sponsored by United Engineers and Constructors, Inc.

St. John's River: Three model studies were conducted: a 1:7 scale model investigation of cooling tower circulating water pump sump; a 1:4 scale model investigation of the cooling tower blowdown pump sump; and a 1:6.5 scale model investigation of the cooling tower makeup water pump sump. Modifications were recommended. Sponsored by Ingersoll-Rand Company.

Two Light Ends Refinery, Absorber Chilling Project No. 25 Cooling Tower: Surface turbulence and occasional rough running of two centrifugal pumps prompted a model study when the pump capacity was to be doubled. A 1:6 model indicated high swirl and periodic air withdrawal for the original design. Performance was unacceptable with the new pumps. Modifications were developed so that acceptable performance resulted. ARL Report No. 66-88/M610F. Sponsored by Exxon Company, U.S.A.

York County Waste-To-Energy Facility, Cooling Water Pump Intake: A 1:6 scale model was used to investigate flow patterns, vortexing, and swirl at the pump in three bays, with possible operation of any two. Modifications involving curtain walls, floor splitters, and wall fillets were recommended. ARL Report No. 161-85/M76F. Sponsored by General Electric Company.

B. Flood Control, Wastewater, Raw Water, and Other Pumping Facilities

Pump intake studies concerned with optimizing flow conditions for various types of pumping facilities are described below.

Allegheny County Wastewater Treatment Influent Pumping Station: Six enlarged pumps deliver the flow to a treatment plant, and a 1:8 scale hydraulic model was used to evaluate altered wet-well flow conditions under increased flow conditions. The pump intakes are located around the periphery of the wet well, which can vary more than 50 ft. The model simulated the complex suction piping to each pump. Numerous operating conditions for the three inflow interceptors, wet well levels, and pumps were tested to determine swirl angle and vortex severity. Testing indicated generally low vortex activity and swirl angles. A preferred operation plan was developed. ARL Report No. 190-95/M502F. Sponsored by Camp Dresser & McKee, Inc. and Allegheny County Sanitary Authority.

Broad Street Pumping Station: A model study was conducted to develop the approach flow and sump geometry for the station expansion to help alleviate flooding in low lying regions of the city. Significant changes in sump geometry were made to provide favorable flow conditions for new and existing pumps. ARL Report No. 130-89/M636F. Sponsored by Pepper & Associates, Inc. and Sewerage and Water Board of New Orleans.

Broad Street Pumping Station, Pump Upgrade: As part of a pump station expansion, one phase was to accommodate two new 600 cfs pumps. Additional investigation by the design engineer indicated that two 1,200 cfs pumps could be installed in the same expansion area with only a small increase in total cost. Because of the increased flow, head losses between the canal and suction basin were evaluated in a model. The previously developed canal configurations was altered by moving guide walls, and the head loss was considered acceptable. Draft Report. Sponsored by Pepper & Associates, Inc.

Charlestown Wastewater Pumping Station, Metropolitan District Commission of the Commonwealth of Massachusetts: Tests conducted using a 1:12 scale hydraulic model of the pumping station indicated a satisfactory hydraulic performance. ARL Report No. 109-84/M502F. Sponsored by Camp, Dresser and McKee, Inc.

Canal Road Water Treatment Plant: To evaluate the hydraulic performance of the finished and raw water pumping station designs, model tests were conducted using 1:5 geometric scale models. Based on the test results, which showed coherent core, sub-surface vortices for the original design, modifications were proposed by ARL. These included the use of splitters, fillets, and shorter filler walls, saving considerable construction costs. Tests conducted after the design modifications indicated satisfactory flow conditions for all pump operating conditions. ARL Report No. 99-93/M563F. Sponsored by Camp, Dresser & McKee, Inc. and Elizabethtown Water Company.

Drainage Pumping Station 4W Prentiss, London Avenue Canal: Energy losses would be increased by the installation of Pumping Station 4W and construction of flood protection walls by the U.S. Army Corps of Engineers. These walls are on the canal side of the existing walls. A 1:30 scale model was used to evaluate the increased head losses due to the increased pumping station flows and the new walls. Modifications to the station discharge and junction area plus other changes minimized the losses. Draft Report August 1996. Sponsored by Design Engineering, Inc.

Jackson Pike Wastewater Project: A 1:6 model indicated skewed approach patterns and objectionable free surface and sub-surface vortices for three centrifugal pumps. The original approach flow conditions were eliminated by two 90 degree turns, a sluice gate, and protruding walls. A flow straightener in combination with curtain walls and other modifications resulted in an acceptable design. ARL Report No. 154-91/M137F. Sponsored by Flygt Corporation.

Jefferson Parish Pumping Stations 1 and 4: Two stations, including approximately 1000 ft of approach canal and canal junction, were modeled at a 1:25 scale. The canal junction, pump approach, and details at the pumps were optimized to minimize head losses, surface vortexing, and swirl. ARL Report No. 22-83/M429EF. Sponsored by Burk & Associates, Inc.

Jefferson Parish Pumping Station No. 2: A 1:16 scale model was used to evaluate the approximate doubling of a pump station capacity. Testing indicated that approach conditions, head losses, and vortexing at the pumps were unacceptable. Remedial measures included approach channel modifications, and appurtenances at the pumps. ARL Report No. 98-82/M429AF. Sponsored by Burk & Associates, Inc.

Jefferson Parish Pumping Station No. 3: A 1:16 scale model was used to evaluate flow patterns at a pumping station with eight vertical pumps. The original design and approach channel were modified, and curtain walls added at the pumps to eliminate air drawing vortices. ARL Report No. 68-81/M429F. Sponsored by Burk & Associates, Inc.

Lake Bluff Raw Water Pumping Station: Flow conditions and potential vibrations for an extraordinarily long unsupported pump column were evaluated using a 1:7 scale model. Original unacceptable hydraulic performance was improved by a deflector wall and baffle. Vibration amplitude was substantially reduced with improved flow patterns. ARL Report No. 2-90/M502F. Sponsored by Camp, Dresser & McKee, Inc.

Mamaroneck Wastewater Treatment Plant, Effluent Pump Intake: A 1:8 scale model was tested to insure satisfactory performance for a wide range of pump operating conditions, pump flows, water levels, and inflow combinations. Because of high swirl angles and sub-surface vortices, modifications to improve performance were adopted. Splashing and air entrainment from a 48 inch gravity fed inflow pipe were decreased with a deflector plate. Sponsored by Camp, Dresser & McKee, Inc.

Merrill Creek Reservoir Pumping Station: Investigation of a river pumping station to store Delaware River flow for low flow augmentation was conducted using a 1:15 scale model. Testing indicated that there was minimal vortex activity and that the pump house could be reduced in size. A 1:40 scale model of the river adjacent to the pump station was used to evaluate flow patterns at proposed wedge wire screens and the relative effectiveness of schemes to deflect moving bed material around the screen trench. ARL Report No. 15-82/M196GF. Sponsored by Charles T. Main and Public Service Electric and Gas.

Multi-Stage Transfer Pump Testing: A characteristic head-flow curve is being established for a new pump design. Additional pump operating points at other than the design speed are also being tested to demonstrate stable operation. The test program is using air, and the results extrapolated to hydraulic operating conditions. Study in progress. Sponsored by Westinghouse Electric Corporation.

New Orleans Sewerage and Water Board, Pumping Station No. 6: A discharge basin for an enlarged pump house was evaluated in a 1:25 scale model. Testing indicated that the basin would accommodate the increased flows without increasing water levels. ARL Report No. 36-83/M429DF. Sponsored by Burk & Associates, Inc.

Quarles Water Treatment Plant, Chattahoochee Raw Water Intake and Pumping Station: A 1:5 geometric scale model was used to evaluate the hydraulic performance of an existing pumping station with an unusual approach flow and pump suction pit. Design modifications were derived by ARL, which resulted in satisfactory flow conditions, with no objectionable swirl or vortices. ARL Report No. 14-94/M502F. Sponsored by Camp, Dresser & McKee, Inc.

Salem Generating Station, Units 1 & 2: A 1:4 model was used to evaluate hydraulic performance of the existing sump to improve flow conditions for new pumps. Surface and sub-surface vortices plus swirl severity were evaluated. Modifications at the pumps included floor fillets and flow splitters. The second purpose of the model was to remedy significant sediment deposition within the intake. Based on similitude criteria, granulated lime was used in conduction with appropriate model flow scaling to reproduce field conditions. Curtain walls, which restricted the flow opening in the approach to the pumps, were effective in preventing deposition. ARL Report no. 133-93/M247F. Sponsored by Johnston Pump Company, Texas, and Public Service Electric and Gas Company.

Williams Road Pumping Station: A 1:5 scale model study is being conducted to determine if any unfavorable flows exist in the prototype pump sumps. The model simulates two wet wells from the supply channel, including the sluice gate entrances, to the sump back wall as well as the intermediate wall thimble between the wet wells. Study in progress. Sponsored by ITT Flygt Corporation and City of Columbus, Ohio.

C. Pumped Storage Plant Intake Structures

Hydraulic model studies of upper and lower reservoir intake/outlet structures for pumped storage projects are conducted to optimize the intake configuration, to observe flow patterns and possible vortex formation, and to determine the head loss coefficients in generating the pumping modes. It is often necessary to model the whole or a part of the upper reservoir so that induced circulation is properly simulated. Detailed measurements of velocity profiles, vortex severity versus stage, and loss coefficient versus Reynolds number are made. A selected listing of model studies in this area conducted at ARL follows.

Bad Creek Pumped Storage Plant: A 1:58 scale model of the upper reservoir and a 1:55 model of the lower reservoir were used for observation of flow patterns and vortices. Velocities and intake losses were determined for both pumping and generation modes. ARL Report Nos. 73-79/M208KF and 94-79/M208LF. Sponsored by Duke Power Company.

Bear Swamp Pumped Storage Project: The entire upper reservoir and intake structure were evaluated in a 1:50 scale model. Testing developed an economical vertical shaft intake near the shoreline. Detailed model versus prototype observations of vortices were conducted. The prototype is operating satisfactorily. ARL Report No. 106-72/M14CF. Sponsored by New England Power Company.

Blenheim-Gilboa Upper Reservoir: The intake structure and reservoir were reproduced in a 1:75 scale model. Remedial measures to avoid strong vortex were recommended. The prototype is operating satisfactorily. ARL Report, 1970. Sponsored by Power Authority of the State of New York.

Coley Creek Pumped Storage Project: Hydraulic performance, potential scour, and effectiveness of a submerged weir to prevent mixing were investigated in a 1:51 scale model of a discharge structure and section of lower reservoir, Lake Jocassee. Due to vortices and non-uniform velocities, modifications were developed. ARL Report No. 138-88/M208F. Sponsored by Duke Power Company.

Cornwall Pumped Storage Project: A 1:80 scale model of the entire upper reservoir and intake structure were tested. There was unique model construction using styrofoam sheets. Observation of vortices lead to revision of the intake design. ARL Report No. 119-79/M118F. Sponsored by Uhl, Hall and Rich, Division of Charles T. Main, and Consolidated Edison Company of New York.

Davis Pumped Storage Plant: A partial 1:50 intake model and a complete 1:360 scale model of an upper reservoir were used to evaluate the intake. Velocity profiles, head losses, vortex observations, and the behavior of simulated floating ice were documented. A transition section in the head race was developed to improve the flow pattern. ARL Report No. 95-72/M7HF. Sponsored by Allegheny Power Service Corporation and Ebasco Services.

Fairfield Pumped Storage Scheme: Flow patterns, head losses, and mixing were evaluated in a 1:70 model of an upper reservoir intake. Modifications to the intake channel and transition structure were recommended. The prototype is operating satisfactorily. ARL Report No. 63-75/M260A. Sponsored by South Carolina Electric & Gas Company.

Ludington Pumped Storage Project: A 1:122 scale model of an upper reservoir and intake structure was tested. Flow patterns during generation, pumping, and initial reservoir filling were evaluated. A perforated wall was developed as a vortex suppressor. ARL

Report, 1970. Prototype operating satisfactorily. Sponsored by Consumers Power Company.

Northfield Mountain Pumped Storage Scheme: Flow patterns, velocity profiles, and vortices were evaluated in a 1:45 scale partial model and a 1:100 model of the intake and part of the upper reservoir. The prototype is operating satisfactorily. ARL Report, 1968. Sponsored by Stone & Webster Engineering Corporation and Northeast Utilities.

D. Reactor Containment Sump Models

The models of reactor containment sumps are designed based on Froude similarity to include the sump and surrounding area with all the structures and piping which would influence the approach flow. In deciding the geometric scale, due considerations of simulation of flow patterns, vortexing, and possible scale effects due to viscous and surface tension forces are given. Testing to observe flow patterns, formation and type of vortices, and pre-rotation and swirl effects is undertaken for the various operating conditions including restrictions due to screen blockage. Evaluation of inlet loss coefficients for the various conditions is made to verify available NPSH. If necessary, vortex suppressors or other design modifications are derived and tested. Studies on possible scale effects, involving high temperature-high velocity testing techniques derived by ARL researchers, were conducted to allow projection to prototype performance. The following reactor sump model studies were conducted at ARL.

Beaver Valley Power Station: 1:3 scale model; ARL Report No. 79-83/M10WWF. Sponsored by Stone & Webster Engineering Corp.

Bellefonte Nuclear Plant: 1:2 scale model; ARL Report No. 56-82/M443F. Sponsored by Tennessee Valley Authority.

D.C. Cook Nuclear Power Station: 1:2 scale model; ARL Report Nos. 108-78/M178PF and 1-80/M178PF. Sponsored by American Electric Power Service Corporation.

McGuire and Catawba Nuclear Power Plants: 1:3 scale model; ARL Report No. 29-78/M208JF. Sponsored by Duke Power Company.

Millstone Nuclear Power Station: 1:3 scale model; ARL Report No. 114-82/M10XXF. Sponsored by Stone & Webster Engineering Corp. for Northeast Utilities.

North Anna Nuclear Power Station, Unit 1: 1:3 scale model; ARL Report No. 123-77/M250CF. Sponsored by Virginia Electric & Power Company.

Parametric Study of Containment Emergency Sump Performance: full scale study to help formulate new NRC Regulatory Guides and investigate possible scale effects in modeling sumps; ARL Report No. 120-80/M398. Sponsored by DOE for the NRC with the Sandia National Laboratory.

Salem Generating Station: 1:2 scale model; ARL Report No. 24-81/M302LM. Sponsored by Public Service Electric and Gas Company.

Seabrook Nuclear Station: 1:4 scale model; ARL Report No. 25-81/M296HF. Sponsored by Yankee Atomic Electric Company.

Shearon Harris Nuclear Power Plant, Unit 1 and 2: 1:3 scale model; ARL Report No. 102-84/M18F. Sponsored by Carolina Power & Light Company.

St. Lucie Nuclear Power Station: full scale model; ARL Report No. 106-82/M7KF. Sponsored by Ebasco Services.

Standard Nuclear Unit Power Plant System: 1:3 scale model; ARL Report No. 30-83/M458F. Sponsored by SNUPPS Nuclear Power Plants.

Three Mile Island Nuclear Power Station: 1:3 scale model; ARL Report No. 46-77/M202F. Sponsored by Burns and Roe, Inc.

V.C. Summer Nuclear Power Station: 1:2 scale model; ARL Report No. 47-81/M260EF. Sponsored by South Carolina Electric and Gas Company.

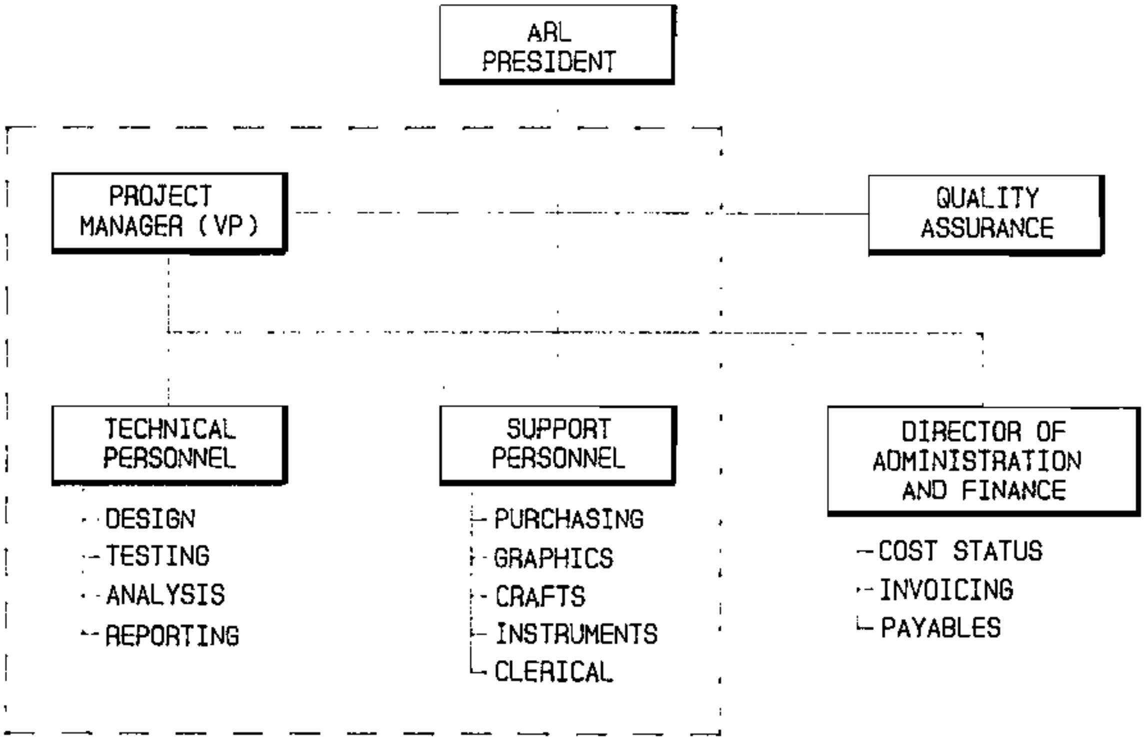
Washington Public Power Supply System, Nuclear Project No. 1: 1:2 scale model; ARL Report No. 3-83/M252HF. Sponsored by United Engineers and Constructors, Inc.

PROJECT MANAGEMENT

Organization

To allow an efficient and controlled execution of the study, be it experimental, analytical, or a field survey, a project team concept is used, illustrated by the dashed lines below. The Project Manager, usually a Vice President of ARL who reports directly to the President, is responsible for the proper conduct of the study and communicates with the client on both technical and contractual matters. Technical personnel are headed by an ARL Research Engineer, who has direct access to the various Support Personnel and financial services, including the weekly cost status reports described below. If the study involves a formal quality assurance program, responsibility for this aspect is assigned to personnel independent from the project team. General technical and administrative support, including questions of priority in allocating ARL resources, is provided by the ARL President.

TYPICAL PROJECT ORGANIZATION



Cost Tracking and Control

Each study is assigned an ARL code, which is used to report time spent on the study and to designate cost allocations for purchased equipment and materials, including computer time. All ARL personnel complete weekly time cards, which, together with purchased items, form the basis for charges. Each study is sub-coded into work phases, such as model design, construction, testing, and reporting, and cross-correlated to internal personnel categories, such as research staff, instrumentation, crafts, etc., to allow clear definition of where and why charges occurred. Purchase orders for equipment and expendable materials require approval by the Project Manager or Research Engineer, and copies of all purchase orders having the study code are forwarded for their files and control. A summary matrix of costs incurred and obligated on each study, organized by work phase and personnel category, is forwarded at weekly intervals to the Project Manager, thus allowing timely feed-back and control of expenditures versus work progress.

Files

The central ARL file system, organized by study sponsor and code, contains all original incoming correspondence and documents, and the color coded file copy of outgoing correspondence. Copies of all incoming and outgoing correspondence are forwarded to the Project Manager and Research Engineer for information and retention in their project files. There is no time delay in transmitting such information since no routing of material occurs. Drawings, reports, etc. required by the project team for conduct of the work are stored in the project files until completion of the study. At that time, all material related to the study, including data sheets, photographs, and reports, are assembled with the central file materials and placed into long term storage. Computer disks holding study data may be filed separately.

ARL GENERAL POLICY
FIXED PRICE CONTRACTS

Alden Research Laboratory, Inc. (ARL) is an independent organization incorporated under the laws of the Commonwealth of Massachusetts. The following ARL policies are in keeping with standard practices for professional services.

Work Authorization

Should the proposed work be authorized, the terms and conditions of this document shall either be incorporated by reference or included in the contract or purchase order, unless otherwise agreed upon.

If verbal authorization is given to initiate a study prior to the issuance of a contract or purchase order, adjustments, if any, related to specific terms and conditions will be negotiated.

Cost and Schedule

Cost and schedule quotes for conducting the proposed scope of work are based on past experience with similar studies. Such quotes are valid for 90 days from the time of proposal submission, unless specifically stated otherwise.

Quotes in ARL proposals are based on information and study objectives furnished by the prospective client at the time of proposal preparation. Changes in work scope and cost may be negotiated after work authorization.

If unusual delays in equipment and material delivery by vendors or subcontractors occur, changes caused by circumstances not in the control of ARL will affect the final schedule and price.

Equipment

Equipment purchased for a study will remain titled to ARL, will be considered ARL equipment, and will be made available to others after completion of the study. If such equipment must be retained by the purchaser after the contracted study, special arrangements must be made as part of the work authorization procedure. ARL has agreed with the local town tax assessor to report purchaser owned equipment.

Space and Facilities

In view of limited test space and the ARL policy to use existing space and equipment when practicable, it is necessary that ARL reserve the option to remove a model or test apparatus subsequent to issuing the final report if the space is needed for other studies. A model may be retained, space permitting, but only if a space rental contract is provided by the purchaser.

ARL maintains a space rental rate schedule and will invoice the Purchaser at the rates applicable at the time of billing. The payment of space rental charges does not indicate a responsibility on the part of ARL to maintain a model or test apparatus in working order subsequent to the completion of the final report. Some effort and cost is usually necessary to recondition a facility for testing.

A rental charge may be made for special ARL facilities or equipment, such as flumes or specialized instrumentation. The amount of these charges will be quoted upon request and will vary according to the involvement of ARL personnel.

Reports

ARL reports will be prepared according to a standard format, unless compelling reasons result in mutually agreeable changes in report organization and content. Acceptance of the final report shall constitute the Purchaser's agreement of the satisfactory completion of the terms and scope of work for the project. Responsibility for use of the study results shall be solely that of the user.

The exchange of ideas, techniques, and data with other research organizations is an aspect of maintaining the leading role of ARL in the field of hydraulic research. To this end, ARL reports may be made available three months after the printing date on an exchange basis with other similar organizations and, at the discretion of ARL, to others at their request. Information obtained from an ARL study may be incorporated in technical papers, and ARL reserves the option for joint authorship of such papers with ARL clients. Drawings, data, and techniques not incorporated in ARL reports will remain at ARL and may be used by ARL without written permission after the final report has been released for open distribution.

It is recognized that certain types of work at ARL may be of a proprietary or sensitive nature for a variety of reasons and, for these cases, special arrangements may be made at the time of work authorization.

Invoicing

Work will be invoiced according to standard ARL billing procedures. Purchaser requirements which deviate from this procedure will be accommodated at extra cost.

Billing by ARL will be by monthly invoices. For fixed price contracts, billing will be on a percent completed basis or will be based on completion of pre-established milestones. Payment by the purchaser of the net balance will be made within 30 days after receipt of an invoice.

Termination

If work must be terminated due to unforeseen circumstances, standard ARL billing will cover only work completed and material commitments made prior to and including the termination date. There shall be no extra termination charge by either ARL or the Purchaser.

Insurance

A certificate of insurance itemizing ARL's coverage will be provided upon request. Additional coverage required by the Purchaser, such as naming the Purchaser or a third party as an additional insured, will be billed at cost. ARL does not carry professional liability insurance.

Limited Liability

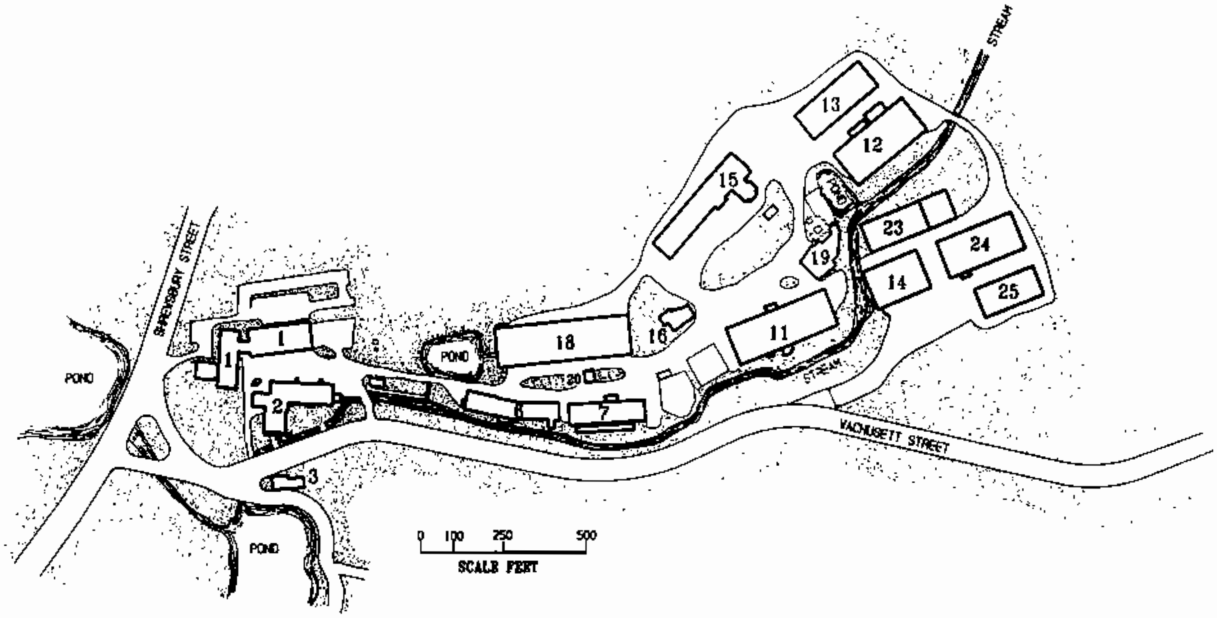
All services provided by ARL shall be performed with due skill and care in accordance with generally acceptable standards of engineering analysis and judgment. ARL's liability shall be limited to reperforming at ARL's expense any portion of the study found within one year to be defective, up to a total cost equal to the total cost of the original study.

ARL STAFF AND FACILITY

The Alden Research Laboratory, Inc. (ARL), located in Holden, Massachusetts, was founded in 1894 as a self-supporting research department of Worcester Polytechnic Institute (WPI), and in 1986 incorporated as a private company. ARL has performed applied research and provided testing services to industry and government since its early beginning, making it probably the oldest continuing hydraulic laboratory in the world. A national and international reputation has been earned in precision flow metering, fish passage and protection, and physical and analytic modeling in various areas of flow engineering, including environmental issues, machinery performance, and hydraulic structures. Consulting services are provided in analyzing and solving flow related problems, and field measurements are made for evaluating turbine and pump performance. Developmental and calibration testing of flow meters to an uncertainty of 0.25% is conducted in ARL's various flow loops using the gravimetric method traceable to NIST.

Over forty full-time people with varying training and expertise comprise the total ARL staff. Of the 13 professional staff, three hold Ph.D. degrees, and almost all others have Master's degrees with specialization in different areas of hydraulics, fluid mechanics, and fisheries biology. The professional staff is involved in national and international society activities, and many staff members have a variety of industrial experience. Model operation and data reduction are handled by experienced engineering assistants, and every ARL study is conducted by a team supervised by a full-time professional staff member. Service functions within ARL which support the technical activities include instrumentation, skilled crafts, heavy construction, purchasing, graphic arts, clerical, and accounting. The scope of ARL capabilities in areas relating to chemistry, computer applications, and life or earth sciences is enhanced by a continuing working relationship with faculty from various WPI departments.

ARL uses about thirty acres of extensive facilities to conduct testing and hydraulic modeling, as shown on the accompanying map. Approximately twenty buildings equipped with flow supplies and control offices are available for hydraulic models or other experiments. Fully equipped and staffed carpentry, machine, and instrumentation shops provide rapid and efficient model construction services. Extensive equipment is available for the construction and alteration of models and test facilities from wood, plastic, metals or combinations thereof required for the conduct of experimental research in the laboratory or field. An instrumentation department provides a variety of measuring and processing devices appropriate to a modern flow engineering laboratory, including a laser doppler anemometer (LDA), hot-wire and hot-film anemometers, swirl meters, various types of velocity probes, temperature sensors, and pressure transducers, all with appropriate readouts and computerized data acquisition. ARL has a graphics and photography section with experienced staff and all necessary equipment, including high speed and time lapse video, and computerized data displays. In addition to fixed facilities providing air and water flow, an inventory of movable flow related equipment, such as pumps, valves, metering devices, etc., is maintained and available.



ALDEN RESEARCH LABORATORY, INC.

1 Administration
Staff Offices
Flow Meter Calibration

2 Flow Meter Calibration
Instrumentation
Carpenter Shop

3 Machine Shop

6 Fish Screen/Flume

11 River Training
Sedimentation

12 Thermal Discharge

13 Hydroelectric Power

14 Pumped Storage

15 Full Size Equipment Testing

16 Construction Equipment

18 River Ice Mechanics

19 Outdoor Basin

23 Fish Guidance
Channel Junctions

24 Pump Intakes
Fish Guidance

25 3D Air Models

GEORGE E. HECKER, P.E.
President

PRESENT POSITION

G.E. Hecker is Chief Executive Officer of ARL, an international consulting engineering laboratory conducting a wide variety of applied hydraulic studies for electric power utilities, architect-engineering firms, equipment manufacturers, and governmental agencies. ARL is an independent corporation employing about 45 people and conducting numerous hydraulic model studies, flow meter calibrations, field and analytical studies each year. In addition to providing general technical supervision and project management for all studies, related activities managed by G.E. Hecker include marketing, proposals, contract negotiations, personnel management, and report editing.

TECHNICAL EXPERTISE

- Hydraulic structures - conceptual design and evaluation of intakes, outlets, stilling basins, pump sumps, navigation locks, control gates, spillways, etc.
- Environmental hydraulics - convection and dispersion of effluents; fish guidance, passage, and screening; flow characteristics of water treatment plants
- 3D air model studies - duct work, stack breeching, precipitators, etc.
- Field testing - flow measurement, equipment and machinery performance, hydrographic surveys
- Physical model studies - scale effects, instrumentation, model-field correlation
- Analytical models - flow transients, buoyant discharge, integral and 2D numerical models
- Coastal engineering - wave forces, erosion, harbor development
- Basic flow phenomena - flow induced vibration, energy dissipation, jets, vortices, manifold flow, air entrainment, stratified flow, sedimentation and scour, etc.

EXPERIENCE

Director and Research Professor at Alden Research Laboratory, Worcester Polytechnic Institute, 1975 to 1986. Responsible for managing all fiscal, administrative, and technical aspects of a self-supporting research department. Technical sections included Hydraulic Structures, Free Surface Flow, Closed Conduit Flow, Fluid Equipment, and Flow Measurement, each conducting experimental, analytic, and field studies.

Assistant Director and Assistant Professor at Alden Research Laboratory, Worcester Polytechnic Institute, 1971 to 1975. Supervision of engineering personnel for studies on a variety of hydraulic structures, thermal discharges, and other fluid mechanic phenomena related to power production. Conducted a variety of studies for consulting firms, utilities, and governmental agencies. Also, teaching of graduate course, thesis supervision, and preparation of research proposals.

EXPERIENCE (Continued)

Senior Hydraulic Engineer at Stone & Webster Engineering Corporation, 1968 to 1971. Supervision and coordination of engineers to predict environmental effects of cooling water discharges from thermal power plants. Preparation of specifications and evaluation of proposals to select sub-contractors for field and model studies. Also, analytical studies, preparation of conceptual designs for cooling water systems, site feasibility studies, and report preparation.

Research Engineer at TVA Engineering Laboratory, 1962 to 1968. Direct responsibility for laboratory and field studies of various types of hydraulic structures related to hydro-power and navigation facilities, and air and gas duct models for steam power stations. Supervision of engineers and technicians to design and operate models and field test equipment. Evaluation of data, preparation of reports, and recommendations for design changes.

EDUCATION

B.E., Yale University, 1961, Civil Engineering (magna cum laude)
M.S., Massachusetts Institute of Technology, 1962, Civil Engineering (fellow)

REGISTRATION

Professional Engineer, Massachusetts

SELECTED PUBLICATIONS

"Hydrodynamic Forces on Single Intake Gates," with Elder, Proceedings, 14th Congress, International Association for Hydraulic Research, 1971, Volume 2, Paper B-28, p. 229.

"Cooling Water Structures for FitzPatrick Nuclear Plant," with Gunwaldsen and Brodfeld, American Society of Civil Engineers, Journal of the Power Division, P04, December 1971, p. 767.

"Model Versus Field Data on Thermal Plumes from Power Stations," with Neale, Proceedings, International Symposium on Stratified Flows, IAHR, Novosibirsk, Published by ASCE, 1972, Paper 18, p. 397.

"Effect of Branch Spacing on Losses for Dividing Flow," with Nystrom and Qureshi, American Society of Civil Engineers, Journal of the Hydraulics Division, Vol. 103, No. HY3, March 1977, p. 265.

"Model-Prototype Comparison of Free Surface Vortices," American Society of Civil Engineers, Journal of the Hydraulics Division, Vol. 107, No. HY10, October 1981, p. 1243.

"Heated Discharge in an Estuary: Case Study," with Nystrom and Moy, American Society of Civil Engineers, Journal of the Hydraulics Division, Vol. 107, No. HY11, November 1981, p. 1371.

"Scale Effects in Pump Sump Models," with Padmanabhan, American Society of Civil Engineers, Journal of Hydraulic Engineering, Vol. 110, No. 11, November 1984, p. 1540.

"Swirling Flow Problems at Intakes," Chapters 2 and 8, IAHR Hydraulic Structures Design Manual, A.A. Balkema, Rotterdam, 1987.

PROFESSIONAL ACTIVITIES

Membership

American Society of Civil Engineers (ASCE)
International Association for Hydraulic Research (IAHR)

International Activities: IAHR

Founding Chairman - Section on Experimental Methods and Physical Modelling (1978-84)
Chairman - Working Group on Scale Effects (1984-)
Co-Chairman - International Conference on Physical Modeling of Transport and Dispersion (1990)

Selected National Activities

- ASCE
  - Chairman and Member - Committee on Hydraulic Structures (1970-74)
  - Corresponding Member - Task Committee for Revision of Manual on Hydraulic Models (1974-80)
  - Member and Secretary - Executive Committee of the Hydraulics Division (1975-77)
  - Chairman - Task Committee on Intake Vortices (1977-80)
  - Chairman and Member - Executive Committee of the Hydraulics Division (1980-84)
  - Member - Management Group D; Contact Member of Hydraulics Division EC (1984-89)
  - Chairman - Task Committee on Standards in Hydraulics (1989-1994)
  - Member - Steering Committee, Water Power '89; Program Committee, Water Power '91
- Hydraulic Institute (HI)
  - Intake Design Committee

Awards

Centennial Award, 1980, ASME
Hydraulic Structures Medal, 1994, ASCE

ADDITIONAL ACCOMPLISHMENTS

George E. Hecker is a recognized expert in hydraulic engineering with almost 35 years of broad experience in optimizing the performance of hydraulic structures, flow systems, and machinery through application of hydraulic models, field measurements, and analytical techniques. He has conducted and supervised more than 300 studies dealing with free surface and closed conduit flow, fluid mechanic equipment, convection and dispersion of effluents, and industrial hydraulics generally related to hydro and steam electric power generation. Technical findings in areas such as manifold flow, free surface vortices, model to prototype comparison of thermal plumes, and pump intakes (including reactor sumps) were presented at numerous national and international conferences. G.E. Hecker is recognized for his leading role in determining the effects of insulation debris and air entraining vortices on reactor residual heat removal systems. He has been invited to participate in various national workshops for EPRI and NSF, and has served as a consultant to State and U.S. Governmental agencies, consulting firms, electric power utilities, the U.N., and foreign organizations. He is listed in various Who's Who references, and is a member of various honor societies.

JOHANNES LARSEN

Vice President, Hydraulic Structures

PRESENT POSITION

Responsible for overall managing and technically supervising a team of engineers and support staff to solve flow problems related to hydro and steam generating stations. Pump intake evaluations are also conducted by this group for flood control and waste water plants. The development of data acquisition systems and controls for hydraulic models and field studies is a related function. Field measurements at plant sites and hydrographic surveys are conducted by his group. This position requires the preparation of proposals, considerable interaction with industrial clients, and presentations to Federal and State regulatory agencies. As a Vice President of ARL, Mr. Larsen is also responsible for general facilities management.

Mr. Larsen has over twenty-five years of experience relating to the design and modeling of hydraulic structures.

EXPERTISE

- Optimizing the performance of hydraulic structures and hydro power intakes, particularly at navigable lock and dam sites
- Pump intake hydraulics and remediation
- Planning and operation of very large sediment, navigation, and hydro power models including one simulating ice jams
- Conceptualizing and developing new, unique applications of PC's to hydraulic modeling, including: transfer of field topography to scaled model templates; molding topography using robotic machinery; efficient model control, automatic data acquisition, and analysis
- Site and hydrographic surveying including a wide range of field instrumentation
- Development of fish diversion and guidance devices for steam power plants
- Passage and guidance, upstream and downstream, of East Coast fish migrants

PROJECT EXPERIENCE

Mr. Larsen has extensive hydraulic engineering experience with hydro power generation and the arrangement of forebay and tailrace channels for run of the river hydro projects. Minimizing head losses, meeting turbine acceptance criteria for intake velocities, and reducing sedimentation and impacts on navigation have been successfully addressed. A reduction in project costs has resulted, and an excellent relationship has been maintained with the U.S. Corps of Engineers. He also has many years of experience relating to pump intake evaluation, canal hydraulics, and fish guidance.

PROJECT EXPERIENCE (Continued)

His group has recently been responsible for the following projects, selected from the many under his supervision:

Hydro Power - Niagara Power Project:
Simulation of ice flows using innovative materials and measuring techniques in extremely large distorted river model. On site determination of river flow patterns through GPS. Modifications to reduce intake blockage and increase operation.

Lock and Dam Projects - Arkansas River Lock and Dam Nos. 9 & 13:
Intake, discharge, sedimentation, and navigation studies relating to hydropower development

Spillway and Dam Projects - Deerfield Dam No. 5 and Sherman Dam:
Rehabilitation and redesign of existing dam and upgrading of a spillway for higher PMF

Fish Migration Studies - Vernon Dam, Bellows Falls, Conowingo Dam, Holtwood, and Safe Harbor Dam:
Improving the passage survivability of downstream migrants

Pumping Stations (Flood Control) - City of New Orleans and Jefferson Parish:
Optimizing intake flow patterns at enlarged or new pumping stations and upgrading canal flow capacity

Cooling Water and Other Pump Intakes - Cross Generating Station, Allegheny County Sewage Pumping Station, Maura Tawar Combined Cycle Power Plant, Williams Road Sewage Lift Plant, Quarles Raw Water Pumping Station

Prior to being promoted to Vice President in 1986, previous positions at ARL, starting in 1971, included Research Engineer and Lead Research Engineer. As a Laboratory Engineer at Chalmers Institute of Technology from 1965 to 1968, responsibilities included the planning and execution of large scale hydrographic field investigations.

CONSULTING

Complete hydraulic design and layout of a slotted fishway for upstream yearly migration of 300,000 shad. This design included interaction with U.S. Fish and Wildlife Service.

EDUCATION

B.S., Tekniska Gymnasiet Goteborg, 1968, Civil Engineering
M.S., Worcester Polytechnic Institute, 1971, Mechanical Engineering

SELECTED PUBLICATIONS

"Intake Modeling, Section 10.2," Pump Handbook, with Padmanabhan, McGraw-Hill Book Co., New York, New York, 1986.

"Louvered Offshore Intake for Diverting Fish," with Mussalli, Taft, and Toennies, ASCE Journal of the Energy Division, Vol. 107, No. EY1, May 1981.

SELECTED PUBLICATIONS (Continued)

"Offshore Water Intakes Designed to Protect Fish," with Mussalli and Taft, ASCE Journal of the Hydraulics Division, Vol. 106, No. HY11, November 1980.

"Model to Prototype Comparison of Intake Vortices in a Pumped Storage Reservoir," with Hecker et al., Joint ASME/ASCE Mechanics Conference, Boulder, Colorado, 1981.

"Physical Model Application to Small Hydro Sites," with Pennino, ASCE Hydraulics Division Conference on Computer and Physical Modeling, Chicago, Illinois, 1980.

"Laboratory Evaluation of Larval Fish Impingement and Diversion Systems," with Taft et al., Workshop for Advanced Intake Concepts, San Diego, California, 1981.

PROFESSIONAL ACTIVITIES

Member, American Society of Civil Engineers
Member, International Association for Hydraulic Research

DEAN K. WHITE, P.E.
Project Engineer

PRESENT POSITION

Mr. Whites responsibilities as a Project Engineer include supervision of staff designing and operating hydraulic models, data evaluation, project management, and reporting. As a highly experienced civil engineer specializing in hydraulics, with over 25 years of experience in testing and evaluating hydraulic structures, his focus has been optimizing structures related to hydro power, fish migration, flood control canals, and pumping stations. Field testing responsibilities include coordination and supervision of surveys measuring river currents and intake velocities.

EXPERTISE

- Extensive hydraulic design and model testing experience on a wide variety of hydraulic structures, primarily for the hydro-electric power industry
- Knowledgeable on various aspects of fish ladder design, and facilitating the upstream and downstream migration of fish
- Pump intake optimization for power and waste water industries
- Field testing - hydrographic surveys
- Civil design, construction, and management experience as an officer (Commander) in the U.S. Navy Civil Engineer Corps

PROJECT EXPERIENCE

Mr. Whites projects involve hydraulic performance evaluation and optimization. For power intakes, approach velocity distributions, intake velocities, and head losses are evaluated. The flow capacity of large flood canals and junctions has been maximized. Pump intakes having skewed flow patterns and vortices have been improved. Fish passage, diversion, and guidance devices have been optimized for both upstream and downstream migrants without penalizing output or imposing significant operational difficulties. Mr. Whites Seabee construction experience, in combination with his hydraulic engineering background, brings a unique combination of skills to a project. The following recent projects indicate his experience:

Hydro Power Projects - Niagara, Swan Falls, Vischer Ferry, Crescent, Lock & Dam No. 9 powerhouse, Dunbar Brook diversion, Great Falls, Lockwood

Fish Migration Studies (upstream and downstream) - Hadley Falls, Bellows Falls forebay, Bellows Falls fishway, Wilder Dam, Holtwood, Safe Harbor, Conowingo Dam

PROJECT EXPERIENCE (Continued)

Flood Canal and Junction Projects - Metairie Canal, Palmetto Canal, Fontainbleu/Broad Street Canals, Carrollton Avenue box culvert, Lower Hoeys Basin Canal System

Dam and Erosion Projects - Lock & Dam No. 9 navigation, Lock & Dam No. 13 sedimentation, Barry Steam Station, Vernon Spillway rating and erosion

Pump Intakes - Raw Water Pumping Station, Cobb Countys Quarles Treatment Plant, Great Plains Plant, BRUP Flexicoking, Anclote Station, Drainage Pumping Station No. 6, Broad Street Station, Cross Generating Station, Brooklyn Navy Yard Cogeneration Plant, Allegheny County Sewage Pumping Station, Maura Tawar Combined Cycle Plant, Williams Road Sewage Lift Plant, Attraction Water Pumping Station at Priest Rapids Dam

Cement Erosion - Potential cement erosion due to flowing water was investigated by using large "molds" composed of prototype materials.

Prior to being promoted to Project Engineer, previous positions at ARL included: Lead Research Engineer, Principal Research Engineer, Engineer, and Plant Engineer. From 1968 to 1971, U.S. Navy Civil Engineer Corps assignments included public works officer, Naval Air Station, Kingsville, Texas; and base turnover engineer, South Vietnam. From 1965 to 1968, as a Graduate Research Assistant, investigations included hydraulics and soil mechanics. For J.H. White Consulting Engineers, Boston, Massachusetts, assignments included design and inspection of an earth fill dam and discharge structure; details of a large flow calibration facility were designed. Active Naval Reserve Officer, 1971-1991.

EDUCATION

B.S., Worcester Polytechnic Institute, 1965, Civil Engineering
M.S., Worcester Polytechnic Institute, 1968, Civil Engineering

Additional Training

Middle Management Course, U.S. Navy
Contracts Management Course, U.S. Navy
Public Works Maintenance Management Course, U.S. Navy

REGISTRATION

Professional Engineer, Massachusetts and Maine

SELECTED PUBLICATIONS

"Calibration of a Movable Bed River Model," with Hecker and Larsen, Proceedings, ASCE International Symposium on Sediment Transport Modeling, New Orleans, Louisiana, August 1989.

SELECTED PUBLICATIONS (Continued)

"*Hydraulic Model Study of the Cooling Water Pump Intake, Maura Tawar Combined Cycle Power Plant,*" with Larsen, ARL Report No. 200-95/M292F, 1995.

"*Hydraulic Model Study of the External Flow Conditions at the Safe Harbor Dam Fish Lift,*" with Larsen and Nguyen, ARL Report No. 1-94/M10F, 1994.

"*Hydraulic Model Study of Powerhouse Intake, Swan Falls,*" with Larsen, ARL Report No. 2-92/M568F, 1992.

"*Hydraulic Model Study Investigation of Flow Patterns in Bellows Falls Forebay to Aid in the Design of Improved Downstream Migration Facilities,*" with Larsen, ARL Report No. 3-91/M14F, 1991.

"*Model Studies of Spillway Rating and Erosion Reduction at Vernon Dam,*" ARL Report No. 14-91/M14F, 1991.

"*Hydraulic Model Study, Conowingo Dam East Fish Passage Facility,*" ARL Report No. 129-89/M10F, 1990.

PROFESSIONAL ACTIVITIES

Member, American Society of Civil Engineers
Member, Boston Society of Civil Engineers Section
Member, Chi Epsilon
Associate Member, Sigma Xi