PSEG Nuclear LLC

Salem Generating Station
NJPDES Permit No. NJ0005622

Custom Requirement G.2.b.ii Fish Return System Evaluations
Section 316(b) Special Condition
Final Report

Prepared for:

PSEG Services Corporation
Estuary Enhancement Program

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Executive Summary

On August 1, 2001, the New Jersey Department of Environmental Protection (NJDEP) issued the five-year New Jersey Pollutant Discharge Elimination System (NJPDES) Permit to PSEG Nuclear, LLC (PSEG) for the Salem Generating Station (Salem or the Station). The Station, located in Salem, New Jersey, is a 2,200-megawatt power plant that draws cooling water from the Delaware River. The NJPDES Permit (Permit number NJ0005622) included conditions relating to wetland restoration, other components of the Estuary Enhancement Program, and the study of fish protection technologies. Custom Requirement G.2.b.ii of the Permit required an evaluation of ways to reduce fish mortality associated with the fish collection pool and the fish return sluice at the Station's Circulating Water Intake Structure (CWIS). Specifically, the G.2.b.ii assessment considered how parameters such as velocities, volumes, and water depths in the fish collection pool and return system may affect fish mortality. In addition, G.2.b.ii required an evaluation of fish mortality independent of the Ristroph traveling screens, *i.e.*, mortality rates of fish re-entering the estuary.

The evaluations included a comprehensive literature review of potential stressors in the fish return/collection systems. This review identified the types and magnitude of stressors found to be injurious to fish. These stressors include shear, abrasion, turbulence, and impact. The literature values were then compared to Computational Fluid Dynamics (CFD) models of the existing Salem fish return system. The facility simulated the end-of-pipe discharge, the return troughs, and the fish collection pools to quantify stressors within these system components. These portions of the fish return/collection system had been previously identified by ESSA Technologies Limited (ESSA) as having potentially injurious hydraulic conditions that could increase fish mortality (ESSA 2000). Although the stressor values calculated for the existing Salem Station CWIS in the CFD analysis were lower than those reported in the literature as being injurious to fish, alternative designs were evaluated to reduce stressors.

Subsequent to the CFD analysis, fish testing facilities of both the end-of-pipe discharge and the fish collection pool were constructed at an offsite laboratory. These facilities were used to evaluate the latent mortality of live fish (alewife and weakfish) under conditions similar to those that exist at the Station. No significant mortalities of test fish were observed after exposure to either the end-of-pipe discharge or fish collection pool hydraulic conditions.

Although not specified in the G.2.b.ii Work Plan, the test facility results for the fish collection pool were subsequently verified by conducting on-site testing of the existing fish collection pool at the Salem Station. Alewives were introduced to the collection pool under both high and low flow conditions (3 or 13 cfs) with two depths of cushion water (25 and 50 cm). The on-site results confirmed the findings of the laboratory study; there is no significant mortality associated with the fish collection pool.

In addition, PSEG conducted additional analyses not included in the work plan of traveling screen spraywash pressures to determine if the wash pressures were contributors to mortality of fish returned to the river. A fully functioning pilot-scale traveling screen was constructed in a laboratory flume. Alewives were introduced to this screen under varying spraywash pressures

(0 to 100 psi) and held for 48 hours. No significant mortality was found to be associated with spraywash pressures up to 100 psi (the maximum pressure in the Station's debris removal system).

These results confirm the Salem Station's fish return system is designed to maximize fish protection potential. While there is some mortality associated with the impingement process, the data clearly demonstrate that the fish collection pools, end-of-pipe discharges, fish/debris return troughs, and spraywash systems are not contributors to this overall impingement mortality. Furthermore, changes to the design or operation of the fish return system would not be expected to improve overall fish survival potential at Salem Station's CWIS.

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Section 1
Introduction

1.1. Background

On August 1, 2001, the New Jersey Department of Environmental Protection (NJDEP) issued a five-year New Jersey Pollutant Discharge Elimination System (NJPDES) Permit to PSEG Nuclear, LLC for the Salem Station (Salem or the Station). The Station, located in Salem, New Jersey, is a 2,200-megawatt power plant that draws cooling water from the Delaware River. The NJPDES Permit (Permit number NJ0005622) included conditions relating to wetland restoration, other components of the Estuary Enhancement Program, and the study of fish protection technologies. The Permit also included provisions concerning biological monitoring, fish ladder construction, and the creation of artificial reef habitats.

The studies reported herein address one portion of Custom Requirement G.2 (G.2) of the Permit. This requirement specifies that PSEG must evaluate potential improvements to the cooling water intake structure (CWIS) that could affect a reduction in impingement mortality. Custom Requirement G.2.b.i requires the submission of a ranking of vulnerability of Representative Important Species (RIS) to impingement mortality to determine for which species the Ristroph screens are most effective at minimizing mortality. Custom Requirement G.2.b.ii (G.2.b.ii) requires an evaluation of ways to reduce fish mortality associated with the fish collection pool and the fish return sluice at Salem. Specifically, the G.2.b.ii assessment considers how parameters such as trough velocities, volumes, and water depths in the fish collection pool and return system may affect fish mortality. In addition, G.2.b.ii requires an evaluation of fish mortality independent of the Ristroph traveling screens, *i.e.*, mortality rates of fish re-entering the estuary. The results of G.2.b.ii evaluations and studies performed by Alden Research Laboratory, Inc. (Alden) and PSEG are detailed in this report.

1.2. Study Objectives

The primary objective of the study program was to identify sources of, and measures that might improve, post-impingement survival in the Salem fish return system. Areas of greatest concern were targeted through the identification and quantification of stressor levels to which fish are exposed as they move through the return system to either the fish collection pool or back into the Delaware River. Stressors are any factors such as turbulence, shear or abrasion that can potentially cause fish injury or mortality.

1.3. Study Approach

The investigation was developed as a two-phase examination of the fish return system to determine if any components of the system were causing fish mortality and if so, to develop alternative designs that would reduce impingement mortality. The Phase 1 system assessment was conducted in several steps:

1) assessment of current hydraulic conditions in the existing fish return/collection system by conducting a site inspection;

2) review of current literature and reports to identify potential stressors and critical thresholds that could cause injury or mortality within the system;

3) development of Computational Fluid Dynamics (CFD) models of the fish return/collection system components to identify potential causes of mortality;

4) development of alternative designs that might reduce stressor levels and subsequent CFD analyses of these alternatives;

5) design (including HEC-RAS modeling[1]) and construction of a test facility that replicates hydraulic conditions experienced by fish in both the existing and proposed alternative fish return/collection systems; and

6) preliminary field testing of the existing fish collection pool design at Salem.

Phase 2 studies would be based on findings from Phase 1, if alternative measures identified in Phase 1 demonstrated meaningful reductions in mortality.

Various analyses and studies of the following fish return and sampling system components were conducted in Phase 1:

- the fish return trough/pipe;
- the sampling pool (fish collection pool or FCP); and
- the return pipe discharge to the Delaware River and potential end-of-pipe (EOP) mortality.

The return system was investigated using a combination of information gathered during a site assessment, gleaned from review of technical drawings and Station documents, identified from the available literature, gathered from CFD and HEC-RAS modeling, and tests conducted using live fish both in the laboratory and during field testing at Salem.

This report presents the findings of the various analyses and studies conducted to identify potential improvements to the Salem fish return and collection systems. Section 2 provides a description of the existing systems at Salem which serve as a baseline upon which improvements could be made. Section 3 presents the literature review, the process by which alternative system designs were selected, and the results of modeling of the existing and alternative designs.

[1] The HEC-RAS (Army Corps of Engineers Hydraulic Engineering Center's River Analysis System computer program) software package performs one-dimensional Steady and Unsteady flow water surface profile calculations. For our analysis, HEC-RAS was used to determine the volume of flow and the trough geometry that would best match hydraulic conditions present in the end-of-pipe and fish collection pool sections of the fish return system at Salem.

Section 2
Description of Existing Fish Return System

During a December 9, 1999 site visit personnel from ESSA Technologies Limited (ESSA) examined the fish return system at Salem as part of the NJPDES permitting process. As part of a final report submitted to the NJDEP on June 14, 2000, ESSA identified portions of the fish return system as potentially causing fish mortality (ESSA 2000). In the report they state:

> "It is possible that the mortality rates measured using the sampling pool overestimate actual impingement mortality. It is also possible that actual mortality rates of fish after returning to the Delaware River are equivalent or even higher than those estimated via the sampling pool. Actual impingement mortality could be higher due to physical trauma caused by high water velocity in the sluice combined with the physical trauma that must occur when fish and debris abruptly hit the surface of the river. Because the sluice is open and above the river surface, fish and debris must hit the water abruptly as opposed to entering the river below the surface. Predation by fish and water foul of fish potentially stunned by their return to the river could be high. Thus, it is judged that the mortality of impinged fish returning to the Delaware River is likely not accurately described by the mortality estimates determined with the sampling pool and holding tanks."

They also stated:

> "We became concerned about fish survival in the trough after observing the system during our December 9 site visit…Another unknown is the mortality rate for fish as they enter the estuary from the fish return trough (see also Section 2.2). It is probable that mortality occurs during this passage and it will likely be species specific. According to the literature, fish survival through a transport system with flow exceeding 1 m/s tends to be species specific, with robust species such as American eels (*Anguilla americana*) (Patrick and Sim 1985, McKinley and Patrick 1987) and rainbow trout (*Salmo gairdneri*) experiencing very low mortality (<5%), whereas other species such as yellow perch (*Perca flavescens*) and alewife (*Alosa pseudoharengus*) tend to suffer considerable higher (up to 28%) mortality. Such species specific mortality should be expected at Salem GS [generating station] in its fish return system. Furthermore, Fletcher's (1990) paper on Ristroph screens also indicates a species specific mortality rate. Fish mortality associated with the fish return system should be evaluated independently from the Ristroph Screens to determine mortality rate as fish enter the estuary. Emphasis should be placed on reducing potential mortality of susceptible species."

It was with these comments in mind that the existing fish return system at Salem was examined for potential stressors.

As a first step toward assessing potential stressors within the Salem fish return system, design and operational information on the circulating water intake traveling screen spraywash, fish collection, and return systems was gathered and reviewed. Stressors are factors that may cause injury or mortality to fish as they pass through these systems. The physical parameters of the in-place design needed to be verified and the hydraulic conditions that exist in the system also needed to be documented. To gather this information, a site assessment was conducted by Alden and PSEG personnel in February, 2002. The information collected provided critical input to the modeling efforts and structural data that was needed to effectively evaluate potential alternative system designs.

The Existing System

The existing intake at Salem is comprised of two primary components, the traveling water screens that collect fish and debris from incoming water, and the fish return system that returns collected fish and debris back to the Delaware River. The following is a description of system components and the path that incoming fish and debris follow as they move through the system. Portions of the description are taken from PSE&G (1999) NJPDES Permit renewal application – Attachment G-1.

Incoming water

Salem has two generating units. Each unit withdraws cooling water from the Delaware River through six intake bays. At full operation, the pump in each bay withdraws water at the rate of approximately 175,000 gallons per minute (gpm). Each intake bay is 11 ft wide and 50 ft high and is equipped with two sets of screening devices – a trashrack system for preventing large debris and aquatic organisms from entering the intake and a traveling water screen designed to remove smaller organisms and debris from incoming water. Organisms or debris that pass through the 3 inch clear space trashrack encounter the traveling water screen.

Traveling Water Screens

Each screen consists of 62 screen panels, which are 10 ft wide by 21 in. high (Figure 1). The screens rotate at four speeds; 6, 12, 17.5, and 35 ft per minute. The screen speed is adjusted upward automatically, as the differential pressure across the screens increases. As the screen rotates, screen panels move up and over the head sprocket and down the back of the screen (Figure 2). The baskets are made of a nonmetallic composite material with ¼ x ½ inch Smooth-Tex® wire mesh and a fish bucket at the bottom of the panel. The Smooth-Tex® was put in place to minimize scale loss and abrasion that was common with earlier types of screening material. The bucket is designed to minimize turbulence that can cause damage to fish (Figure 3). A flow spoiler along the front edge creates an area of stalled fluid where the fish can remain submerged as the screen rotates upward.

Figure 1. A replacement traveling screen at Salem Station awaiting installation.

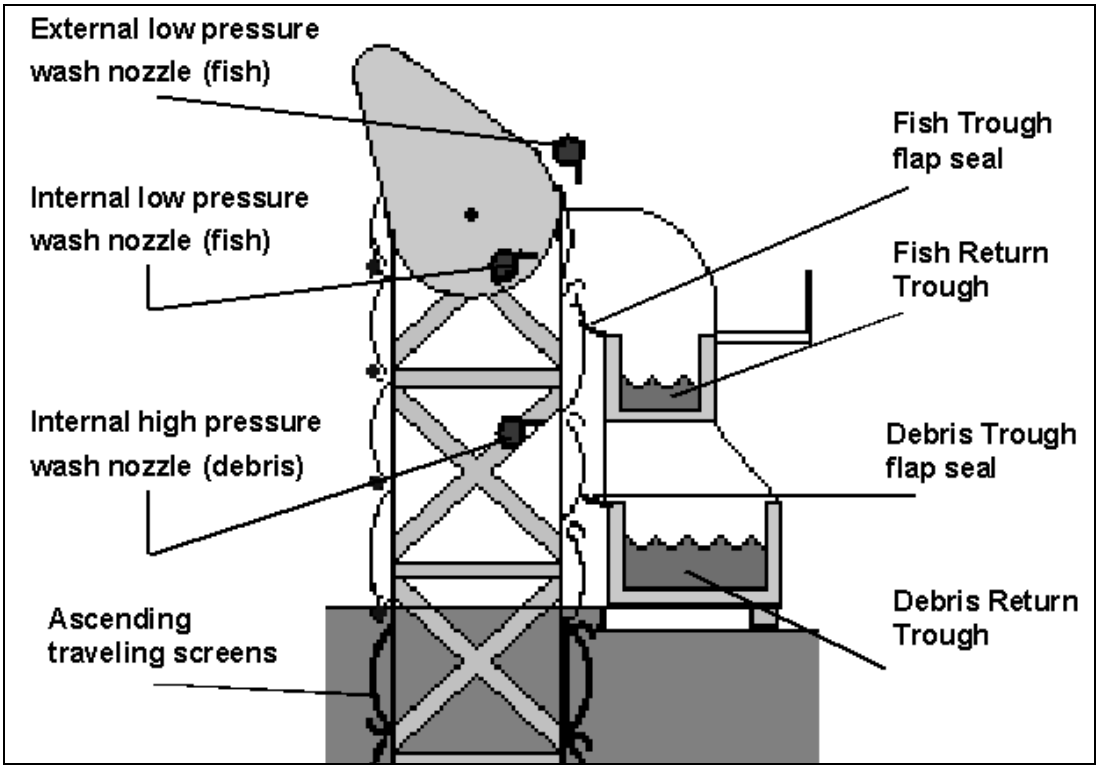


Figure 2. A centerline schematic of a traveling water screen. Flow is from left to right.

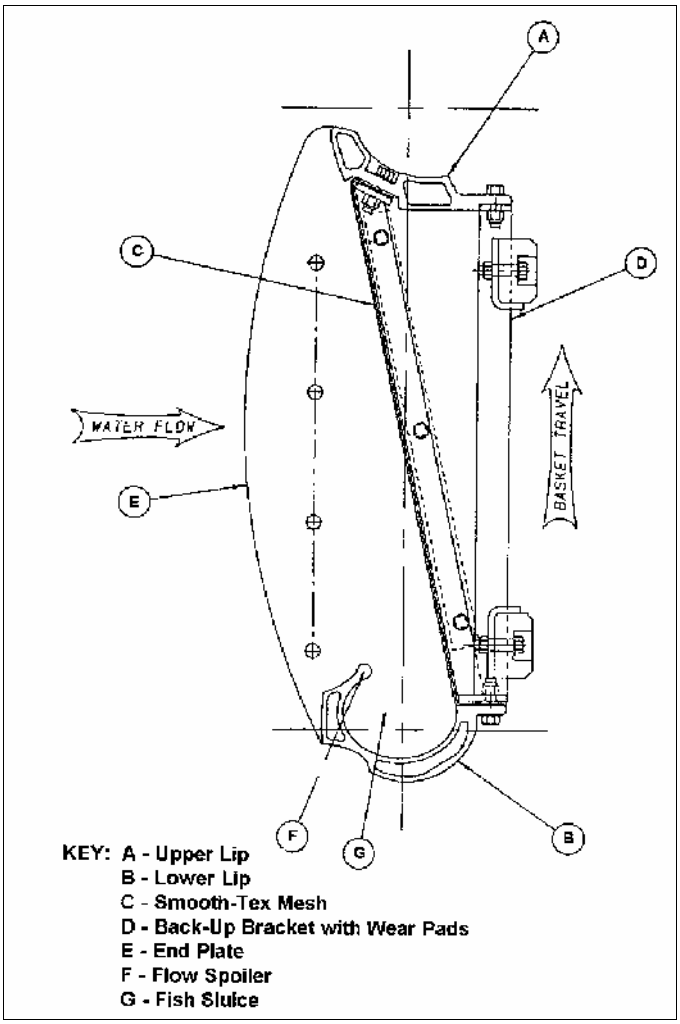


Figure 3. Example of a traveling water screen basket modified to reduce turbulence and reduce abrasion damage (EPRI 1999)

Once the basket has ascended past the head sprocket, it is exposed to the two spraywash systems – the fish spraywash and the debris spraywash. The upper system, the fish spraywash, consists of three spray headers, two mounted internally between the ascending and descending screen faces and one mounted outside washing downward (Figure 4). The fish spraywash system operates at low pressures (5-20 psi) and is designed to gently wash fish from the screens, past a flap seal, and into the fish return trough. The flap seal is an angled rubber edged seal that extends parallel to the lip of the passing basket. It is designed to prevent fish from dropping through the gap between the screens and the fish return trough. Fish that slip between the flap seal and the descending screen are exposed to the high-pressure debris spraywash system. The debris spraywash has two spray headers located between the ascending and descending screen faces. The system operates at high pressures (80-120 psi) and is designed to prevent clogging by removing debris adhering to the descending baskets. The debris trough is also fitted with a flap seal to shunt falling debris and organisms into the debris return trough. Each trough is fitted with a housing, designed to contain spraying water, debris and fish within the trough (Figure 5).

Figure 4. External low pressure spraywash header for the fish return trough at Salem.

Located immediately above the debris trough, the fish trough is constructed of fiberglass and is 30 in. wide by 18 in. deep. The debris trough is constructed of epoxy lined concrete. As the two troughs exit the screenhouse, the fish trough slopes downward and the two flows join forming a combined "return" trough. Water depths and velocities were measured in the fish and debris troughs during the site assessment. Fish trough depths/velocities ranged from 9 in. / 0.2 ft/sec at the upstream end of the trough to 5.5 in. / 3.1 ft/sec as the water exited the screenhouse. Debris trough depths/velocities ranged from 7.25 in. / 3.5 ft/sec to 14 in. /0.25 ft/sec. Flow measurements taken during the assessment indicated that the fish return trough flow was 3 cubic feet per second (cfs) exiting the screen house. Flow from the debris trough was 8.5 cfs. Of the 12 traveling water screens at Salem, 11 were in operation at the time of the assessment. The total projected flow for 12 screens in operation is 3.25 cfs for the fish return trough and 9.2 cfs for the debris trough.

The return system at Salem is bi-directional. By opening and closing sets of fiberglass gates, flow can be shunted to either the North or South return system. This design allows the operators to return fish and debris to the River in the direction of the tidal current so fish and debris will be moved away from the intake. The system helps reduce the possibility of re-impingement of discharged material.

Figure 5. Fish return and debris return troughs covered by housings.

The two return systems differ in their exact configuration but they have similar components. Shared features are described below. Elevations and angles of the individual return systems are illustrated on Figure 6 (North end) and Figure 7 (South end).

Water leaves the screenhouse from either the upper (fish) or lower (debris) trough. After exiting the screenhouse, the fiberglass fish trough angles downward to meet the debris trough and the flows combine into a single return trough (Figure 8). The return trough continues into a sampling building (one building on each end of the CWIS). Within the building, water can be diverted into a collection pool via a swing gate (sampling gate) or passed down the return trough and into a more steeply sloped return pipe to the River. There are minor realignments of the return troughs as they extend through the sampling buildings before passing through the sheetpile bulkhead, and transitioning back to the river.

The fish collection system within each building consists of four major components, a sampling gate (Figure 9), a spoon shaped discharge trough (Figure 10), the fish collection pool (Figure 11), and a double screen system designed to release flow while retaining organisms and debris. Impingement abundance and survival samples are collected by diverting flow into the collection pool via the sampling gate.

Sampled flows impact against the gate, turn sharply into the sampling trough, and move down into the spoon shaped terminus (spoon) before spilling into the fish collection pool. The sampling gate crosses the return trough at a 30 degree angle and the spoon portion of the sampling trough is 7 ft long and drops 5.5 ft to the concrete floor of the fish collection pool (Figure 10). The sampling gate, the spoon and the floor/screen within the fish collection pool were identified as being potentially injurious to fish because of the perceived high water velocities and turbulent flows (ESSA 2000).

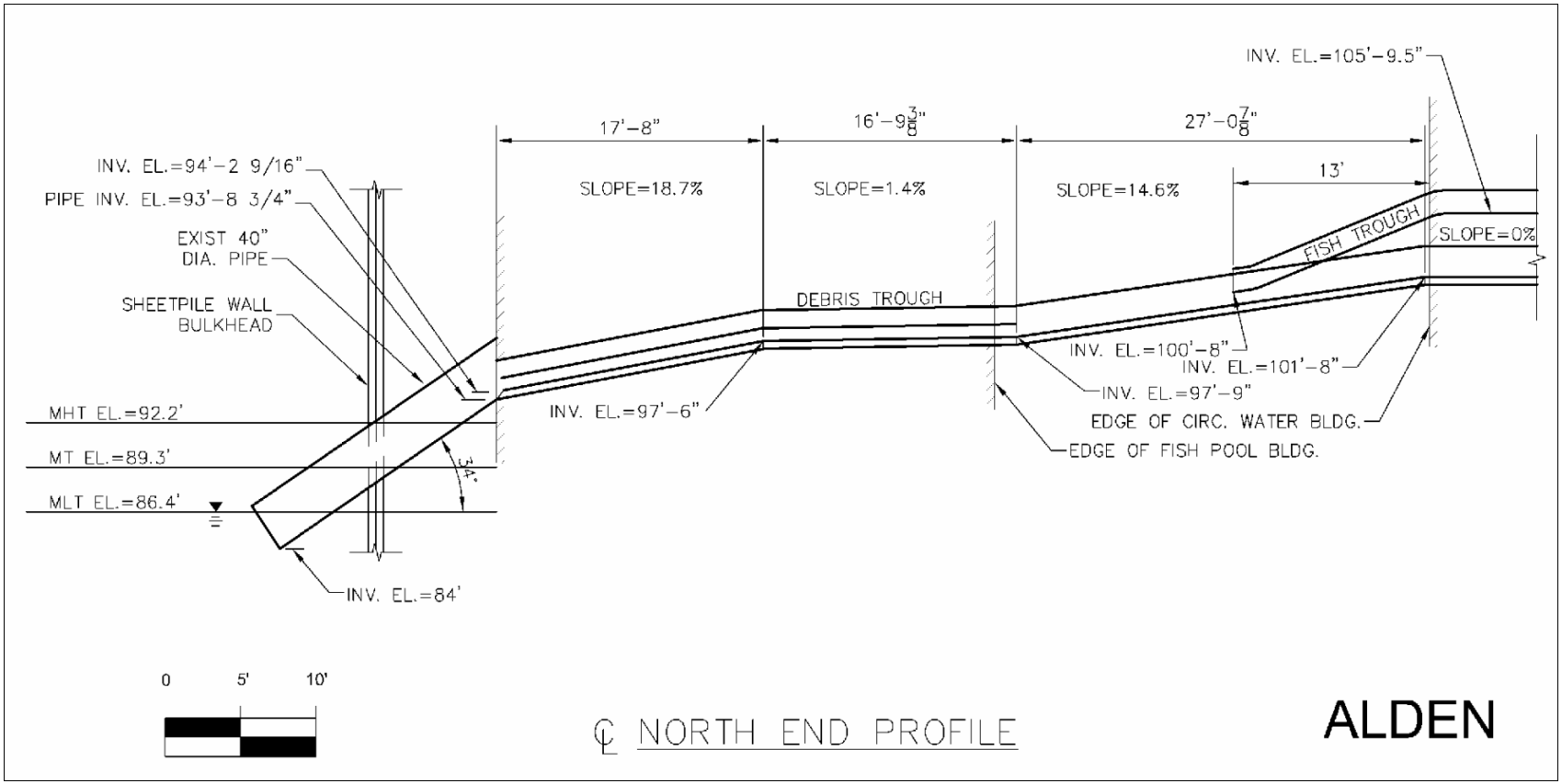


Figure 6. The existing North fish return system at Salem.

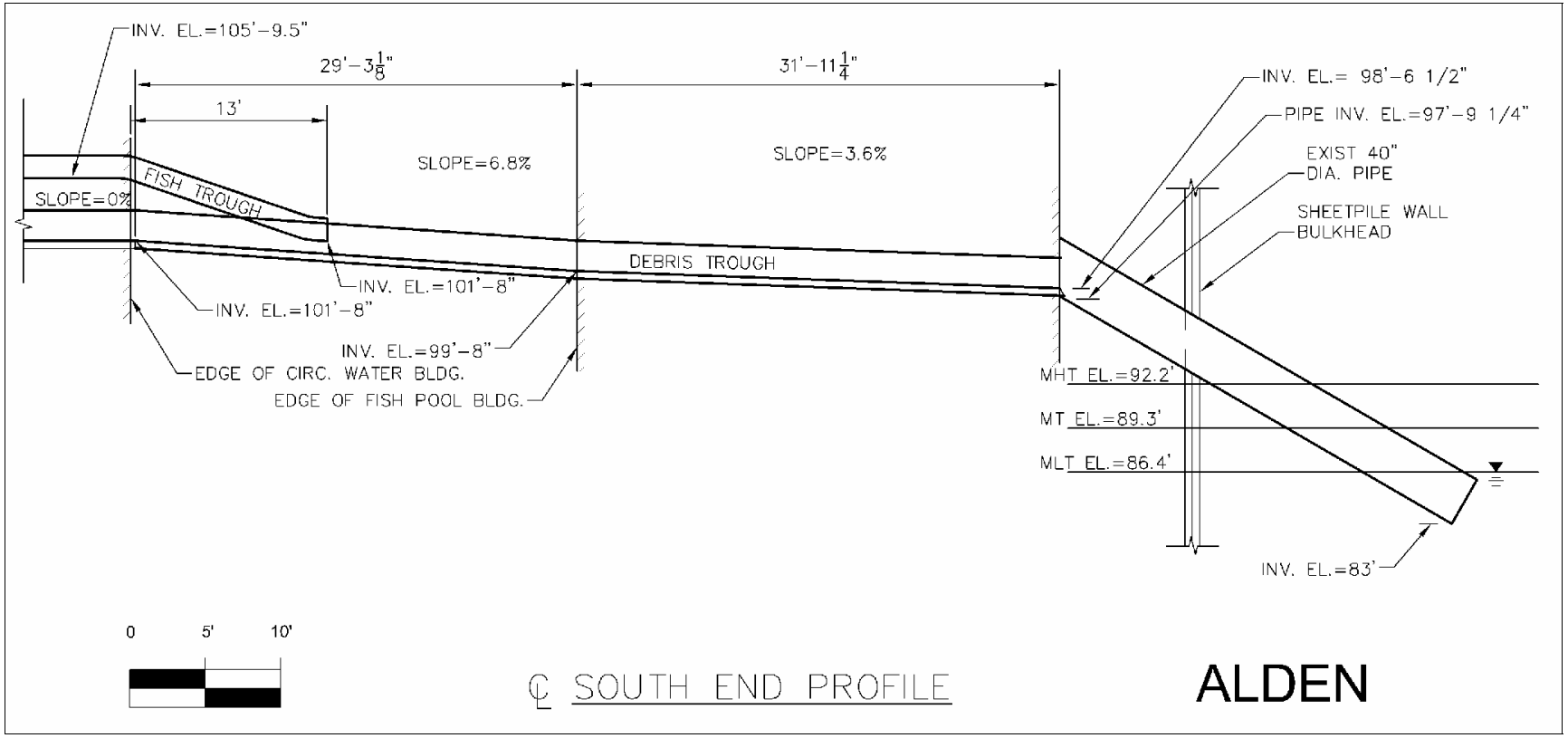


Figure 7. The existing South fish return system at Salem.

Figure 8. Confluence of the fish and debris return troughs - North end, Salem Station.

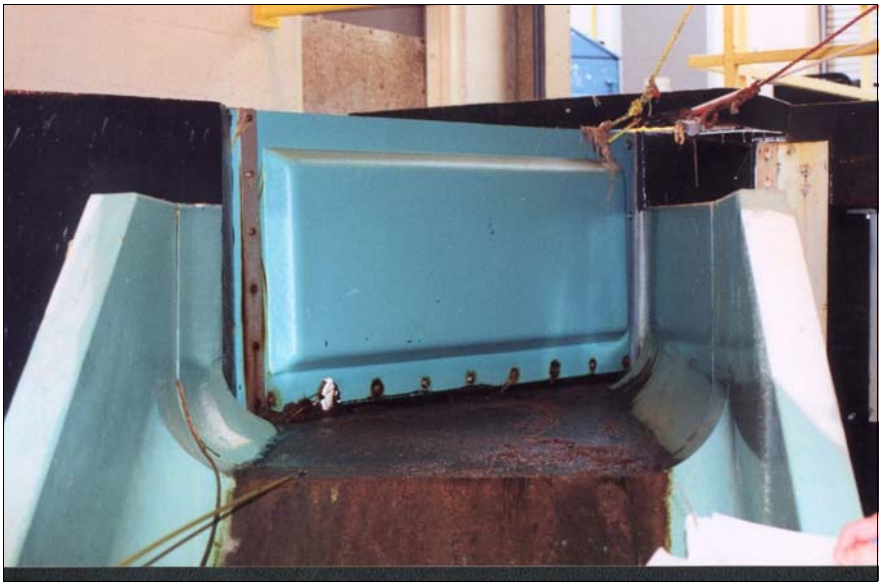


Figure 9. Sampling gate in the North fish collection pool.

Figure 10. Spoon portion of the collection pool discharge trough.

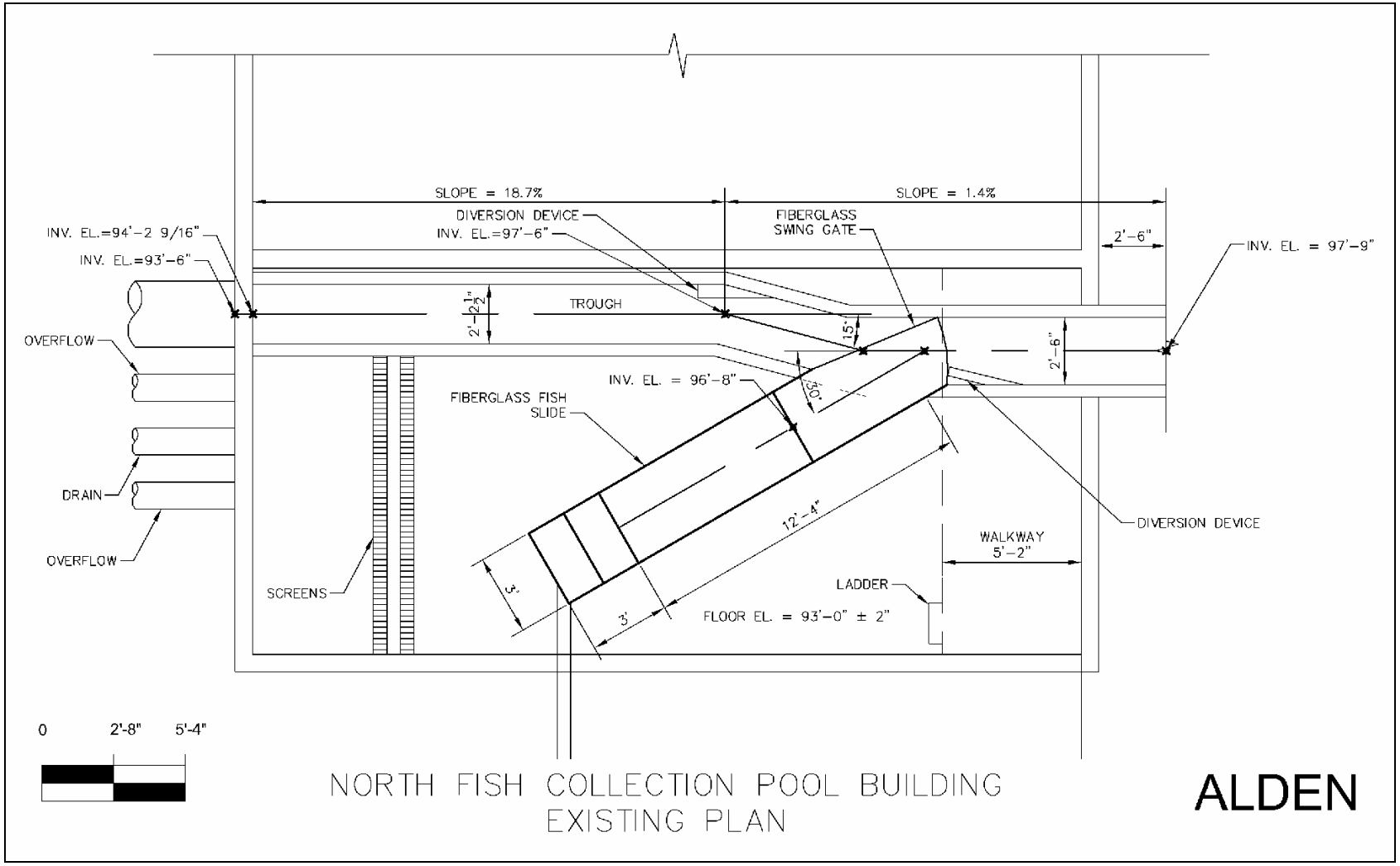


Figure 11. Plan of North end fish collection pool.

Flow returning to the river via the return trough transitions into a more steeply pitched 40 in. diameter pipe (end-of-pipe or EOP). As the flow enters the pipe, it detaches from the trough bottom and arcs downward before reattaching and entering a turbulent zone (referred to as a hydraulic jump). The end of the pipe is either partially or fully submerged when discharging.

The site assessment examined both the North and South fish return and sampling systems for system-specific differences in each system component in water depths; flows; and velocities. In addition, the following information was reviewed for the fish return system (Table 1) and the fish collection pool (Table 2)

Table 1. Fish return system information (both North and South end systems).

Design	Operations	Hydraulic
Fish and debris trough dimensions, elevations, lengths and slopes, including flap seals Discharge pipe materials, dimensions, lengths and slope Security issues, condition of all components (*e.g.*, spalling of concrete, rusting of steel and other roughness factors that could influence the coefficient of friction), identification of all design features for validation of station drawings	Design water flow rates in fish, debris and combined troughs (based on spraywash volume)	Actual flow rates through the entire system, water depths and velocities in all trough and pipe sections, presence of hydraulic jumps, visible flow features at pipe discharges over the tidal cycle

Table 2. Fish collection/collection system information (both North and South systems were reviewed).

Design	Operations	Hydraulic
Inlet trough and sampling pool materials, dimensions, elevations, lengths and slopes, condition of all components (*e.g.*, spalling of concrete, rusting of steel), identification of all structures in the sampling pool for validation of station drawings	Design water flow rates in the sampling trough, normal sampling procedures Seasonal variations in procedures and reasons for them (*e.g.*, heavy debris loading), constraints on normal operations, if any	Actual flow rate entering the sampling pool water depths and velocities in the sampling trough section, visible flow features in the sampling pool over a complete sampling period, identification of hydraulic conditions (turbulence, impact) that may result in fish injury

Section 3
Literature Review and Selection of Alternative Fish Collection and Return Configurations

With a thorough understanding of the design and operation of the existing fish return and collection systems at Salem, it was possible to identify potential areas of injury and mortality within the systems, to identify specific stressors that might cause such effects, and to determine, based on the available literature, if the stressor levels at Salem exceed the levels reported to be non-injurious to fish. To assist in the identification of stressor levels, CFD analyses of portions of the existing fish return system and fish collection pool were conducted. On the basis of the literature review and CFD analyses, it was concluded that the existing systems at Salem do not create stressor conditions that are injurious to fish. Nonetheless, alternative designs were evaluated to determine if the low stressor levels in the existing systems might be reduced even further. Subsequently, a CFD analysis of the alternative designs was performed for comparison to the baseline design. The results of these efforts are presented Section 3.3.

3.1. Literature Review

A review of literature was conducted to identify specific stressors to fish that may be present within the existing Salem CWIS fish collection and return system and to quantify the impact to fish of each potential stressor. Whenever possible, quantifiable units for reporting stressor levels (such as turbulence, shear, and abrasion) were identified. To the extent possible, acceptable ranges for safe fish movement or upper/lower thresholds were developed. In addition, stressor thresholds identified during the literature review were compared to the values calculated from the existing Salem CWIS fish return system (measurements taken during site visit, HEC-RAS analysis, and CFD analyses) and thus determined the extent to which the existing components of the fish return and collection systems potentially impact fish survival.

A cursory review of recent and ongoing research indicated the following as key stressors associated with fish mortality in fish conveyance systems: pressure; impact and abrasion; turbulence and shear; and velocity. As such, these were used as key terms in an electronic literature search utilizing several reference databases including: Applied Science and Technology Index; Aquatic Sciences and Fisheries Abstracts; Biological Abstracts; Digital Dissertations; IDEAL; JSTOR; Science Citation Index; and Web of Science. In addition, resources available through the World Wide Web were searched via the Google search engine. Government and university reference libraries, as well as the Alden's in-house library, were searched for documents and publications detailing fish stressors at both CWISs and other facilities. To the extent possible, relevant "gray literature" were obtained.

Much of the available literature on stressors of fish is based on observations of fish that have interacted with man-made structures (*e.g.*, fish return system, hydroelectric project spillway, hydro turbine). Fish may be exposed to several different stressors during their exposure to such structures. When injury occurs under complex flow situations, as is common in fish conveyances, it can be difficult to determine which stressor caused the injury. Similar types of injury can be caused by different stressors (Table 3).

Table 3. Primary injuries observed during laboratory studies of pressure, shear, and strike (from Turnpenny et al. 1992).

Observed Injury	Source of Injury		
	Pressure	Shear	Strike/Impact
Ruptured swim bladder	Yes	No	No
Eye hemorrhaging	Yes	Yes	No
Scale loss	No	Yes	Yes
Mucous loss	No	Yes	Yes
Internal hemorrhaging	No	Yes	Yes
Egg loss	Yes	No	No
Gill/Operculum damage	No	Yes	No

The situation is further complicated by the relationship between stressors and/or other physical forces. For example, velocity, which is not a stressor in and of itself, plays a role in the magnitude of shear forces and turbulence. Likewise, the potential for impact injury is related to the velocity of the fish at the time of impact.

Fish response to stressors is species- and life stage-specific. For example, studies by Grasser et al. (1979) indicated that fish larvae were injured passing over a relatively low dam (3.1-m high). Several other studies indicate that later life stages (juvenile and adult) show no adverse effects after passage over dams of similar height. In addition, species-specific differences in mortality were observed, with filiform shad larvae experiencing greater damage than the more robust catastomid larvae. Much of the available data on fish response following exposure to stressors is for salmonids and thus the applicability to Salem is unknown.

3.1.1.1. Reviews and Guidelines

Guidelines for the fish conveyances and other fish handling systems (fish return systems, fish bypasses, spillways, intakes, fish screens, etc.), have been developed by federal, state and professional organizations (*e.g.,* American Society of Civil Engineers, National Marine Fisheries Service, U.S. Fish and Wildlife Service, Canadian Department of Fisheries and Oceans). These guidelines were developed through an understanding of the hydraulic conditions likely to produce fish injury and how to avoid them, common sense, and the best professional judgment of fish passage experts. While guidelines do not specifically address individual stressors, they do provide criteria for the design of fish-friendly passage.

With all guidelines, site-specific factors will dictate the applicability of any one of the criteria. Reviews of factors influencing fish return system design led to the development of criteria for sluiceway and pipeline design (Table 4; ASCE 1982) and are the most relevant to the fish return system at Salem. In general, the goal of the ASCE guidelines is to create conditions that allow for efficient and safe transport of fish back to their natural environment.

Table 4. Criteria for the design of fish conveyance structures (modified from ASCE 1982).

Criteria	Stressor(s)
All surfaces of conveyance structures must be smooth to prevent abrasion to fish. Suitable materials include fiberglass, polyethylene or coated steel to prevent injury to fish.	Abrasion
The system size must be based on the number and size of fish. Use a minimum water depth of 6 in. (15.2 cm), minimum width 18 in. (45.7 cm). Appropriate free board must be provided based on the jumping capability of the strongest fish to be transported.	Abrasion and impact. Maximizes the number of fish returned to water body
Transport velocities must be larger than the sustained cruising speed of the fish, often 2 to 4 fps (0.61 to 1.22 m/sec).	Limits physiological exhaustion to fish
Materials used for the structures must minimize biofouling.	Abrasion and reduction in impediments to fish movement
Long radius (r/d > 2.5) bends must be provided so that fish do not abrade on the sides of the bend.	Abrasion
Pipe joints must be constructed carefully so that all edges match and there are no jagged protuberances.	Abrasion and impact
Valves, meters, etc. must provide clear passage for the fish and create as little obstruction as possible.	Impact and reduction in impediments to fish movement
All transitions must be gradual to prevent flow separation and rapid changes in velocity.	Shear and turbulence
Smooth transitions must be provided where flow from several pipes or channels combine.	Abrasion and impact
In Northern latitudes, above ground sluiceways or pipes must be protected from freezing. Buried pipes must be located below the frost depth.	Impact and reduction in impediments to fish movement
Velocity control weirs must have drainage orifices to reduce entrapment of fish and debris when the water supply is shut down for cleaning screens. The sluiceway must completely drain following shut down.	Minimize stranding fish

3.1.1.2. Pressure

Fish responses to both pressure increases (multiple atmospheres) and exposure to partial vacuum (*i.e.,* pressure below 1 atmosphere) have been observed. Research on pressure has been conducted under both laboratory and field conditions. Because observations of fish injury under field conditions are complicated by the presence of multiple stressors and the difficulty in determining the source of injury, laboratory studies are better suited to the study the effects of an isolated stressor. Pressure changes occurring within cooling water intakes and fish return systems are dependant on the intake flow, depth of the intake, and the path that fish take as they are returned to the water body.

The body of research concerning pressure effects indicates that fish are generally more sensitive to pressure drops than to increases (Cada 1990). Studies by Cada (1997), Cook et al. (1996), and Abernethy et al. (2001) each suggest that subatmospheric pressures can be harmful to fish,

particularly if they are either physoclistous (having no direct airway between the swim bladder and the gut) and/or acclimated to higher pressures (*i.e.,* deep water habitats). The authors differ in their suggested maximum percent drop in pressure before swim bladder rupture (60%, 30%, and 10% of acclimated pressure levels respectively). However, they agree that there are species- and family-specific factors that should be taken into account when determining the effect of pressure decreases on entrained fish and all agree that limiting those decreases will help prevent injury.

The effect of pressure change on fish varies by species and life stage. In general, the physiology of the swim bladder and associated venting mechanism will determine the relative susceptibility of each species to pressure changes. Physostomous fish (*e.g.,* most soft-rayed fishes like salmon, trout, catfish, minnows, shad, and gar) have a pneumatic duct that connects the swim bladder directly to the gut. These fish are able to shunt air via the pneumatic duct to and from their air bladders. Because of this adaptation, physostomous fish can quickly expel excess gas and are thus more resilient to large pressure decreases. Physoclists (*e.g.,* most spiny-rayed fishes such as perch, bass, and bluegill sunfish) have no mechanism for rapid release of air from the swim bladder and so are more susceptible to swim bladder damage when exposed to sub-atmospheric pressures. Under normal conditions, physoclists move oxygen into their swim bladder via a rete mirabile system (highly vascularized countercurrent mechanism whereby oxygen is diffused from the blood across a membrane into the swim bladder). Equalizing internal and external pressures via the rete mirabile system may take hours depending on the pressures and volumes to be equalized.

The effect of pressure changes on fish can vary by life stages. Fish eggs and newly hatched larvae do not have swim bladders making them less susceptible to damage caused by brief drops in pressure (Cada 1990). In addition, some fish that are physoclists as adults have a physostomous larval stage that may be less impacted by pressure than adult life stages, including striped bass (Hadley et al. 1987 in Cada 1990).

Several studies have been conducted to assess the effects of pressure on the early life stages of fish. A summary of these studies is provided in Table 5 .

Table 5. Survival of the early life stages of several species of fish exposed to pressure change.

Species	Life Stage – Average Size	Pressure Exposure	Survival	Reference
striped bass (*Morone saxatilis*)	Eggs and larvae	Exposure to 0.4 atm Exposure to 0.14 atm – back to atmospheric – pressurized to 3.3 atm	No significant mortalities for either scenario	Beck et al. (1975) in Keevin et al. (2000)
Atlantic herring (*Clupea harengus*)	Larvae & Early Juveniles 11-39 mm	Rapid increase from 1 atm to 5 atm and quickly back to 1 atm	11-20 mm fish had no increased mortality 25-29 mm exhibited increased mortality over controls 30-39 mm fish had no increased mortality	Hoss and Blaxter (1979) in Keevin et al. (2000)
Atlantic herring (*Clupea harengus*)	Juvenile 120-150 mm	Rapid increase in pressure from 1 atm to 3 atm	Resulted in rupture of pro-otic membrane. Smaller juveniles and larvae were less at risk	Hoss and Blaxter (1979) in Keevin et al. (2000)
Herring	6-8 mm larvae without bulla or swim bladder	Exposure to 5 atm followed by decompression	Not harmed	Bishai (1961) in Keevin et al. (2000)
bluegill (*Lepomis machrochirus*)	Larvae	Exposed to turbulence, shear and pressures from ~2 atm to 0.5 atm in simulated power plant condenser tube	Little or no mortality was observed	Kedl and Coutant (1976) in Keevin et al. (2000)
common carp (*Cyprinus carpio*)	Larvae			
white bass (*Morone chrysops*)	Larvae			
striped bass (*Morone saxatilis*)	Larvae			

Species	Life Stage – Average Size	Pressure Exposure	Survival	Reference
common carp (*Cyprinus carpio*)	Larvae	Exposed to pressures as low as 0.5 atm in simulated power plant condenser tube	No harmful effects	Ginn et al. (1978) in Keevin et al. (2000)

Recently, the effects of pressure on the early life stages of bigmouth buffalo (*Ictiobus cyprinellus*), blue catfish (*Ictalurus furcatus*), bluegill (*Lepomis macrochirus*), largemouth bass (*Micropterus salmoides*), and walleye (*Stizostedion vitreum*) were evaluated to determine the potential impact to eggs and larvae (Keevin et al. 2000). A pressure vessel was used to simulate pressure changes resulting from water column mixing. Fish were subjected to one of three experimental treatments: 1) Pressure gradually raised to 4.4 atm over 1 h, held for 30 min, returned to 1 atm in 5 seconds; 2) Pressure raised to 4.4 atm within 5 seconds, held for 10 min, and returned to 1 atm in 5 seconds; and 3) Pressure raised to 4.4 atm within 5, held for 30 min, and returned to 1 atm in 5 seconds. For each group of experimental treatment fish, a control group was used to estimate mortality associated with handling and exposure to pressure vessel. Very little mortality was observed for any of the treatments and no significant difference was detected between treatment and control groups.

The effects of pressure on adult fish have been studied extensively. The species tested and the exact test protocols used to examine pressure effects on adult fish vary between studies, but generally one of the following three scenarios were used:

- surface acclimated fish were exposed to sub-atmospheric pressures;
- surface acclimated fish were pressurized for a length of time then exposed to sub-atmospheric pressures; or
- deep water (*i.e.,* higher pressure) acclimated fish were exposed to subatmospheric pressures.

Since many of these studies were conducted to mimic site specific conditions, the length of time that fish were pressurized or depressurized and the magnitude of the pressure change often were set to represent best and worst case scenarios at that site. A summary of several pressure related investigations are presented in Table 6 through 9. Whenever possible the following information is given: species tested; pressures to which fish were exposed or the proportional increases and decreases in pressure; type of injury sustained; and survival.

Table 6. Critical pressure drop percentages by species.

Species/Family	Critical Pressures	Effect	Reference
perch	exposed to 60% of acclimated pressure or lower	Swim bladder rupture	Jones (1951) in Cada (1997)
bluegill	exposed to 10% of acclimated pressure or lower	Swim bladder rupture	Abernethy et al. (2001)

Table 7. Swim bladder rupture pressures and estimated volume expansion required for rupture (Turnpenny 1992).

Species	Number Tested (*n*)	Acclimation Pressure (atm)	Rupture Pressure (atm)	Volume Expansion for Rupture (%)
pout (*Trisopterus luscus*)	14	1.3	0.6 +/- 0.1	203
whiting (*Merlangius merlangus*)	10	1.3	0.5 +/- 0.1	250
bass (*Dicentrarchus labrax*)	12	1.3	0.6 +/- 0.1	215
sand smelt (*Atherina boyeri*)	8	1.0	0.6 +/- 0.1	163
brown trout (*Salmo trutta*)	18	1.0	No rupture*	n/a
herring (*Clupea harengus*)	20	1.0	No rupture*	n/a

* tested to 0.2 atm: gas venting prevented rupture
n/a = not applicable

Table 8. Swim bladder damage and survival of fish exposed to varying pressures (Turnpenny 1992).

Species	Exposure	Results	Notes
Atlantic salmon (*Salmo salar*)	Brought from 3.9 to 0.1 atm	10%-30% swim bladder rupture	7-day overall survival 90%
European eel (*Anguilla anguilla*)	Tested down to 0.1 atm	No ruptured swim bladder evident	7-day survival 100%. Freshwater phase eels maintain a reduced volume of air in their swim bladders so damage due to pressure reductions is unlikely for this life stage
sole (*Solea solea*)	Tested down to 0.1 atm	No adverse reaction	7-day survival 100%. Sole are benthic and possess no swim bladder. No damage of any type was observed as a result of pressure changes
bass (*Dicentrarchus labrax*)	Tested down to 0.1 atm	15% swim bladder rupture at 0.3 atm, 94% rupture at 0.1 atm	No mortalities occurred despite damage to swim bladders
dragonet (*Callionymus lyra*)	Tested down to 0.1 atm	100% swim bladder rupture at 0.1 atm, 0% at 0.3 atm	7-day survival 86%
corkwing wrasse (*Crenilabrus melops*)	Small group tested down to 0.1 atm	No immediate swim bladder damage evident	Only 5 fish were tested and they were immediately sacrificed to check for damage -No 7-day survival data were available
golden grey mullet (*Liza aurata*)	Tested down to 0.1 atm	79% swim bladder rupture at 0.1 atm, 0% at 0.3 atm	Fish exposed to 0.1 atm had 60% 7-day survival

Table 9. Mortality of fish exposed to rapid and brief pressure reductions in laboratory test chambers (modified from Cada et al. 1997; Turnpenny 1992).

Species	Acclimation pressure, P_a (atm)	Exposure pressure, P_e (atm)	P_e / P_a	Mortality (%)	Source
sockeye salmon	1.0	0.7	0.7	0.0	Harvey (1963)
sockeye salmon	3.4	1.0	0.3	0.5	Harvey (1963)
sockeye salmon	1.0	0.7	0.7	2.0	Harvey (1963)
sockeye salmon	2.0	0.7	0.4	21.0	Harvey (1963)
perch	3.0	1.0	0.3	70.0	Tsvetkov et al. (1972)
largemouth bass	1.0	1.0	1.0	0.0	Feathers and Knable (1983)
largemouth bass	1.9	1.0	0.5	25.0	Feathers and Knable (1983)
largemouth bass	3.6	1.0	0.3	41.7	Feathers and Knable (1983)
largemouth bass	3.6	1.0	0.3	45.8	Feathers and Knable (1983)
bluegill	1.0	0.2	0.2	33.0	Hogan (1941)
bluegill	1.0	0.2	0.2	50.0	Hogan (1941)
crappie	1.0	0.4	0.4	100.0	Hogan (1941)
crappie	1.0	0.2	0.2	50.0	Hogan (1941)
largemouth bass	1.0	0.2	0.2	80.0	Hogan (1941)

Species	Acclimation pressure, P_a (atm)	Exposure pressure, P_e (atm)	P_e / P_a	Mortality (%)	Source
largemouth bass	1.0	0.2	0.2	100.0	Hogan (1941)
largemouth bass	1.0	0.2	0.2	50.0	Hogan (1941)
Atlantic salmon, brown trout, rainbow trout	1.0	0.1	0.1	0.0	Turnpenny et al. (1992)
brown trout	3.4	0.3	0.1	10.0	Turnpenny et al. (1992)
rainbow trout	3.4	0.3	0.1	0.0	Turnpenny et al. (1992)
herring	3.4	0.3	0.1	4.0	Turnpenny et al. (1992)
coho salmon	1.0	0.1	0.1	0.0	Muir (1959)
coho salmon	1.0	0.1	0.1	10.0	Muir (1959)

In addition to the potential for physiological damage as a result of exposure to changes in pressure, secondary effects, such as gas bubble trauma (GBT), may also occur. Recently, survival studies were conducted at the Pacific Northwest National Laboratory with bluegill, chinook salmon and rainbow trout examined the occurrence of GBT and the role of pressure changes in the survival of fish acclimated to different water depths (Abernethy et al. 2001). GBT can occur when fish are exposed to high-pressure systems that allow water to become supersaturated with dissolved gasses (120% or greater); a condition unlikely to occur within a fish return system. Results indicated that there were species-specific differences in measured tolerances to both GBT and pressure changes. Bluegill were least affected by GBT followed by chinook salmon and rainbow trout. However, bluegill were extremely susceptible to swim bladder rupture from pressure drops that had a nadir of 0.1 atm. Chinook salmon experienced burst swim bladders when acclimated to 1.9 atm prior to testing, but rainbow trout did not exhibit burst swim bladders regardless of total dissolved gasses or acclimation pressure (Abernethy et al. 2001).

Fish acclimated to deeper waters are more susceptible to injury and mortality caused by pressure reductions (Abernethy et al. 2001). Physostomes, while less likely to be injured by swim bladder

rupture during a low pressure event, are susceptible to embolism from gasses dissolved in their blood and tissues, particularly when they are acclimated to deeper water habitats. Differential mortality rates experienced by salmonids acclimated to varying pressures are given in Figure 12. Note that as pressure drops, mortality increases relative to initial acclimation depth (USACE 1991).

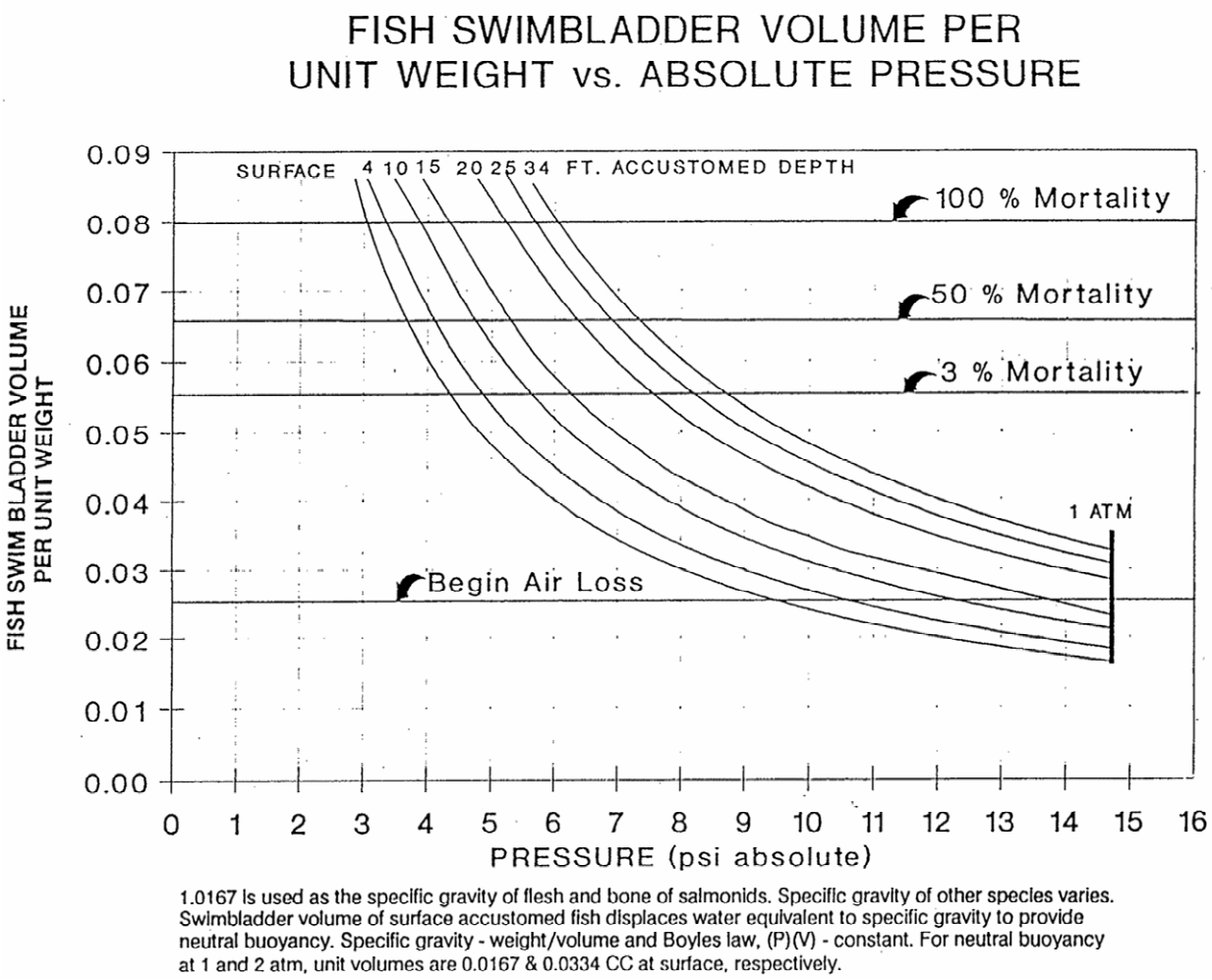


Figure 12. Differential survival of salmonids acclimated to different depths/pressures (USACE 1991).

One approach to determine the potential effect of a stressor on the survival of a multi-species assemblage is to focus upon the most susceptible member of that assemblage and thus bound the lower limit of survival. Prior to the work by Turnpenny (1992) on sand smelt and herring, studies were conducted at Alden Research Laboratory to observe the effect of pressure on the fragile species alewife (SWEC 1977). Mean length of alewife tested was 10 cm (range 2.5 to 20.0 cm). During pressure chamber testing, fish were quickly brought from 1 to 2.4 atm and held for 15 min. Pressure was then returned to 1 atm over a period of 2 minutes. As chamber pressure was increased and their air bladders became compressed, the alewife experienced some signs of disorientation and had trouble maintaining position. By the end of the fifteen minutes the fish were swimming normally again. Following the release of pressure, the alewife appeared in good condition and no burst swim bladders were evident. One week survival of treatment fish was close to control groups, though high mortality was observed at the end of the fifth test. These mortalities coincided with the occurrence of a bacterial infection in both groups of fish.

Pressure as a potential factor in the survival of fish at Salem can be assessed by comparing existing conditions within the fish return system at Salem to those determined to be injurious at other sites. Existing literature indicates that pressure effects are most injurious to fish when:

- pressures are substantially above or below atmospheric pressures;
- fish are acclimated to high pressure (deep water) prior to exposure to low pressure;
- the magnitude of the pressure drop is large;
- pressure drops occur over a short period of time; and/or
- the duration of exposure to low pressure is long.

The review of site conditions at Salem indicates that the following conditions exist within the cooling water intake and fish return systems:

- fish may be drawn into the system from as deep as 35 – 40 ft (~2 atm);
- fish drawn into the intake are predominantly physoclistous;
- transit times are relatively long (compared with turbine passage times and the duration of most laboratory studies) allowing fish time to acclimate to pressure changes over a longer period of time ;
- at no point are fish exposed to sub-atmospheric pressures; and
- there is no evidence of gas supersaturation in the return water or river where the return pipe exits the plant so there is minimal potential for GBT.

3.1.1.3. Velocity

Velocity is not in and of itself a stressor to fish, but is one characteristic of the flow field that determines the relative intensity of other stressors. Fish can travel at uniform high velocities within a body of water without deleterious effects. Other stressors such as turbulence (the

fluctuation in velocity magnitude over time in one location) and shear (the relative difference in velocity and direction between two moving bodies of water) result from uneven or unsteady flow conditions and the potential adverse impact to fish is associated with velocities within the flow field.

3.1.1.4. Abrasion and Impact

Abrasion or other injuries to the skin can result in one or more of the following conditions: 1) flooding of internal tissues with excess water (through osmosis); 2) acute toxicity resulting from the liberation of toxins sequestered in the injured tissue and/or; 3) creation of pathways for the penetration of pathogenic organisms (Ruggles and Murray 1983). Often abrasion injuries do not result in immediate mortality, but difficulties in osmoregulation, exposure to histamine-like toxins or the onset of latent fungal infections can lead to delayed mortality.

Abrasion in fish return systems can occur on rough surfaces. As part of the conversion from a conventional traveling water screen to a modified Ristroph screen, the 3/8 in. mesh on the Salem screens was replaced with 1/2 by 1/4 in. Smooth-Tex® mesh, thereby minimizing potential for abrasion at the screens. The fish trough is made of fiberglass while the debris trough is smooth concrete with an epoxy liner designed to minimize abrasion and snagging. In addition, other characteristics of the fish return system (such as the lack of sharp corners and physical impediments) act to minimize the potential for abrasion.

Development of criteria for the safe passage of fish over high head hydroelectric dams led researchers to examine the effects of fish exposed to freefall conditions. The majority of research in this area has been conducted with salmonids since most of the high head dams in the U.S. are in the Northwest, and anadromous salmonids are abundant and important commercially and recreationally. Smith (1938; in Ruggles and Murry 1983) and Holmes (1939; in Ruggles and Murry 1983) showed juvenile salmon (5 to 10 cm) could survive freefalls of up to 56 m. At the Glins Dam on the Elwha River, survival of 92% was observed for yearling coho salmon that freefell 55 m into a pool (Regenthal 1957; in Ruggles and Murry 1983).

Based on these early studies it became evident that velocity at the time of impact was of greater importance than the height of the fall. Laboratory studies were conducted at the University of Washington to calculate terminal velocities of fish of varying sizes. While fish 10 to 13 cm length reached terminal velocities of 16 m/s in falls of 30.5 m, larger fish (~60 cm) reached terminal velocities in excess of 58 m/s and would continue to accelerate during falls as high as 213 m (Richey 1956; in Ruggles and Murry 1983). Further, testing with live sockeye salmon (*Oncorhynchus nerka*) ~18 cm long reached terminal velocity of 16 m/s when falling from a 45-m high tower (Richey 1956; in Ruggles and Murry 1983).

Further study (data presented in Bell and DeLacy 1972) indicated that fish could not experience an impact greater than 16 m/s without incurring damage to gills, eyes or internal organs. Survival of fish dropped from helicopter into a hatchery pond was dependent upon the size of the fish dropped and the height of the fall (Table 10). In all cases, smaller fish, whose velocities at the point of impact were less than those of larger fish dropped from the same height, experienced greater survival.

Table 10. Survival of salmon smolts dropped from various heights (from data presented in Bell and DeLacy 1972).

Fish Size (cm)	30.5-m drop		61-m drop		91.5-m drop	
	% Survival	(*n*)	% Survival	(*n*)	% Survival	(*n*)
15-18	98.5	(200)	97.5	(199)	98.5	(200)
25-28	94.8	(198)	82.0	(189)	81.4	(189)
30-38	67.0	(6)	83.4	(6)	20.0	(5)

Sweeney and Rutherford (1981; cited in Ruggles and Murry 1983) observed the mortality of Atlantic salmon smolts and kelts following falls from either 10.6 or 18 m. No significant initial mortalities were observed for fish experiencing falls from either height. During the 8-day delayed mortality observation period, the kelts dropped 18 m suffered 12.5% mortality. By contrast, kelts dropped 10.6 m experienced no delayed mortality.

Based on the observation of Richey, Regenthal and others, it appears that the terminal velocity of fish 18 mm and smaller is less than the lethal impact velocity for salmonids tested.

Bell and DeLacy (1972) point out that fish falling within a column of water may experience injuries as a result of shear forces resulting from the rapid deceleration of the water as it enters the receiving pool and that those injuries are similar to those resulting from impact (See Section 3.1.1.4). Bell and DeLacy (1972) acknowledge that additional mortalities may have been caused by repeated exposure to a stressor (*e.g.,* fish getting caught in turbulent flows). Shear and other stressors likely added to the observed mortalities, but no measurement of shear or other stressors were collected. A compilation of survivals observed under different hydraulic conditions are summarized in Table 11.

Table 11. Summary of expected survival of salmonids exposed to different hydraulic conditions (from Bell and DeLacy 1972).

Hydraulic Condition	Survival and Conclusions
Fish striking a fixed object at velocities <20 ft/s.	No data, but expected survival to be low based on data collected at higher velocities.
Falling in constricted areas where deceleration was controlled by baffles and walls.	Survival dropped quickly for velocities over 40 ft/s and was likely as low as 70% in the 20-30 ft/s range. Some mortality may have been from shear.
50 ft/s entering a pool from freefall.	98-100% survival
60 ft/s entering a pool from freefall.	80% survival
80 ft/s and greater entering a pool from freefall.	Approaching 0% survival.
Entering a pool within a column of water and decelerating with the jet without mechanical deflection.	Survival may equal best freefall conditions (98-100%).
Entering a pool within a column of water and decelerating with the jet and deflected by a baffle.	Approximately 93% survival.
Fish traveling through a hydraulic jump or large stilling pool (single passage through stressor).	Approaches best conditions, 93-98% survival.
Fish striking a fixed baffle or object.	Approaching 0% survival.

Fish surviving impact is determined not only by the relative velocity between the fish and the object struck, but is also affected by the physical characteristics (*e.g.,* hardness, sharpness, roughness, etc.) of the object struck. For example, at the same velocity, impact against solid objects caused higher mortality than did entry into water (ASCE 1991; Figure 13).

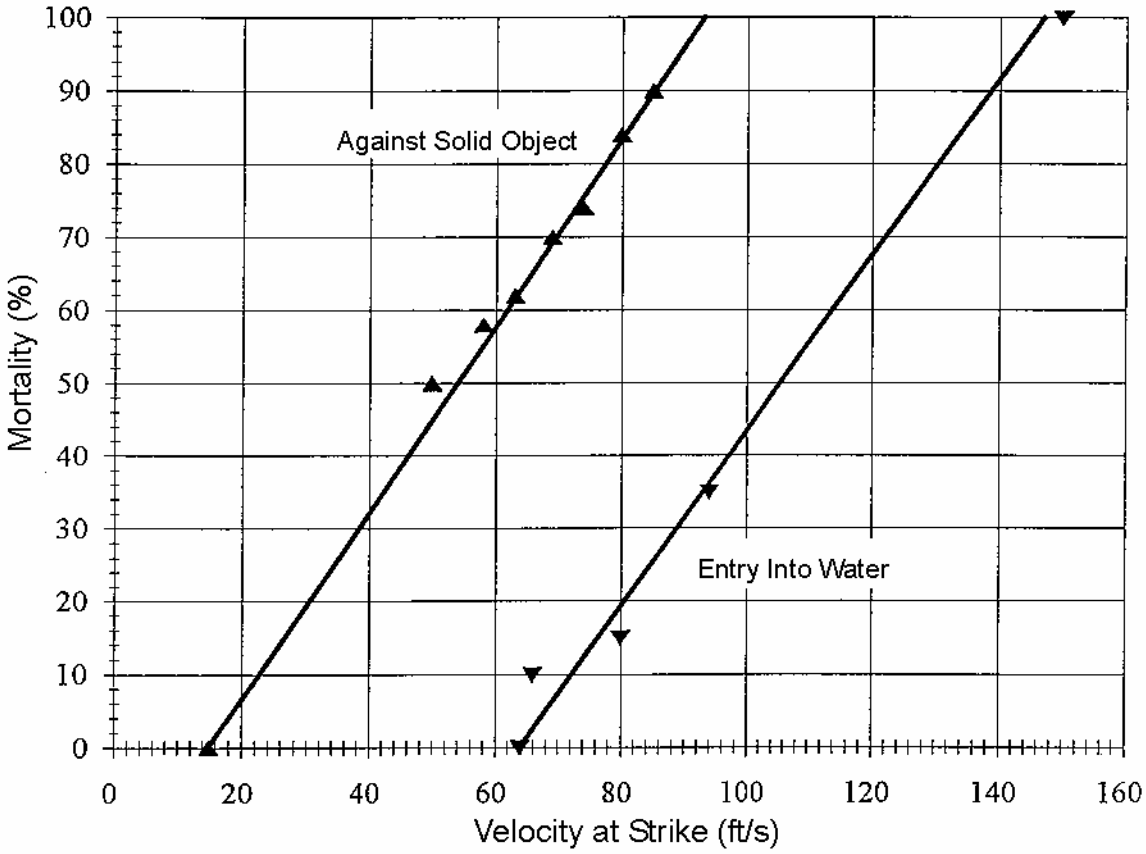


Figure 13. Mortality of fish impacting a solid object vs. entry into water by (USACE 1991).

3.1.1.5. Turbulence and Shear

Turbulence is a measurement of the fluctuation in velocity magnitude about a mean value. In general, it is difficult under both laboratory and field conditions to separate the injury resulting from turbulence and shear. Very little literature exists on the survival of fish exposed to different levels of turbulence, although proposed and on-going research is attempting to identify these effects (*e.g.,* Odeh 2001).

Shear forces arise at the boundary between fast and slow moving water and is greatest in areas of rapid acceleration or deceleration. The magnitude of shear forces depends upon the relative net difference in velocity and direction between two masses of water at their interface. The differential between the velocity of the fish and the relative velocity of the surrounding water mass can lead to fish injury. There is a strong link between velocity, shear, and turbulence and in most cases it is impossible to separate the effects of shear from those of turbulence.

Groves (1972) examined the effects of shear using high speed cameras to observe juvenile salmon encountering a high velocity jet. Damage to fish was observed under conditions where water moved at velocities greater than 9 m/s. During this study, localized areas of sharp velocity

differences resulted in injuries that occurred within one millisecond of exposure and in a 2.5 cm square area.

Johnson conducted experiments in the late 1960s and early 1970s on the fingerling salmon exposed to shear forces generated by a water jet entering still water at different velocities (Johnson 1970; 1972 in Ruggles and Murray). Fingerling salmon (18 to 20 cm) were jetted into a pool of water through a 15 cm nozzle at a velocity of 17.5 m/s. No mortality was observed (immediate or delayed) during the seven-day post test holding period. Tests using a 10-cm nozzle and velocities of 20.3 cm/s resulted in low mortality (0 to 5.4%). Johnson concluded that the critical threshold velocity for smolts 18-20 cm length was near 20.3 m/s.

In subsequent tests, Johnson (1972 in Ruggles and Murray 1972) exposed salmon and steelhead (*O. mykiss*) to a wide range of velocities (Table 12). Johnson concluded that velocities exceeding 20 m/s can cause injury to fish and that the rate of fish injury rises sharply at velocities greater than 24 m/s.

Table 12. Survival of salmon and steelhead fingerlings fired from a jet at different velocities (Johnson 1972, in Ruggles and Murray 1983).

	Jet Velocity (m/s)			
	17.5	20.3	23.5	28.0
Survival (%)	100.0	97.6	92.8	69.0

The study of most relevance to examining shear effects at Salem was conducted at the Pacific Northwest National Laboratory (PNNL). In previous research, velocity distributions and time series associated with the test conditions have not been reported in all of the studies. Because of this, a definitive comparison between the results of the previous studies cannot be made. A notable exception to this is the Nietzel et al. (2000) report titled, "Laboratory Studies on the Effects of Shear on Fish." This report provides a complete description of the experimental methods and analysis procedures used in their study.

The primary objective of the Nietzel et al. (2000) study was to, "specify an index describing the hydraulic force that fish experience when subjected to a shear environment." In this study, fish were exposed to a shear environment produced by a submerged jet (Figure 14) with velocities ranging from 0 to 70 ft/sec. Fish were released, in either a headfirst or tailfirst orientation, at the edge of the jet stream or within the jet stream and injury was caused by the flow patterns developed by the expanding jet. Test fish included juvenile rainbow trout, spring and fall chinook salmon, and American shad.

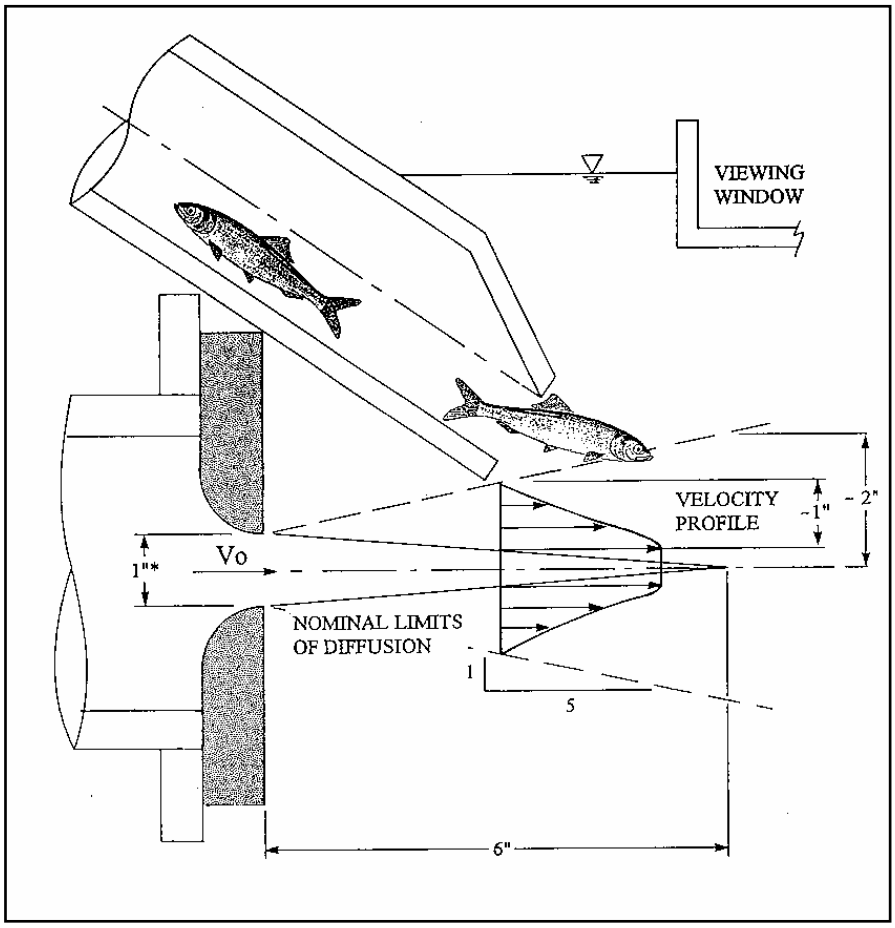


Figure 14. Shear environment testing apparatus (modified from Nietzel et al. 2000).

Strain rate was used as the index of physical force that fish experienced when subjected to the shear environment in the test facility. In their report, Nietzel et al. referred to this force as the *exposure strain rate* (ε) calculated by equation 1

$$\text{Exposure strain rate} = \varepsilon = du/dy = (u_1 - u_2)/\ 1.8\ \text{cm/s/cm} \qquad (1)$$

where: u_1 = the jet velocity (V_o in Figure 14)
u_2 = a velocity measured a small distance away from u_1 (1.8 cm)
1.8 cm = the spatial resolution of the velocity measurements (also the minimum width of salmonids tested)

The dy distance (1.8 cm) was set by Nietzel et al. because it matched the length of the fish they used during their tests. In the experiment, Nietzel et al. released fish into the shear environment

of the test facility (as shown in Figure 14) and recorded the amount of injury sustained by the fish. The exposure strain rate for the test was equal to the maximum strain rate developed by the jet (velocity measurements, used for the calculation of exposure strain rate, were made in the close vicinity of the nozzle where fish were exposed to the most severe and least variable shear environment). The rate of strain experienced by test fish varied from 0 cm/s/cm to 1185 cm/s/cm.[2]

Injuries to the test fish were categorized as minor or major. Minor injuries were those that were visible, but not life-threatening, and tended to heal and disappear during the post-exposure period. Small bruises (< 0.5 cm in diameter) with minor discoloration were also given a minor injury rating. Major injuries were those that resulted in prolonged loss of equilibrium and the more severe injuries that persisted throughout the post-exposure observation. For example, large bruises (> 0.5 cm in diameter), damage to spinal column, cuts with bleeding, injured eyeballs, gill damage, and descaling.

For each test, the percentage of test fish with minor injury, major injury, or death was calculated. The results of tests with American shad are shown in Figure 15. In these tests, as with other Nietzel et al. (2000) tests, the percentage of injured fish and the severity of injury increased as the exposure strain rate rose.

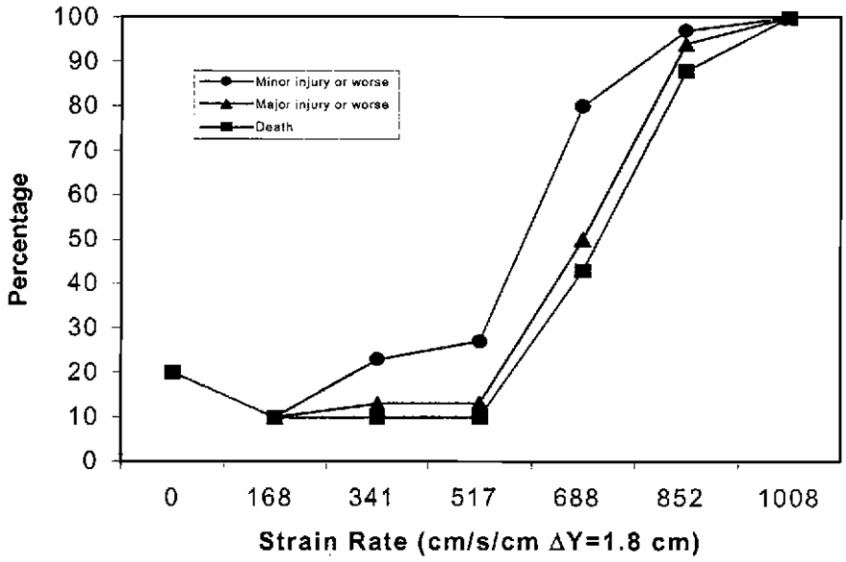


Figure 15. The percentage of American shad (mean FL = 10 cm) injured or killed during headfirst exposure to different strain rates (N = 150) (modified from Nietzel et al. 2000).

As a result of their testing, Nietzel et al. (2000) concluded "that juvenile salmonids and American shad should survive shear environments were strain rates do not exceed 500 cm/s/cm at a dy of 1.8 cm." In Figure 15, for example, *major injury or death* was not observed when

[2] A complete description and justification of the experiment can be found in Nietzel et al. (2000).

exposure strain rates were less than 500 cm/s/cm (when adjusted for control mortality). When strain rates were less than 341 cm/s/cm no significant injuries to any fish were reported. However, when strain rates were greater than 1008 cm/s/cm, no fish survived

3.2. Selection of Alternative Designs to Reduce Stressor Levels at Salem

Based on the literature review, it appeared that the existing Salem fish return system may meet most criteria and guidelines for the safe transport of fish. Of the potential stressors examined (pressure, velocity, impact, abrasion, turbulence and shear), shear was the only measurable stressor that could not be quantified for the existing fish return and collection systems. Therefore, Alden proceeded with examining the existing fish return and collection systems to identify any areas where shear levels might exceed recommended values, with the idea that improvements in these areas might provide additional protection to fish at Salem.

Shear, expressed as exposure strain rate, is a useful metric since strain rates are quantified in the literature. The exposure strain rates reported by Nietzel et al. (2000) can also be thought of in terms of velocity. In their experiment, Nietzel et al. reported the maximum exposure strain rate associated with a given flow condition. Typically, this was the exposure strain rate calculated from velocity measurements made near the orifice (See Figure 14). By equation 1, u_1 was the jet velocity, and u_2 was the speed of the receiving water located 1.8 cm away – typically zero. Using this approximation, one could convert an exposure strain rate of 341 cm/s/cm to an equivalent velocity of 20 ft/sec and an exposure strain rate of 500 cm/s/cm to an equivalent velocity of 30 ft/sec (these being literature-based threshold values for minor and major injury). Since flow velocities do not exceed 30 ft/s anywhere in the discharge pipe or the fish collection pool, it is unlikely that these components of the system contribute significantly to the mortality of fish. However, the locations of maximum flow velocity are easily identified at Salem and Alden proceeded with a CFD analysis of the existing systems to quantify shear levels. Alden then identified changes in the existing designs that would reduce velocities (and thus strain rate) and might, therefore, reduce the potential for injury. Alden fully considered ESSA's comments in evaluating alternatives.

Criteria were developed by which alternative fish return system and collection pool designs could be identified, and these alternatives were subjected to CFD analyses to determine their ability to reduce stressor levels (strain rate) at Salem. The criteria are described below, followed by a discussion of the existing and alternative design CFD analyses.

3.2.1 Criteria for Selecting Alternative Designs

Three criteria were developed to ensure the process of selecting a preferred alternative was reasonable and unbiased:

> *Criterion 1* - The alternative should result in stressor levels that are conducive to fish survival and that decrease the potential for injury and mortality to a level below that in the existing system.
>
> *Criterion 2* - The alternative should involve the minimum structural changes needed to achieve stressor levels consistent with Criterion 1 to maximize its cost/benefit ratio.

Criterion 3 – The alternative should involve the minimum changes to existing operations and maintenance procedures needed to achieve stressor levels consistent with Criterion 1, thereby increasing the probability of success and maximizing the cost/benefit ratio.

Based on the results of the literature review and the thorough evaluation of the existing fish return and collection pool systems at Salem, a variety of biological, engineering, and cost-related considerations were defined that would apply to the potential implementation of any alternative design at Salem, as summarized below.

Biological Considerations

- The alternative should minimize fish contact with solid objects;
- The alternative should provide acceptable stressor levels at all tidal levels;
- The alternative should reduce stressors for all debris loading conditions (during light and heavy debris periods);
- The alternative should avoid sub-atmospheric pressures that can cause air bladders to rupture;
- Transport velocities should be greater than the sustained cruising speed of the fish (generally 2 ft/sec or above);
- Modifications within one portion of the system should not create or exacerbate injurious conditions in another part of the system; and
- The alternative should not decrease one stressor(s) while increasing another stressor(s) to an unacceptable level.

Engineering Considerations

- The alternative should avoid hydraulic jumps;
- If bends are required, they should be long radius ($r/d > 2.5$);
- The height of freefall discharges to the river should be minimized;
- The alternative should accommodate the full range of flows occurring in the fish return and collection pool systems;
- The alternative should provide unobstructed passage of fish and debris to the river;
- The alternative should be compatible with other existing system components that are not being changed;
- The alternative should not include any projections that may be injurious to fish under normal flow conditions;
- All surfaces of conveyance structures should be smooth to prevent abrasion to fish;
- Pipe joints should be constructed carefully so that all edges match and there are no jagged protuberances;
- Gates and valves should provide clear passage for the fish and create as little obstruction as possible;
- All transitions should be gradual to prevent flow separation and rapid changes in velocity;

- Smooth transitions should be provided where flow from separate pipes or troughs combine;
- The alternative should avoid abrupt trough/pipe contractions or expansions;
- Alternative return pipe designs should be located where receiving water is of sufficient depth to ensure that fish do not impact the bottom;
- The alternative should not reduce the amount of time over which a sample can be taken (FCP);
- The alternative should not block access to any plant doorway or equipment;
- The alternative should be sufficiently durable to withstand weather and sampling activities; and
- The alternative should not impact station security.

Cost-related Considerations

- The alternative should minimize installation costs;
- The alternative should avoid substantial increases in power requirements;
- The alternative should not require undue or excessive maintenance to remain in operating condition;
- The alternative should not negatively impact station operations; and
- The alternative should not negatively impact station safety.

As stated previously, the locations of maximum flow velocity and turbulence in the fish return system and collection pool were easily identified. It was similarly easy to identify areas of turbulence that might lead to injury as a result of shear or impact. In the fish return system, the highest velocities and turbulence levels occur at the end of the 40 in. diameter return pipe where it discharges into the river. At this location, high velocities drop rapidly as the return flow passes through a hydraulic jump within the pipe at the air/water interface. In the fish collection pool, maximum velocities occur at the sampling gate and at the bottom of the trough slide as it enters the pool (referred to as the spoon). Therefore, efforts were concentrated on determining what changes in design would reduce velocities (and thus strain rate) and might reduce the potential for injury in these areas.

For the end-of-pipe location, three alternatives were identified based on the criteria and considerations listed above:

- Cutting off the pipe at the sheetpile wall to allow the flow to freefall about 1.3 ft (max.) into the river, thereby eliminating the hydraulic jump;
- Complete removal of the pipe and installation of a trough extension at a shallower angle that would create a freefall of about 6 ft (max.) and eliminate the jump; and
- Same as above and installation of a floating trough extension to minimize the height of the freefall.

It was judged that the first two alternatives had the best potential to reduce stressor levels in a cost-effective manner by lowering velocities and alleviating the existing hydraulic jump.

For the fish collection pool, three alternatives were identified:

- A circular screening system in the existing pool area that would reduce screen velocities and turbulence;
- Removal of the spoon resulting in a freefall into the pool with 2 ft of cushion water in the pool initially. Cushion water is the water introduced into the collection pool prior to sampling. The existing sampling protocol calls for 10 in. of cushion water; and
- Removal of the spoon resulting in a freefall into the pool with 3.6 ft of cushion water in the pool initially.

The different freefall heights result from changes to the existing pool that would permit varying amounts of water to be retained without losing fish. Increasing the water depth within the FCP would reduce the freefall height, reduce the velocity of the water as it hits the surface, and reduce turbulence by providing a larger cushioning pool of water. All three alternatives would limit the potential for fish impact on the bottom and sides of the pool.

The three EOP and three collection pool alternatives were subsequently subject to analysis to determine stressor levels that would be achieved, as described below.

3.3. Computational Fluid Dynamics (CFD) Analyses

Computational Fluid Dynamics (CFD) analysis techniques were used first to model flows into the existing fish collection pools and through the fish return system at Salem (North and South ends). The results of the studies were used to identify flow patterns that could be injurious to fish. The procedure used to carry out the analyses was as follows.

1. literature describing the effects of hydraulic forces on fish was reviewed and quantitative measures for predicting fish injury were identified (*e.g.,* exposure strain rates), as presented previously;
2. computer models of the North and South fish collection pools and return system were developed;
3. simulations of flow through the fish collection pools and in the return system were carried out for typical operating conditions;
4. exposure strain rates were calculated from the results of the computer models;
5. the likelihood of major injury or death to fish was assessed; and
6. the same procedure (*i.e.,* steps 1-5) was used to study the performance of alternative collection pool and return system designs to determine if the existing flow patterns through these components could be improved (*i.e.,* to see if exposure strain rate levels could be reduced).

Visual observations of the hydraulic conditions within the fish collection and return systems at Salem would indicate that there might be areas within each system that are potentially injurious

to fish. For example, flow entering the fish collection pools moves very quickly and is quite turbulent (Figure 16). However, the extent of fish injury that might be caused by this flow and the flow through the return pipes was not known.

Figure 16. Fish collection pool (insert: approach flow).

The principle objective of the study was to carry out a numerical analysis that would provide the data needed to calculate exposure strain rates, and to relate these data to the amount and degree of fish injury observed by Nietzel et al. (2000). The numerical analysis was based on the application of CFD modeling techniques used to simulation the flow into the fish collection pools and through the return pipes.

3.3.1. General CFD Methodology

The methods used to estimate the amount of fish injury caused by flows into the fish collection pools and through the return pipes were based on a CFD modeling technique developed for the analysis of dynamic, free surface flows. In this study, computer models of the fish collection pool and the return pipes were constructed for as-built conditions and several modified conditions. Three-dimensional, free surface flows through these structures were determined, and maximum exposure strain rates were calculated. The amount fish injury was then estimated from the results of the Nietzel et al. (2000) study. Details regarding the analysis procedure and the numerical techniques are provided in the following sections.

A five-step procedure was used to quantify potential stressors associated with flows into the collection pools and through the return pipes at Salem. This same procedure was also used as the basis for a comparative analysis of modified collection pool and return pipe designs. A description of each step in the analysis follows.

Step 1: Literature Review

Literature describing the effects of hydraulic forces on fish was reviewed and quantitative measures for predicting fish injury were identified. *Exposure strain rate*, as defined by Nietzel et al. (2000), was chosen to be the index used to predict injury to fish.[3]

Step 2: Model Construction

Three-dimensional computer models of the fish return and collection pool systems were constructed within the framework of the CFD software package ***FLOW-3D***. The flow of water into the fish collection pools and through the return pipes was thought to have the most potential for fish injury due to the chaotic nature of the observed flow patterns (*e.g.,* flow tends to stream through the fish collection troughs with little evidence of large-scale turbulence; however, the flow into the collection pool and in portions of the return troughs and pipes is very turbulent and disorganized).

Step 3: Flow Simulation

Simulations of flow in the fish collection pools and return pipes were carried out using nominal boundary conditions describing typical operating conditions. The Navier-Stokes based solver that is part of ***FLOW-3D*** was used for the computations. This program uses the Volume-of-Fluid (VOF) method to calculate solutions to complex free surface flow problems (Hirt & Nichols 1981). Other CFD software programs claim to use the VOF method, but ***FLOW-3D*** is the only commercially available CFD program that contains the fully implemented VOF algorithm of Hirt & Nichols (1981).

Step 4: Calculate Exposure Strain Rates

Results from Step 3 were used to calculate exposure strain rates in the fish collection pools and return pipes according to equation (1) (Nietzel et al. 2000). The maximum exposure strain rate calculated for each scenario was recorded.

Step 5: Assess Injury Potential

Exposure strain rates, calculated in Step 4, were compared to the results of Nietzel et al. (2000) and an assessment of the amount and severity of potential fish injury was made.

The same procedure (*i.e.,* Steps 1 through 5) was also used to determine the behavior of alternative collection pool and return pipe designs to see if exposure strain rates could be reduced.

[3] Other researchers have proposed similar indices. However, the work of Nietzel et al. (2000) is unique in the level of detail that his experiment and calculation procedures were documented. Simply put, it was possible to design our numerical analysis so that it matched the Nietzel et al. report. Therefore, the results of our analysis could be compared to Nietzel et al's exposure strain rate index in a reliable way. It should be also noted that the results of Nietzel et al's work are consistent with the results of many previous studies.

As stated, computer simulations of flow into the fish collection pool and through the return system were developed within the framework of the ***FLOW-3D***, Computational Fluid Dynamics (CFD), software system (Flow Science 2002). The numerical approach involved solution of the three-dimensional equations of fluid motion (*i.e.,* Navier-Stokes Equations), and the solution of an additional pair of equations to account for turbulent effects in the flow (*i.e.,* a coupled turbulence model). ***FLOW-3D*** was used for these analyses because of the relative ease that computations can be setup (FAVOR) and for its unique ability to simulate dynamic, free surface flows (VOF).

3.3.1.1. Fractional-Area-Volume-Obstacle-Representation (FAVOR)

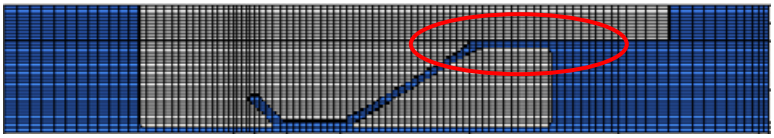
FLOW-3D computations are performed in a non-uniform, structured mesh comprised of six-sided control volumes. The size of the control volumes can be varied so that additional cells can be located in areas where flow changes quickly (or in areas of special interest). A partial volume technique known as FAVOR (Fractional- Area-Volume-Obstacle-Representation) is used to place obstacles within the structured mesh.

Figure 17 shows an elevation (frame [a]) and plan view (frame [b]) of the computational mesh used to calculated flows into a fish collection pool. The size of control volumes in the mesh was smaller in areas where greater detail in the solution was required (*e.g.,* near the bottom of the trough that carries flow into the fish collection pool –this area is circled in frame [a]).[4] Blue areas in Figure 17 show the location of obstacles placed in the mesh. With FAVOR (Hirt & Sicilian 1985) control volumes can be totally blocked, or partially blocked (refer to detail area of frame [b]): a feature that combines the flexibility of an unstructured mesh with the simplicity and numerical accuracy of structured meshing.[5]

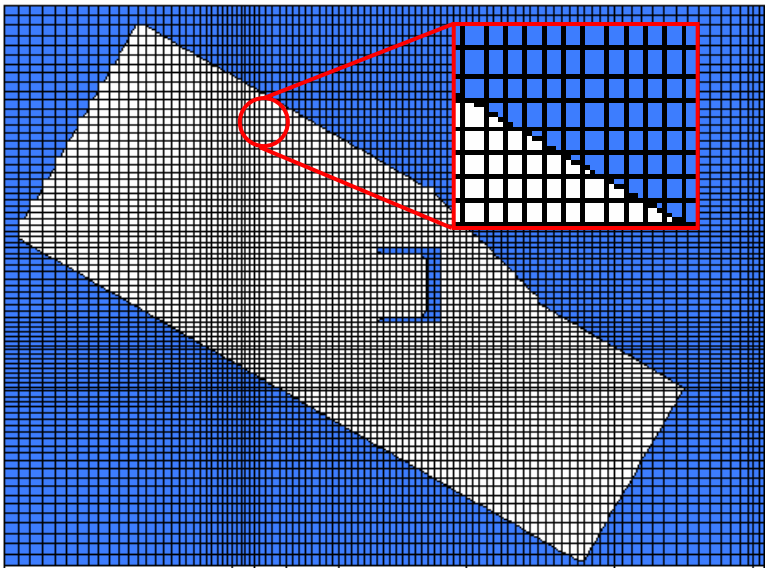
All calculations discussed in this report required the use of FAVOR.

[4] 1.8 cm grid spacing was used in areas of particular interest so that equation 1 could be used to calculate exposure strain rates

[5] FAVOR effectively eliminates "stair-stepping" that is associated with structured meshing.



(a)



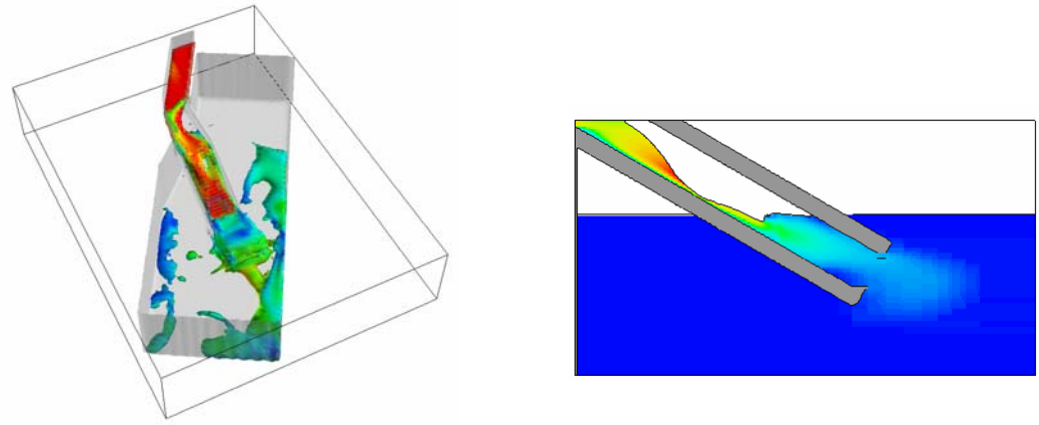
(b)

Figure 17. Computational mesh with obstacle overlay (all grid lines not shown) (a) elevation, (b) plan.

3.3.1.2. Volume-of-Fluid (VOF) Method

FLOW-3D uses the VOF method of Hirt & Nichols (1981) to locate and track the movement of fluid regions within the computational mesh. With this method, the transient, three-dimensional, Navier-Stokes equations govern fluid motion in cells that are *fully filled* with fluid, and free surface boundary conditions are applied at cells that are partially filled with fluid (*i.e.,* the fluid free surface is treated as a moving boundary). This feature makes it possible to simulate the filling of the fish collection pools in an efficient and time accurate way and to predict the position of the free surface within the return pipes (Figure 18, frames [a] and [b]). [6]

[6] ***FLOW-3D*** is the preferred choice of engineers and scientists studying transient, free surface flows.



(a) (b)

Figure 18. Volume-of-Fluid (VOF) method (fluid regions colored by speed - red is fast) (a) predicts evolution of fluid bodies (b) locates fluid free surface.

Exposure strain rates, associated with flows into the fish collection pools and return pipes, were calculated from the results of ***FLOW-3D*** computer simulations. Nominal boundary conditions, descriptive of typical operating conditions, were used in the analyses.

In each analysis (*i.e.,* end-of-pipe and fish collection pool scenarios), as-built conditions were studied as well as three alternative conditions. The intent of these analyses was to estimate exposure strain rates associated with current conditions and to determine if significant reductions in exposure strain rates could be achieved by making reasonable modifications to the existing systems.

The analyses of EOP and FCP hydrodynamics are presented similarly. First, the setup of the as-built numerical model is discussed. Second, as-built simulation results are presented followed by the alternative designs (three in each case). The results of the analyses are summarized in tabular form at the conclusion of each section.

3.3.2. End-of-Pipe (EOP) CFD Analysis

At the end of the fish collection system, flow passes through a round discharge pipe and is returned to the Delaware River Estuary. Figure 19 shows a schematic diagram of the existing, North end, discharge pipe. The direction of flow on Figure 19 is downhill from the right to the left. Velocities and depths in the return troughs are based on uniform flow calculations (Manning's equation).

In operation, flow enters the discharge pipe moving super-critically (Fr > 1), accelerates, and then slows considerably (Fr < 1) when it encounters the receiving waters that inundate the lower portions of the discharge pipe (the amount of inundation changes as the tide moves up and

down). A large amount of energy is dissipated inside the pipe when the flow transitions from super-critical to sub-critical (from Fr > 1 to Fr < 1). However, this transition cannot be easily observed since it occurs within a confined space (*i.e.,* inside the discharge pipe).

The flow that develops inside the discharge pipe could be injurious to fish. For example, the shear environment within the pipe could be intense enough to cause injury, flow patterns that develop within the discharge pipe could cause fish to be trapped for extended periods of time, and/or fish could impact the side walls of the discharge pipe as the flow makes the transition between the return trough and the discharge pipe. For these reasons a three-dimensional hydraulic analysis of the flow through the discharge pipe was carried out. The goals of the study were to:

- Identify flow patterns that could be injurious to fish (based on literature values);
- Estimate exposure strain rates within the discharge pipe; and
- Investigate alternative pipe configurations that could reduce the exposure strain rate.

Hydraulic analyses were carried out for both the North and South end discharge pipes since the speed of the approach flows as well as the discharge elevations were different for both fish return systems. In this report, results of the North end analyses are presented. The similar South end analyses are not presented in detail to reduce the amount of repetition; however, the results of the South end analyses are summarized.

Velocities into the discharge pipes were based on the assumption of uniform flow in the approach channels and the results of the studies were used as a screening analysis to determine the likelihood of injury caused by flows in the discharge pipe.[7]

[7] In reality, flow in the approach channels is gradually varying. However, the depth and velocity of the gradually varying flow into the discharge pipe is very similar to the depth and velocity of flow calculated with Manning's equation. The results of gradually varied flow computations were used to set boundary conditions for the experimental testing that was conducted later.

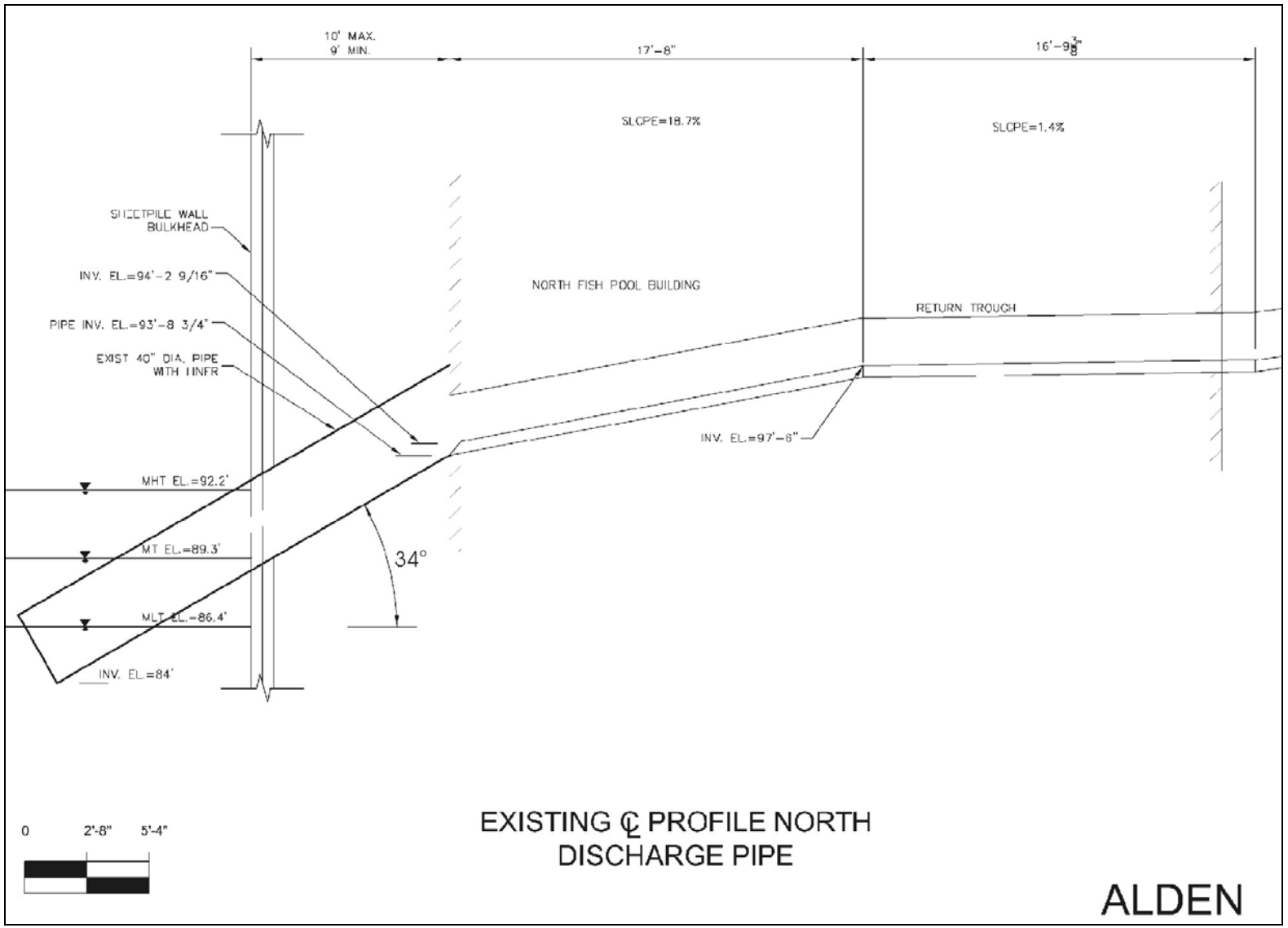


Figure 19. North end discharge pipe configuration.

3.3.2.1. EOP Numerical Model (Setup)

The numerical models of the North and South end discharge pipes extended from the end of the fish collection troughs (*i.e.,* the beginning of the pipe sections), though the entire length of discharge pipe, and into the receiving waters of the Delaware River Estuary (Figure 20 shows the setup for the North end discharge pipe simulation).

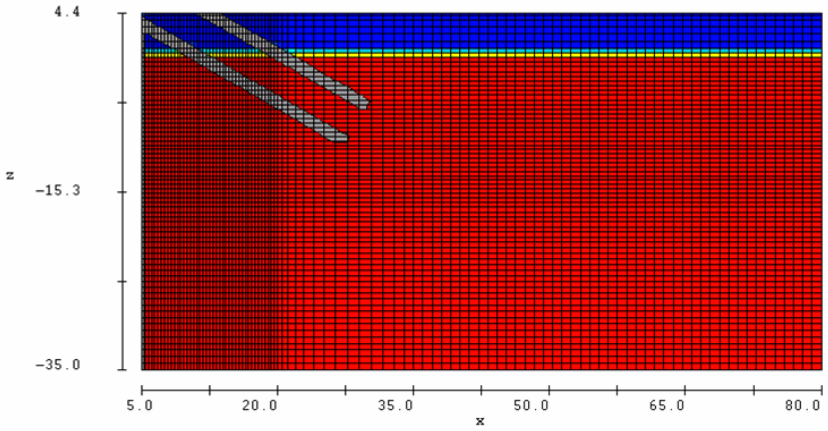


Figure 20. Initial fluid configuration (EOP) (all grid lines not shown).

Velocity boundary conditions were set at the entrance to the discharge pipes and at the open boundary on the opposite side of the model domain (the location x = 80.0 in Figure 20). Specified velocities at the open boundary were about three orders of magnitude less than specified velocities within the discharge pipe. Therefore, the influence of the velocities set at the open boundaries on the computed flow field in the pipe was negligible (*i.e.,* velocities were set at the open boundaries so that the amount of flow entering and leaving the domain would be the same, thus, preventing the model from filling or emptying). Free surface boundary conditions were applied at water/air interface.

The flow was motionless at the beginning of each calculation. At time t = 0.0 velocities at the boundaries were instantaneously switched on. The calculations proceeded until the estimated mean kinetic energy of the flow became steady (Figure 21).

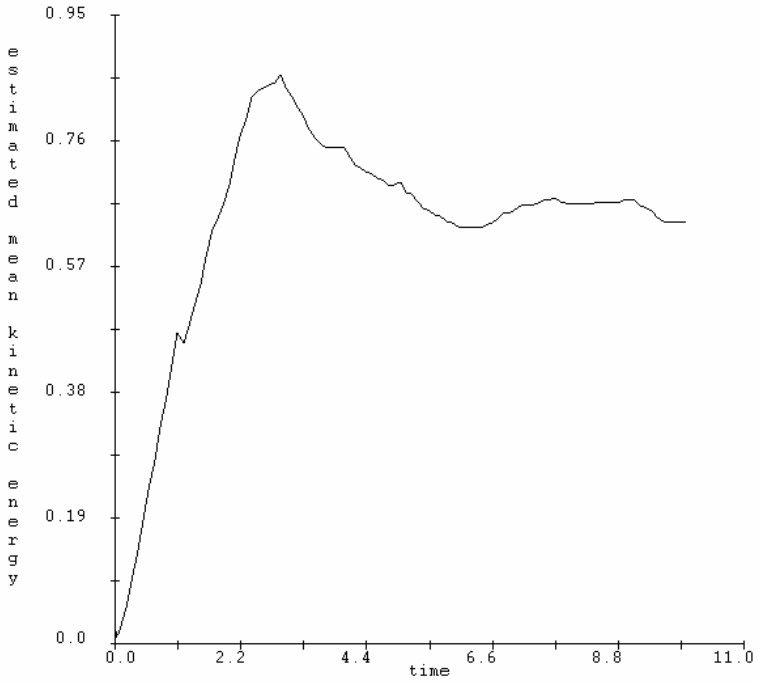


Figure 21. Estimated mean kinetic energy (ft^2/sec^2) versus time (sec).

Exposure strain rates were calculated from the numerical results using equation 1 in the final step of the analysis. The grid spacing within the discharge pipes was equal to 1.8 cm, so adjacent velocities could be used to calculate exposure strain rates in the same way that Nietzel et al. (2000) used velocity measurements spaced 1.8 cm apart to calculate exposure strain rates in their experiment. The mesh used for the EOP calculations contained 625,000 control volumes.

3.3.2.2. As-Built EOP Condition

Exposure strain rates in the as-built discharge pipe were calculated for a condition where the flow rate through the discharge pipe was equal to13 ft^3/sec. The entrance velocity was equal to 17.2 ft/sec.

Figure 22 shows the calculated fluid configuration within the discharge pipe for the 13 ft^3/sec operating condition (note: the pipe has been erased for clarity). Some disturbance of the free surface is noted in the upper left portion of the figure where flow enters the discharge pipe. This disturbance is caused by the abrupt change in slope between the troughs and the discharge pipe (*i.e.*, the flow wants to lift off of the bottom of the channel). Once the flow establishes itself in the discharge pipe it enters a region of pipe that is inundated by receiving water and an abrupt expansion takes place. It is at the beginning of the expansion where the maximum exposure strain rates are calculated (this location is circled on Figure 23).

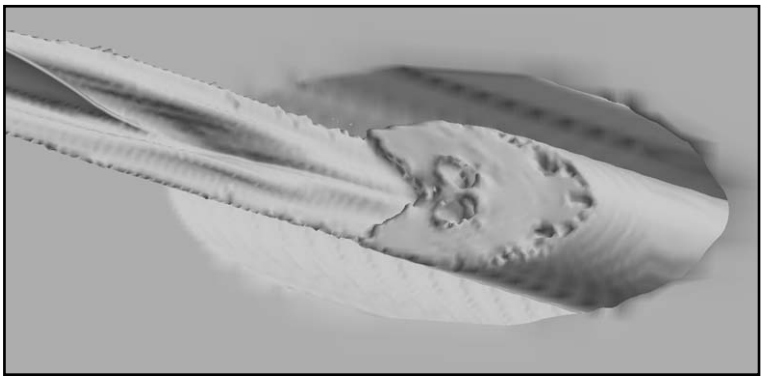


Figure 22. Fluid configuration within discharge pipe (as-built design, 13 ft^3/sec).

For the as-built case, the maximum calculated exposure strain rate was equal to 217 cm/s/cm calculated within the fluid body (*i.e.,* in the flow transition area). The maximum calculated exposure strain rate calculated along the pipe wall was equal to 97 cm/s/cm (assuming a smooth pipe wall).

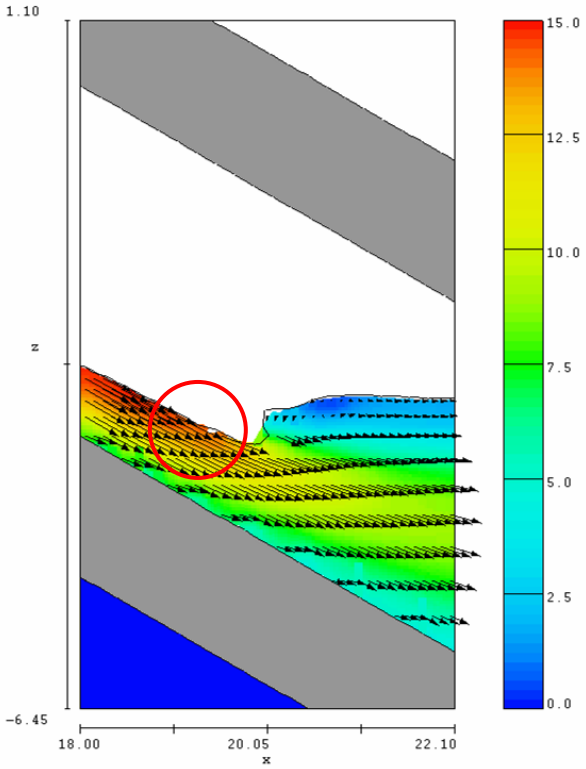


Figure 23. Expansion of flow in discharge pipe (colored by speed, maximum speed is greater than 15.0 ft/sec).

3.3.2.3. Alternatives (EOP)

Three alternative designs were studied with the numerical model of the return pipe. The modifications were intended to reduce the maximum calculated exposure strain rates encountered by fish passing through this part of the system.

Alternative 1 – Cut Pipe at End of Sheetpile Wall

Alternative 1 involved cutting the pipe at the end of the sheetpile abutment (Figure 24). This eliminates the expansion of flow within the discharge pipe for most operating conditions. For Alternative 1, the maximum calculated exposure strain rate was equal to 132 cm/s/cm calculated in the turbulent water surrounding the plunging flow (Figure 25).

Alternative 2 – Debris Trough Extension

Alternative 2 involved extending the return trough to the edge of the building (Figure 26). This eliminates the abrupt transition between the return trough and the discharge pipe and permits an unconfined expansion of flow in the receiving water. For Alternative 2, the maximum calculated exposure strain rate was equal to 151cm/s/cm calculated in the turbulent water surrounding the plunging flow (See Figure 25).

Alternative 3 – Float and Guide Piles

Alternative 3 involved extending the return trough to the level of the receiving water (Figure 27). This eliminates the freefall associated with Alternatives 1 and 2. For Alternative 3, the maximum calculated exposure strain rate was equal to 217cm/s/cm calculated in the turbulent waters downstream of the return structure.

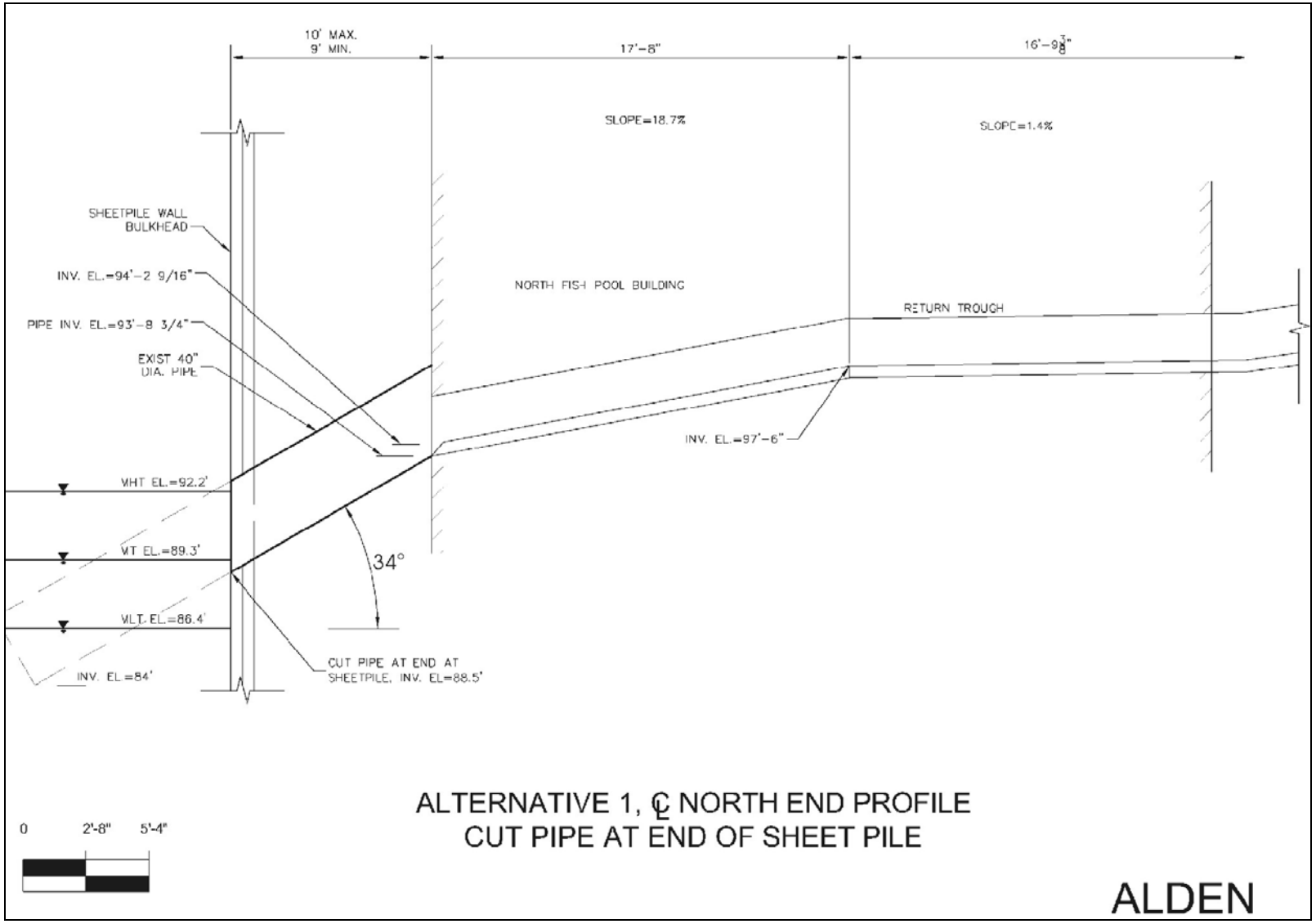


Figure 24. Alternative 1 discharge pipe configuration.

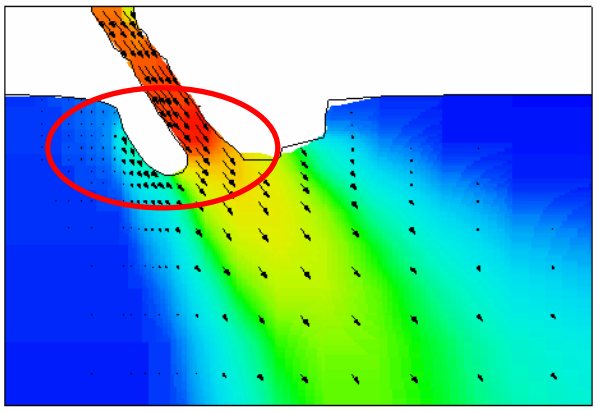


Figure 25. Location of maximum shear in unconfined expansion (colored by speed - red is fast).

3.3.2.4. Conclusions of EOP Analyses

The following conclusions, broken down by alternative, were reached as a result of these analyses:[8]

As-Built System

The maximum exposure strain rate calculated in the existing discharge pipe is less than exposure strain rates associated with fish damage as reported by Nietzel et al. (2000).

The transition of flow into the discharge pipes could be improved by streamlining the entrance to the discharge pipes. This would reduce the amount of flow separation that occurs at the entrance to the discharge pipes but present strain rates are not expected to result in fish damage.

Alternative 1 – Cut Pipe at End of Sheetpile Wall

Calculated exposure strain rates were reduced (North end: 217 vs. 132 cm/s/cm, South end: 168 vs. 139 cm/s/cm) since the expansion of flow was no longer confined in the discharge pipe. The transition into discharge pipe is abrupt (same as as-built condition) for this alternative.

Alternative 2 – Debris Trough Extension

Calculated exposure strain rates were reduced compared to as-built design (North end: 217 vs. 151 cm/s/cm, South end: 168 vs. 160 cm/s/cm), however, the amount of reduction is less than that of Alternative 1 since the discharge elevations for this option are higher. The transition into the discharge pipe is improved for this alternative (the change in slope between the collection troughs and discharge pipe is eliminated by this design).

[8] See Section 7.1.2 for overall study conclusions.

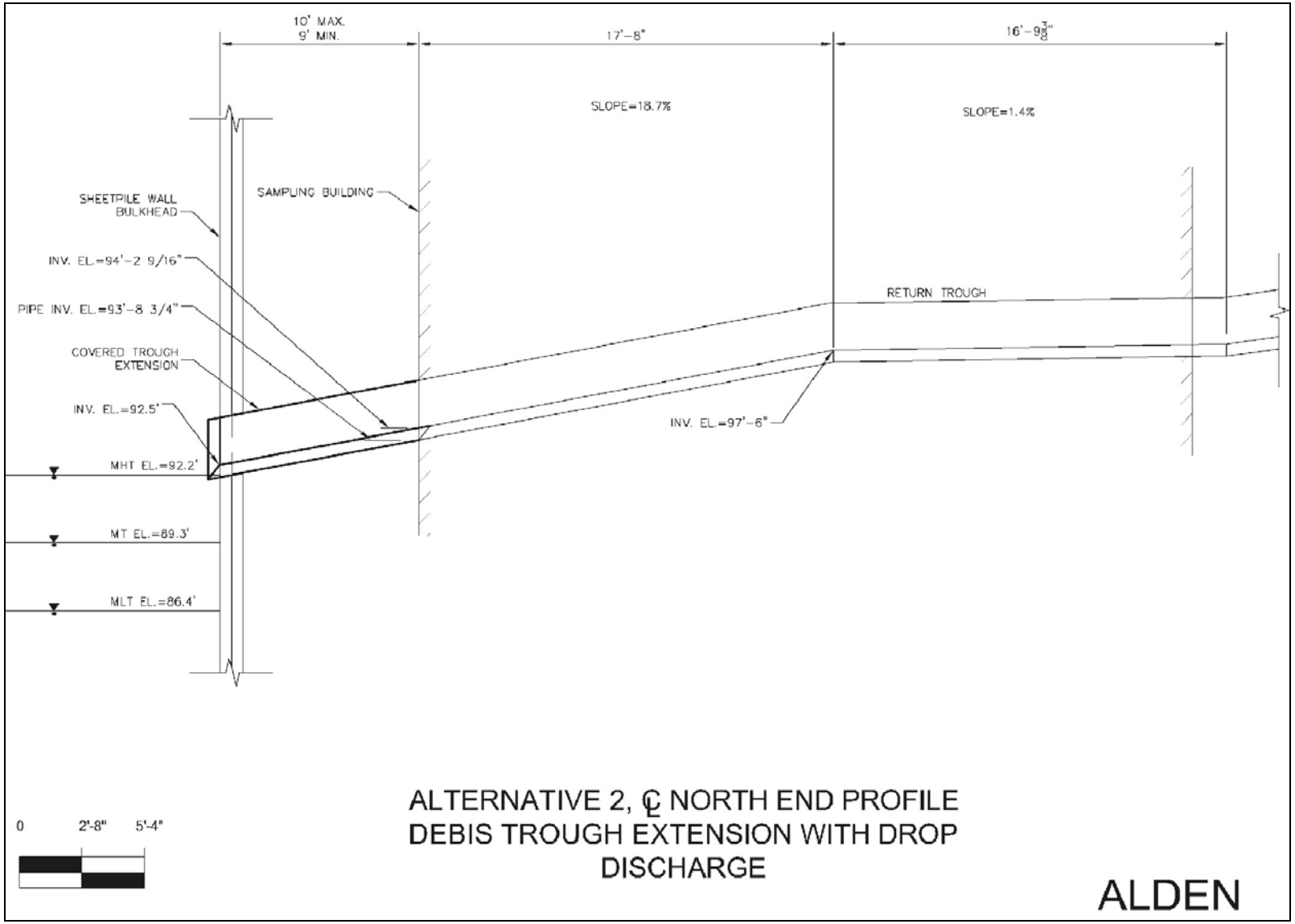


Figure 26. Alternative 2 discharge pipe configuration.

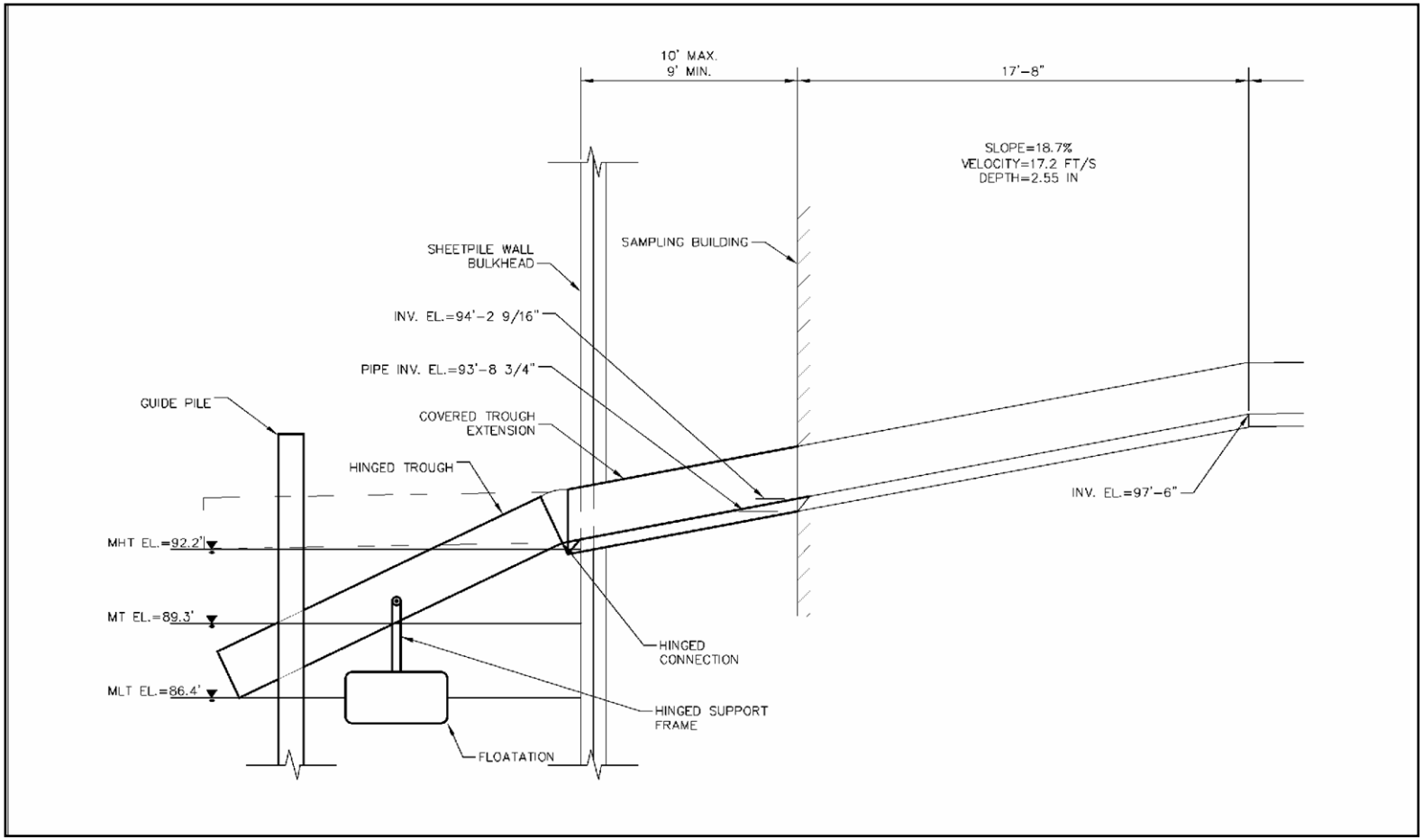


Figure 27. Alternative 3 discharge pipe configuration.

Alternative 3 – Float and Guide Piles

The transition into the discharge pipe is improved for this alternative (similar to Alternative 2: the change in slope between the collection troughs and discharge pipe is eliminated by this design). Calculated exposure strain rates this alternative were similar to those calculated for the as-built condition. A summary of calculated exposure strain rates appears in Table 13.

Table 13. Exposure strain rates (EOP).

Alternative Number	**Feature**	**Shear Rate (sec^{-1})**		**Notes**
		North End	**South End**	
Existing	Return Pipe Wall (smooth)	**97**	**57**	Maximum shear rate calculated along pipe wall
Existing	Return Pipe Flow Transition	**217**	**168**	Maximum shear rate calculated in flow transition
1	Freefall	**132** (88.5 ft)	**139** (92.5 ft)	Maximum shear rate calculated in freefall
2	Freefall	**151** (92.0 ft)	**160** (94.0 ft)	Maximum shear rate calculated in freefall
3	Discharge from pipe mounted on floating dock	**217** (87.4 ft)	**168** (87.4)	Maximum shear rate calculated in freefall

Notes: 1) All elevations are relative to the PSEG datum.
2) All shear rates are calculated for worst case conditions (low tide – 86.4 ft).
3) Discharge elevations shown in parentheses for Alternatives 1, 2, and 3.

3.3.3. Fish Collection Pool

Figure 28shows a schematic diagram of the existing, North end, fish collection pool. The direction of flow on Figure 28 is downhill from the right to the left (a similar fish collection pool is also part of the South end system). Flow is diverted from the return troughs into the fish collection pools (North and South ends) when a sampling gate located at the upstream side of the fish collection pools is swung open (Figure 29). The resulting flow into the collection pools is quite turbulent and was perceived to be potentially injurious to fish. For example, as fish enter the collection pools they could become injured by the flow that develops in the base of the spoon that carries flow into the pools (Figure 30), or they might become injured by the turbulent flows that develop in the pools as they fill (See Figure 16). To gain a better understanding of the hydraulics associated with the collection pools' operation – three-dimensional hydraulic analyses of the filling sequence were carried out for the North end fish collection pool (worst case). The goals of the study were to:

1. Identify flow patterns that could be injurious to fish;
2. Calculate exposure strain rates at three locations:
    a) in the transition of flow from the fish trough to the pool;
    b) in the "spoon;" and
    c) along the floor of the collection pool during filling.
3. Investigate alternative pipe configurations that could reduce exposure strain rate.

In this report, results of North end analyses are discussed. Similar South end analyses were not carried out because the design of the two systems is so similar (*i.e.,* results of the North end analyses remain valid for the South end system).

Velocities into the fish collection pools were based on the assumption of uniform flow in the approach channels and the results of the studies were used as a screening analysis to determine the likelihood of injury caused by flows into the as-built fish collection pool and into three alternative designs.

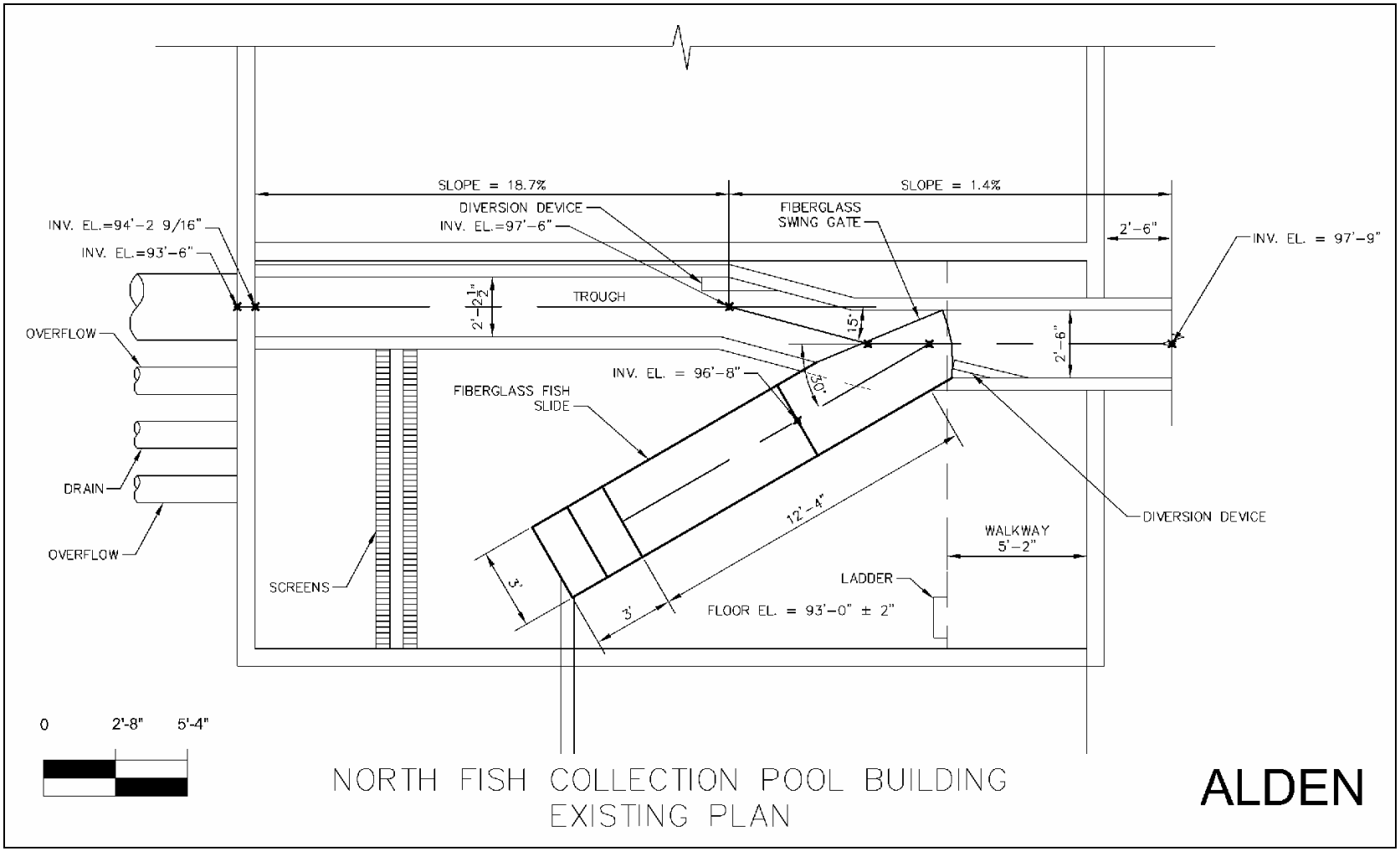


Figure 28. Existing North end fish collection pool.

3.3.3.1. FCP Numerical Model (Setup)

The numerical model of the North end fish pool began upstream of the diversion device (See Figure 28) and encompassed the entire pool (See Figure 17).

Velocity boundaries were established in the approach channel upstream of the diversion device. Water in the collection pool was motionless at the beginning of each calculation. At time t = 0.0 velocities at the inflow boundary were instantaneously switched on and filling of the collection pool began (Figure 31). The calculations proceeded until the collection pool was filled.

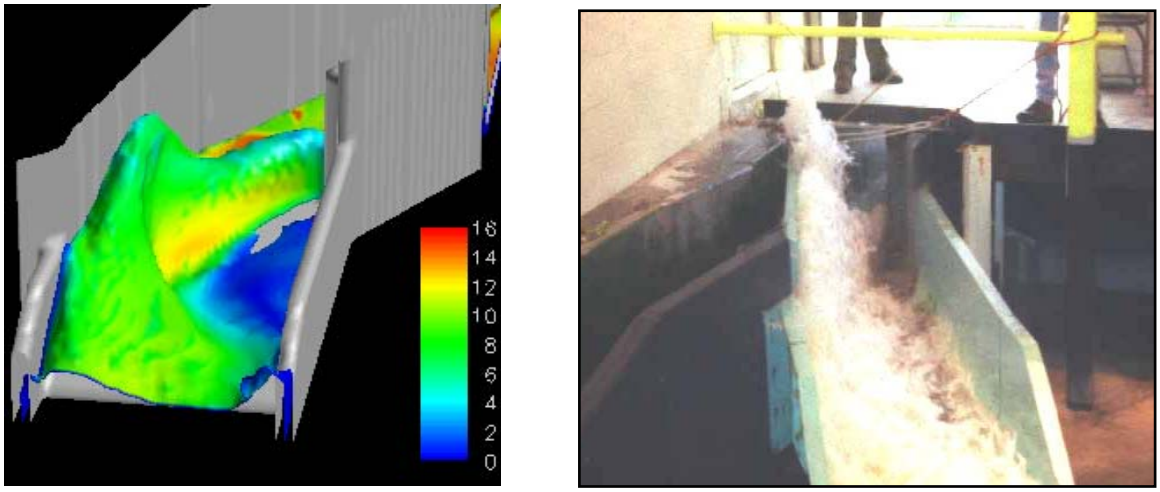
Exposure strain rates were calculated from the numerical results using equation 1 in the final step of the analysis. The grid spacing in critical areas in the pool (*i.e.,* at the bottom of the pool and in the trough that carries flow into the pool) was equal to 1.8 cm, so adjacent velocities could be used to calculate exposure strain rates in the same way that Nietzel et al. (2000) used velocity measurements spaced 1.8 cm apart to calculate exposure strain rates in their experiment. The mesh used for the fish collection pool calculations contained about 300,000 control volumes.

3.3.3.2. As-Built Condition (FCP)

Exposure strain rates in the as-built discharge pipe were calculated for a condition where the flow rate through the discharge pipe was equal to 13 cfs. The entrance velocity was equal to about 16 ft/sec.

Figure 31 shows the calculated fluid configuration in the collection pool shortly after filling begins (no cushion water in collection pool). Locations of particular interest are identified with circles and are numbered. Location 1 is at the diversion structure at the entrance to the fish collection pool (See Figure 29). Location 2 is at the bottom of the trough in the spoon (See Figure 30). Location 3 is at the sides and bottom of the pool.

For this case, the maximum calculated exposure strain rate in Location 1 was equal to 200 cm/s/cm calculated against the wall of the fish trough. The observed fluid configuration at Location 1 is shown next to the computed fluid configuration used to estimate the exposure strain rate of the transition (See Figure 29, frames [a] and [b]).



(a) (b)

Figure 29. Fluid configuration in entrance transition (a) computed (b) observed, (colored by speed, ft/sec).

The maximum calculated exposure strain rate at Location 2 was equal to 187 cm/s/cm calculated in the jump that develops in spoon early in the filling cycle before the spoon is submerged (Figure 30).

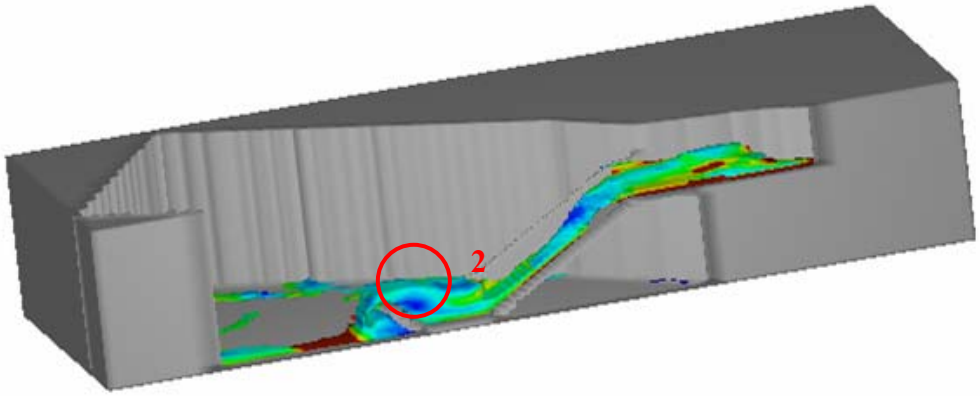


Figure 30. Fluid configuration in spoon (image cut through centerline of trough, colored by speed – red is fast).

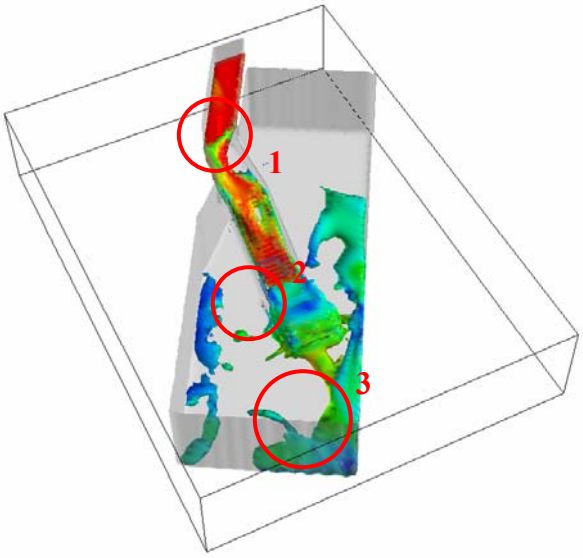


Figure 31. Fish collection pool – filling (colored by speed - red is fast).

The maximum exposure strain rate at Location 3 was equal to 150 cm/s/cm calculated on the bottom the pool where flow first spills out of the spoon when it is overtopped (Figure 32). This exposure strain rate corresponds to a condition with no cushion water in the pool. It should be noted, however, that standard operating procedures require cushion water in the pool. The scenario without cushion water was devised as a worst case scenario, and was used for comparison only.

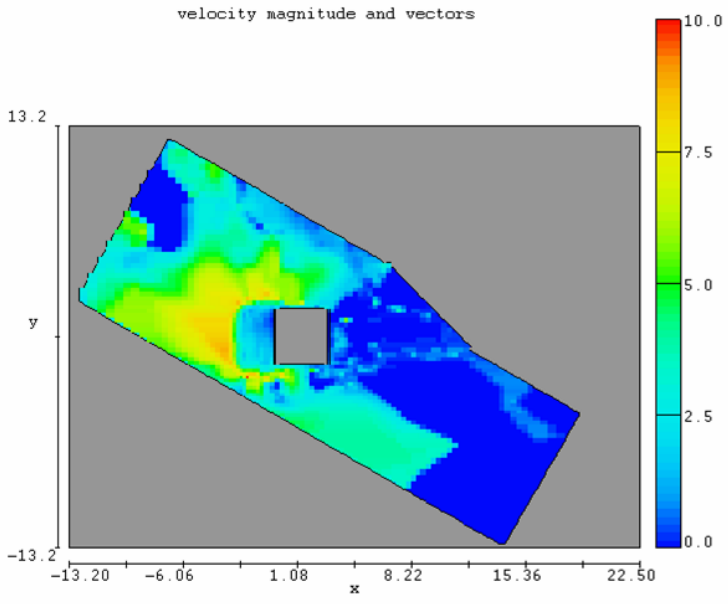


Figure 32. Velocity contours on pool bottom (beginning of filling cycle, colored by speed – ft/sec).

3.3.3.3. Alternatives (FCP)

Three alternative designs were studied with the numerical model of the fish collection pool. The modifications were intended to reduce the maximum exposure strain rates calculated in locations 1, 2, and 3 identified on Figure 31.

Alternative 1 – Circular Screen

Four changes to the existing fish collection pool were made with Alternative 1. First, the slope of the trough leading into the pool was reduced; second, the spoon at the end of the trough was removed; third, 3.6 ft of clean cushion water was put into the pool at the beginning of the filling cycle; and lastly, an 8-ft diameter circular screen was placed in the pool for flow control (Figure 33).

Calculated exposure strain rates were as follows:

- In the entrance to the fish collection pool the maximum calculated exposure strain rate remained 200 cm/s/cm (no design changes were made to this part of the system);
- The maximum calculated exposure strain rate at the end of the trough was equal to 70 cm/s/cm. The reduced slope of the trough and the elimination of the spoon, at the base of the trough, produced more uniform flow patterns in the area where the flow entered the pool;
- The maximum calculated exposure strain rate along the screen face was equal to 75 cm/s/cm (Figure 34); and
- The maximum calculated exposure strain rate at the bottom of the pool was equal to 65 cm/s/cm.

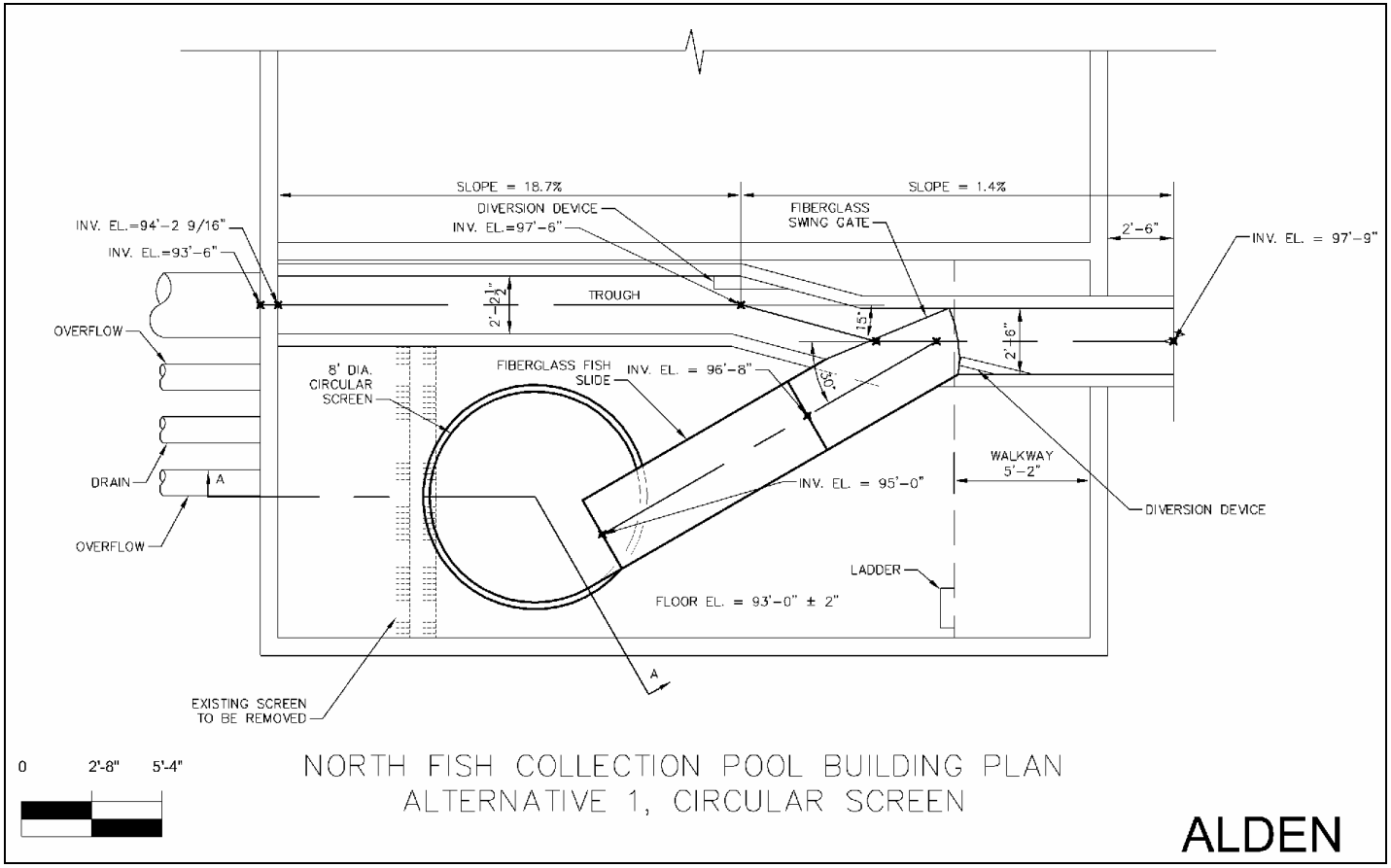


Figure 33. Alternative 1 - fish collection pool.

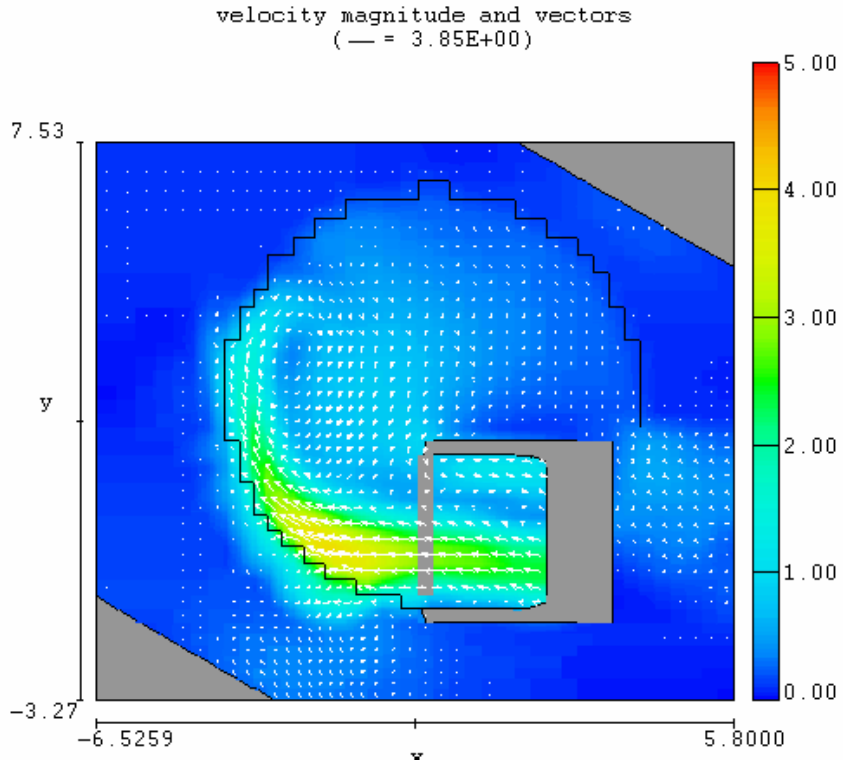


Figure 34. Flow along circular screen face (colored by speed [ft/sec] – all vectors not shown).

Alternative 2 – Drop Pool with 2 ft Cushion Water

Two changes to the existing fish collection pool were made with Alternative 2. First, the steeply angled portion of the trough was removed; and second, 2.0 ft of clean cushion water was put into the pool at the beginning of the filling cycle (Figure 35).

Calculated exposure strain rates were as follows:

1. In the entrance to the fish collection pool the maximum calculated exposure strain rate remained 200 cm/s/cm (no design changes were made to this part of the system);

2. The maximum calculated exposure strain rate associated with the plunging flow entering the pool was equal to 113 cm/s/cm (Figure 36); and

3. The maximum calculated exposure strain rate at the bottom of the pool was equal to 115 cm/s/cm (Figure 37).

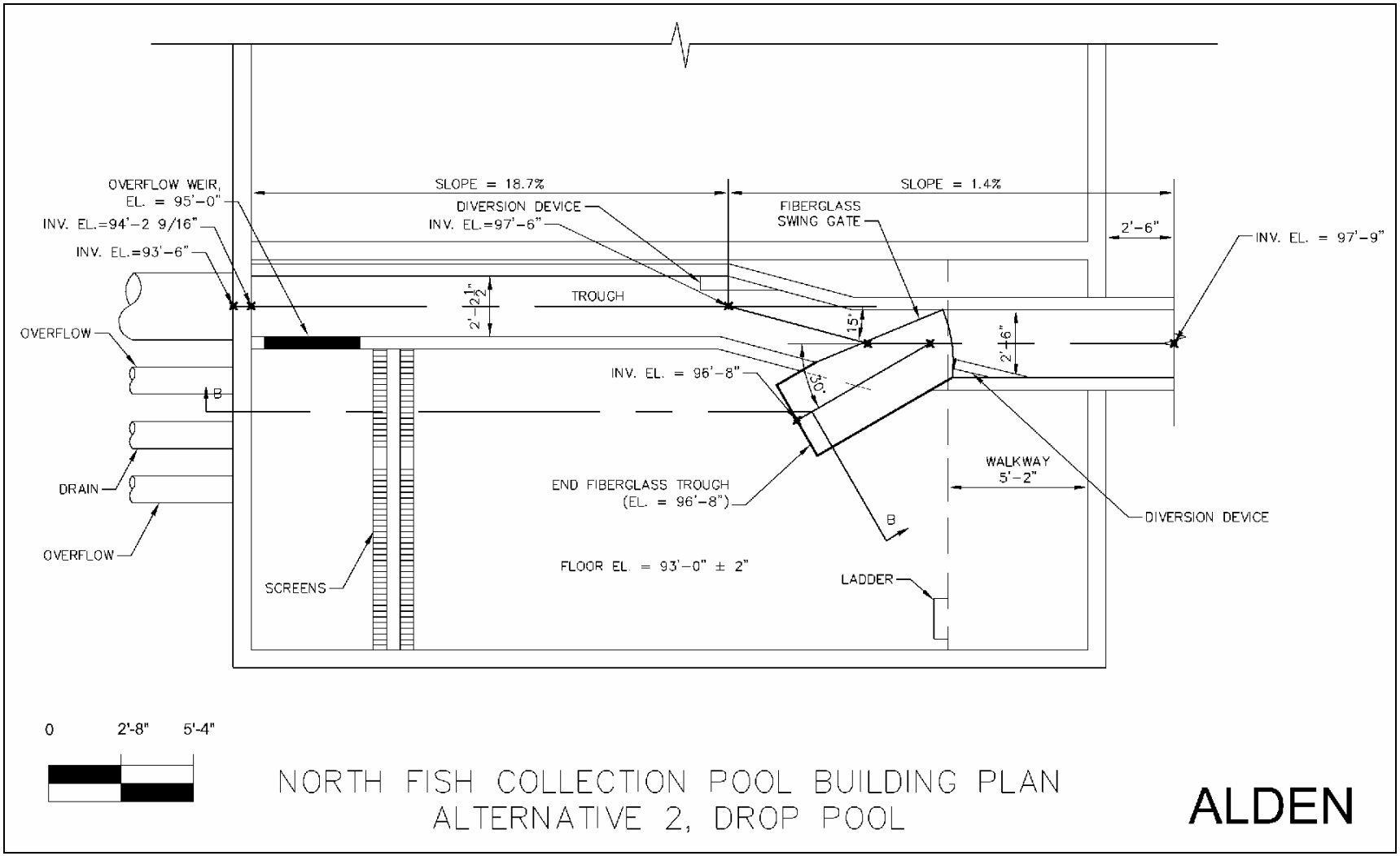


Figure 35. Alternative 2 - fish collection pool.

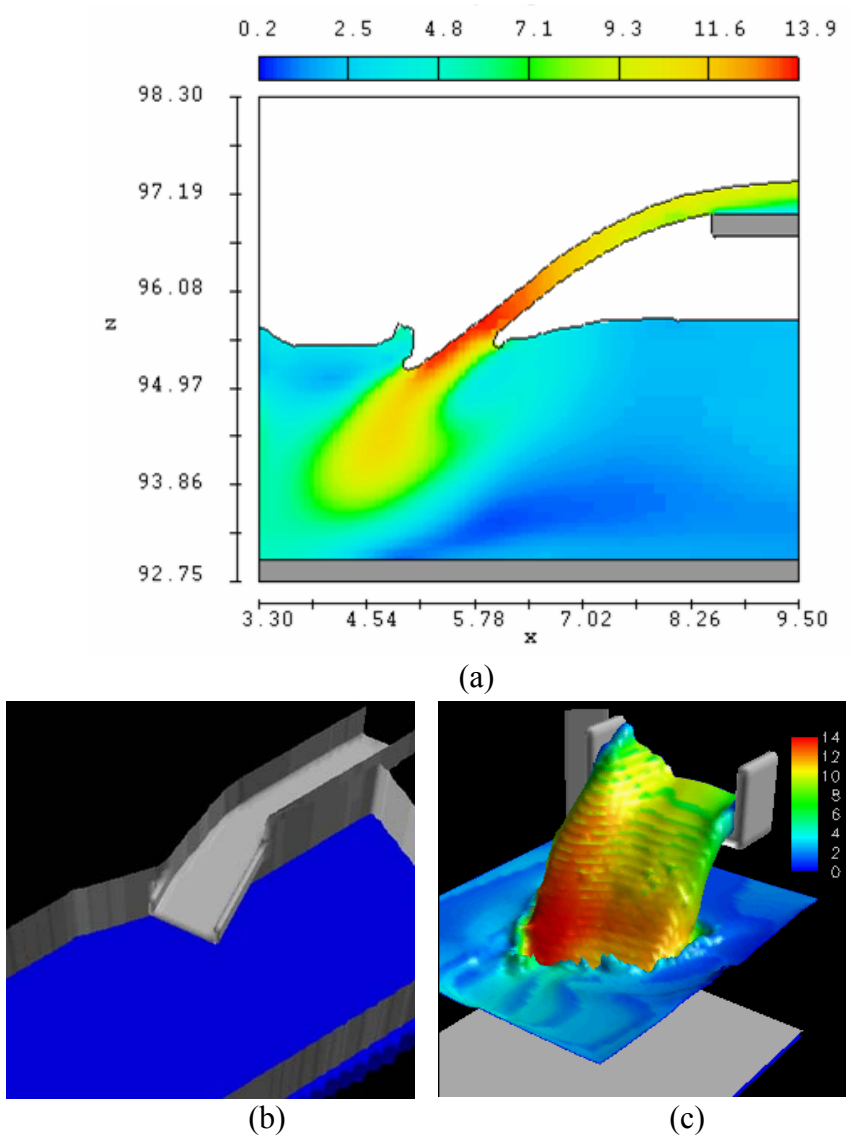


Figure 36. Plunging flow, colored by speed (a) plunging flow entering pool, (b) Alternative 2 geometry, (c) detail of plunging flow.

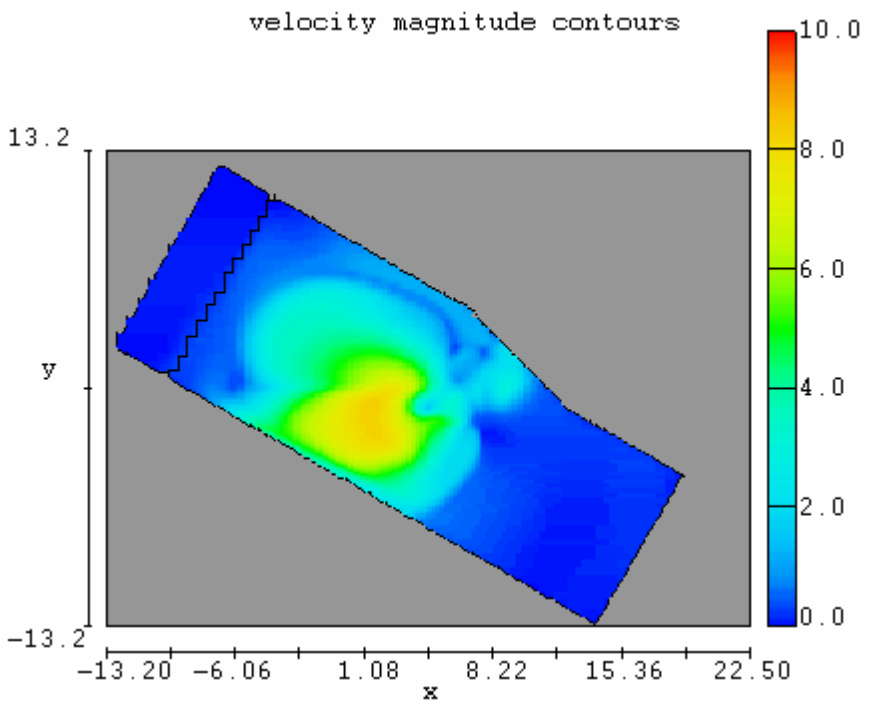


Figure 37. Velocity contours on pool bottom (colored by speed, ft/sec).

Alternative 3 – Drop Pool with 3.6 ft Cushion Water

Two changes to the existing fish collection pool were made with Alternative 3. First, the steeply angled portion of the trough was removed; and second, 3.6 ft of clean cushion water was put into the pool at the beginning of the filling cycle (Figure 38).

Calculated exposure strain rates were as follows:

1. In the entrance to the fish collection pool the maximum calculated exposure strain rate remained 200 cm/s/cm (no design changes were made to this part of the system);

2. The maximum calculated exposure strain rate associated with the plunging flow entering the pool was equal to 100 cm/s/cm (Figure 39); and

3. The maximum calculated exposure strain rate at the bottom of the pool was equal to 65 cm/s/cm (Figure 40).

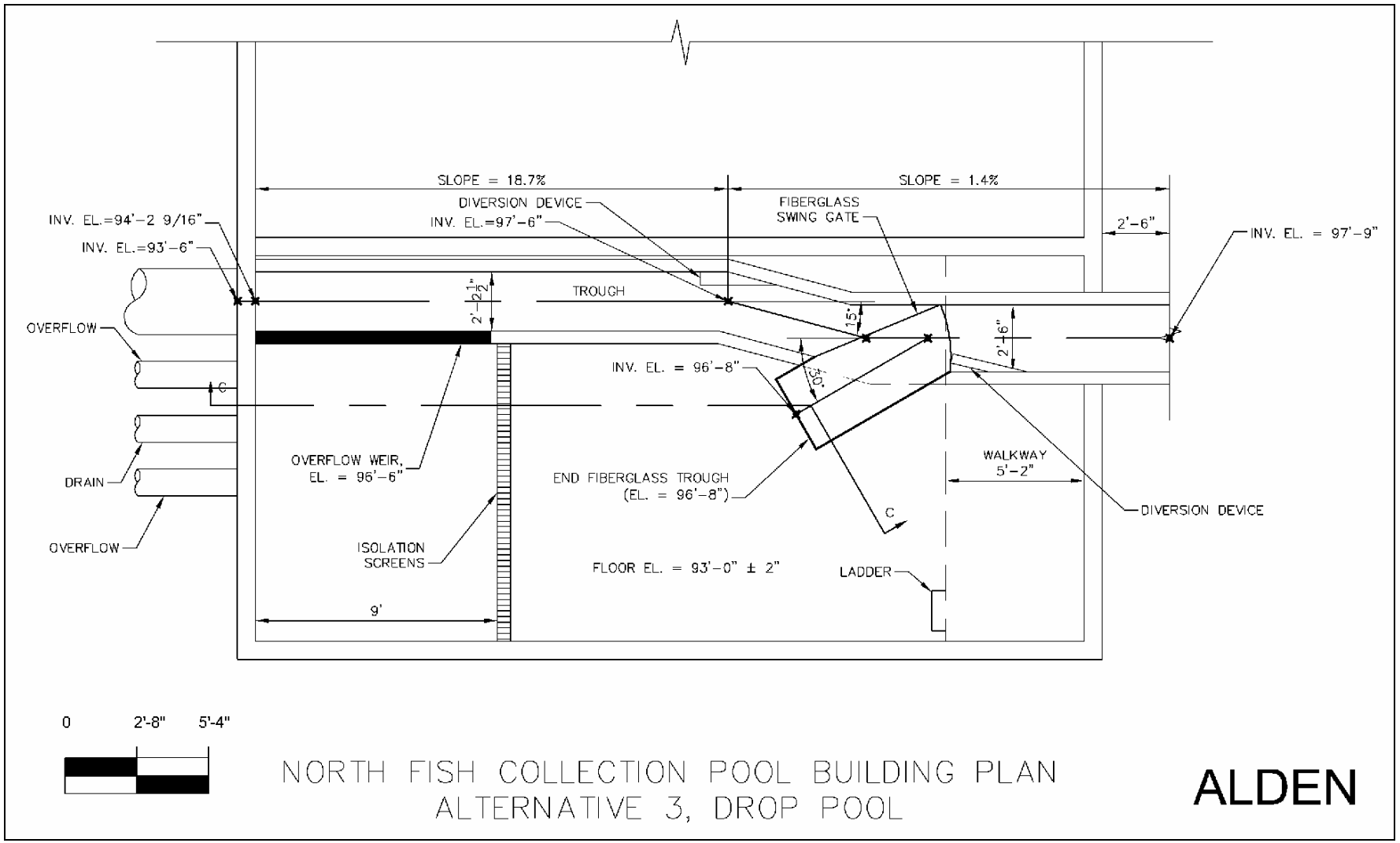
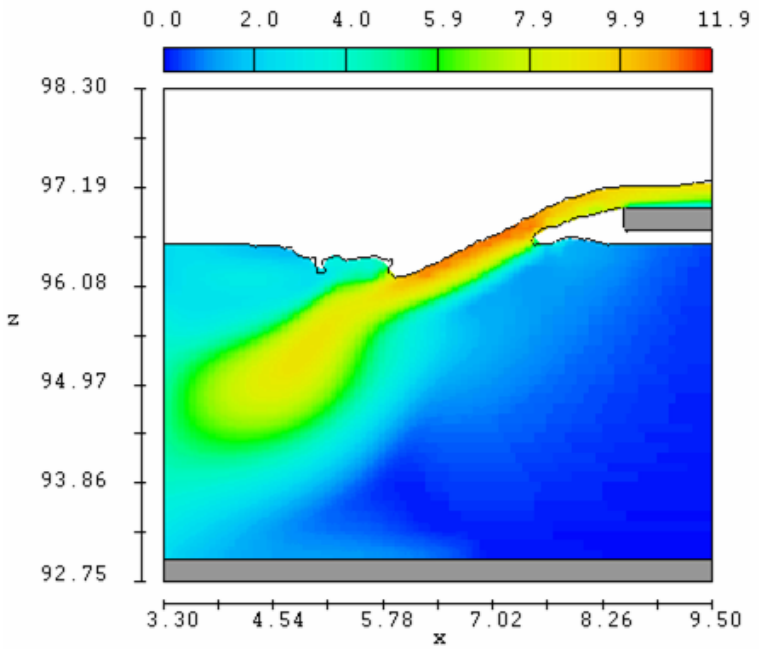
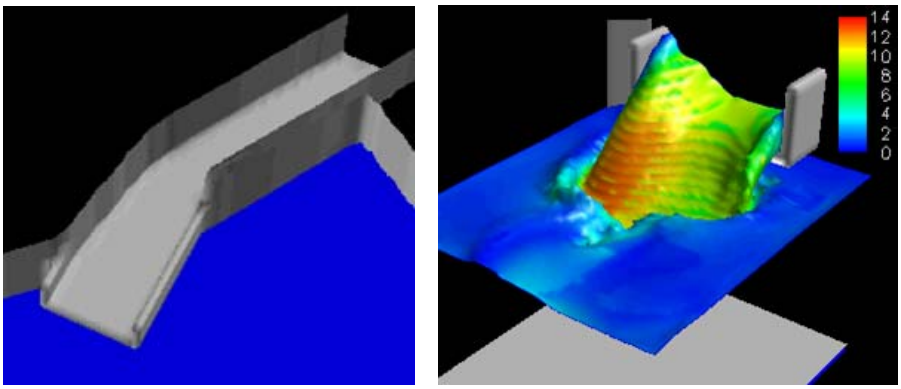


Figure 38. Alternative 3 - fish collection pool.



(a)



(b) (c)

Figure 39. Plunging flow, colored by speed (a) plunging flow entering pool, (b) Alternative 3 geometry, (c) detail of plunging flow.

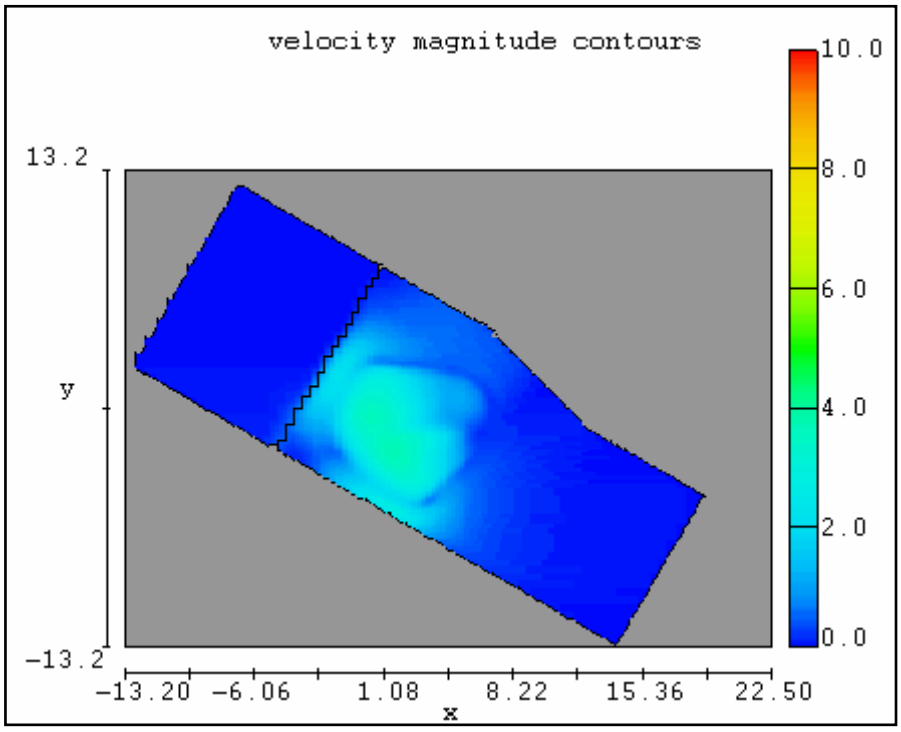


Figure 40. Velocity contours on pool bottom (colored by speed, ft/sec).

3.3.3.4. Conclusions of FCP Analysis

The following conclusions were reached as a result of these CFD analyses:[9]

As-Built System

The maximum exposure strain rate calculated in the fish collection pool is less than exposure strain rates associated with fish damage as reported by Nietzel et al. (2000).

Highest exposure strain rates were calculated in the transition flow at the entrance to fish collection pool (Figure 31 - Location 1). Exposure strain rates calculated at Location 1 were about the same as those calculated in the discharge pipe (200 cm/s/cm versus 217 cm/s/cm).

Exposure strain rates in the spoon (Figure 31 - Location 2) are comparable those in the entrance to the fish collection pool (Figure 31 - Location 1) before the spoon is fully submerged (187 cm/s/cm versus 200 cm/s/cm).

Relatively high exposure strain rates were calculated on the bottom of the pool (Figure 31 - Location 3) without cushion water (150 cm/s/cm).

[9] See Section 7.2.1 for overall study conclusions.

Alternative 1 – Circular Screen

Maximum calculated exposure strain rates at the end of the trough were equal to 70 cm/s/cm (compare to 187 cm/s/cm with the as-built system). The reduced slope of the trough and the elimination of the spoon, at the base of the trough, produced more uniform flow patterns in the area where the flow entered the pool.

The maximum calculated exposure strain rate along the screen face was equal to 75 cm/s/cm.

With 3.6 ft of cushion water - the maximum calculated exposure strain rate at the bottom of the pool was equal to 65 cm/s/cm (compare to 150 cm/s/cm without cushion water).

Alternative 2 – Drop Pool with 2 ft Cushion Water

Maximum calculated exposure strain rates in the plunging flow at the end of the trough were equal to 113 cm/s/cm. Elimination of the spoon and addition of cushion water effectively reduced exposure strain rates associated with the flow entering the pool (compare to 187 cm/s/cm with the as-built system).

With 2.0 ft of cushion water - the maximum calculated exposure strain rate at the bottom of the pool was equal to 115 cm/s/cm (compare to 150 cm/s/cm without cushion water).

Alternative 3 – Drop Pool with 3.6 ft Cushion Water

Maximum calculated exposure strain rates in the plunging flow at the end of the trough were equal to 100 cm/s/cm. Elimination of the spoon and addition of cushion water effectively reduced exposure strain rates associated with the flow entering the pool (compare to 187 cm/s/cm with the as-built system).

With 3.6 ft of cushion water - the maximum calculated exposure strain rate at the bottom of the pool was equal to 65 cm/s/cm (compare to 150 cm/s/cm without cushion water).

A summary of calculated exposure strain rates appears in Table 14.

Table 14. Exposure strain rates (fish collection pool).

Alternative Number	Feature	Velocity (fps)	Strain Rate (cm/sec/cm)
			North End
Existing	Entrance	16	200*
	Base of spoon	11.2	187
	Pool floor	9	150*
1	Entrance	16	200*
	Plunging flow	5	70
	Screen face	4.5	75*
	Pool floor	4	65*
2	Entrance	16	200*
	Plunging flow	14	113
	Pool floor	7	115*
3	Entrance	16	200*
	Plunging flow	12	100
	Pool floor	4	65*

* Exposure strain rate calculated near solid surface

3.4 Conclusions from Literature Review and CFD Analyses

The following conclusions were reached as a result of the evaluations presented above.

1. *Exposure strain rates (ε) in the existing fish collection pools and return pipes are less than exposure strain rates reported to be injurious to fish (Nietzel et al. 2000).*

In the Nietzel et al. study, there were no significant injuries to any fish subjected to exposure strain rates less than 341 cm/s/cm. This is the exposure strain rate associated with a 20.5 ft/sec jet (equation 1). At the Salem facility, maximum velocities in the fish collection pool and return system are less than 20.5 ft/sec. According to the results of the Nietzel et al. (2000) study, fish traveling through the collection pool and return pipe would not be injured.[10]

[10] Minor injuries were those that were visible but not life-threatening and tended to heal and disappear during the post exposure period. Small bruises (< 0.5 cm in diameter) with minor discoloration were also given a minor injury rating (Nietzel et al. 2000).

The exposure strain rate for major injury[11] and death was reported to be 508 cm/s/cm for juvenile salmonids and American shad (Nietzel et al. 2000). This is the exposure strain rate associated with a 30 ft/sec jet. Since typical velocities in the Salem fish collection pool and return system are much lower (about 40% less), the results of this study indicate that no mortality is expected from the hydraulic conditions in the existing fish collection pool and return pipe.

2. *Flow patterns into the fish collection pool and within the return system are different from the flow pattern discussed in the Nietzel et al. (2000) report. Therefore, the thresholds for injury at Salem may be different from the injury thresholds reported by Nietzel et al.*

In the Nietzel et al. study, fish were exposed to a shear environment produced by a submerged jet (See Figure 14) with velocities ranging from 0 to 70 ft/sec. Fish were released, in either a headfirst or tailfirst orientation, at the edge of the jet stream or within the jet stream and injury was caused by the flow patterns developed by the expanding jet.

Flow patterns into the fish collection pool and return pipe are different from flow patterns developed by Nietzel et al's expanding jet. Therefore, it is possible that the injury thresholds (for exposure strain rate) reported by Nietzel et al. may be different than the thresholds for the Salem facility. For instance, the length of time that fish were exposed to the turbulent jet in the Nietzel et al. experiment is likely different from the length of time that fish are exposed to the turbulent flow in Salem's, return pipe and the effect of this difference on injury and mortality cannot be determined from available literature. It is worth noting, however, that exposure strain rates in the Salem facility are about 40% less than the exposure strain rates associated with major injury and death of the Nietzel et al. (2000) test fish.

3. *Direct comparison between the results of the Nietzel et al. (2000) study and the results of other researchers (e.g., Turnpenny et al. 1992) is not possible.*

Previous research has addressed fish injury caused by turbulent flows. However, velocity distributions and time series associated with the turbulent flows have not been reported. Because of this, exposure strain rates reported by Turnpenny (1992) and others cannot be compared to the Nietzel et al. reported values without question. As a result, the Nietzel et al. (2000) study is unique. In many cases, however, the results of previous research supports the Nietzel et al. findings (*e.g.,* Groves [1972] reports that juvenile salmon were unaffected by exposure to jet velocities up to 30 ft/sec).

[11] Major injuries were those that resulted in prolonged loss of equilibrium and the more severe injuries that persisted throughout the post-exposure observation. For example, large bruises (> 0.5 cm in diameter), damage to spinal column, cuts with bleeding, injured eyeballs, gill damage, and descaling (Nietzel et al. 2000).

4. *Laboratory testing to verify the results of the hydraulic analyses is recommended.*

Velocities in the fish collection pool and return system at Salem are less than those associated with major injury and death in the Nietzel et al. study.[12] However, flow patterns in the fish collection pool and return pipe at Salem are different from those in the Nietzel et al. (2000) study. Hence, the mechanisms for fish injury may be different as well (*e.g.,* by design the Nietzel et al. study does not address abrasion; however, abrasion could cause injury to fish as the collection pool fills). For this reason, it was recommended that laboratory testing be performed, to verify the results of the hydraulic analyses. Accordingly, a test facility capable of incorporating existing and alternative return pipe and collection pool components was constructed at Alden. Additionally, studies were conducted at Salem to examine, concurrent with the laboratory studies, the effect of cushion water depth and flow on rate of survival. These laboratory and field studies are presented in Sections 4 and 5.

[12] Typical velocities at Salem are about 40% less than those associated with exposure strain rates that caused major injury and death in the Nietzel et al. study.

Section 4
Study Methods (Laboratory and Field)

4.1. Test Species

The Representative Important Species (RIS) developed as part of G.2.b.i at Salem are presented in Table 15 (PSEG 2001a, 2001b, 2001c). From this list, the alewife was selected to be the target species for evaluating design and operational changes to the fish return and sampling system at Salem. The alewife is considered an appropriate representative for several reasons. Anadromous alewife are collected at Salem and are one of the Salem RIS. Since the alewife is a member of the same family as blueback herring and American shad (both Salem RIS), and since species from the same family exhibit similar morphologies and behaviors, alewife may provide valuable information on several of the Salem RIS. The alewife is a relatively fragile species, in part due to its highly deciduous scales and susceptibility to injury. Thus, the differences in mortality observed under different test conditions using alewife are indicative of other fragile RIS at Salem (*e.g.,* bay anchovy and blueback herring), and should be conservative for other more robust RIS.

Table 15. Common name, family and species comprising the Salem RIS.

Common Name	Family	Species
Blueback herring	Clupeidae	*Alosa aestivalis*
Alewife		*Alosa pseudoharengus*
American shad		*Alosa sapidissima*
Bay anchovy	Engraulidae	*Anchoa mitchilli*
Striped bass	Percichthyidae	*Morone saxatilis*
White perch		*Morone americana*
Weakfish	Sciaenidae	*Cynoscion regalis*
Spot		*Leiostomus xanthurus*
Atlantic croaker		*Micropogonias undulatus*

Alewives similar in length to other impinged RIS species (40 – 130 mm FL) are readily available in large numbers for use in laboratory and field tests and have been successfully held and tested at Alden in many past studies. The completed G.2.b.ii studies were not intended to quantify survival or critical stressor levels for all vulnerable RIS, but rather to generally identify the potential change in survival that might occur if the existing fish return and collection systems were modified. Changes in survival rates can serve as an indication of potential changes that may be realized with the vulnerable RIS.

The lengths of alewife that were evaluated ranged from 48-142 mm FL (mean 79.4 mm). All alewife were collected from Greenwood Lake in Hewitt, NJ and transported via tank truck to either the Alden or Salem fish holding facilities with <1.0% mortality at time of delivery and about 5.0% total mortality 72-hours after delivery. In addition to alewife, a small group (N=178) of weakfish collected in the Delaware River via trawls, were tested in the EOP test facility under conditions that matched the existing Salem EOP system.

4.2. Description of Fish Holding Facility

At Alden, fish were held in a 6,400-gallon (24,227-liter) recirculating system. Fish were held in one of six cylindrical tanks and each tank drained into a central pool. Water was pumped through water treatment filters before being pumped back to the fish holding tanks. Bag filters and an activated charcoal filter were used to remove solid waste materials and other impurities. An ultraviolet light sterilizer and a fluidized bed (sand) bio-filter were used to control bacteria and soluble waste products. Water quality (dissolved oxygen, temperature, and salinity) was monitored daily and salinities were maintained between about 10 and 18 ppt to match conditions at Salem and to minimize the occurrence of fungal growth common on alewife held in fresh water systems. Hardness, alkalinity and ammonia levels were monitored weekly.

Circular flow patterns were maintained in the fish holding tanks to keep fish active and minimize fish contact with the tank walls that could cause scale loss. Fish were initially fed crushed frozen brine shrimp and were weaned onto fine-grained trout chow within a few days of arrival. At no time during holding did any alewife show signs of disease, fungus, or infection by parasites.

4.3. Fish Marking

A method for discerning between treatment and control fish was necessary to permit treatment and control fish to be run simultaneously. However, marking fragile species can result in high mortalities. To determine if scale loss associated with handling alewife during fin clipping would result in unacceptable mortality, a group of 50 fish were clipped and held for 72-hours. No delayed mortality was observed and fin clipping was determined to be a suitable method for differentiating groups of fish. Logistically, fin clipping was not possible for FCP tests conducted at Salem, so a consecutive treatment-control method was used instead.

For EOP and FCP studies conducted at Alden, alewife were marked with a dorsal fin clip to differentiate treatment (unclipped) and control fish (clipped). Fish to be tested were taken from the most densely populated holding tank to maintain consistent conditions between tanks. Fish were marked 24-hours prior to testing using the following methods:

- An anesthetizing solution was prepared in a five-gallon bucket using 1.2 ml of clove oil solution per gallon of water;
- Approximately 50 alewife were removed from the holding tanks with flat nets and placed into the anesthesia bucket;
- Any fish injured, or showing signs of disfigurement were discarded;
- Once anesthetized, individual fish were removed by hand and either clipped and placed in the control recovery bucket, or held and placed in the treatment recovery bucket;
- Fifty treatment and control fish were processed concurrently to ensure that both groups were anesthetized for the same length of time;
- Fish were clipped on the dorsal fin using a hole punch as illustrated in Figure 41;
- In any case where the fin clip was not pronounced (*i.e.,* difficult to discern from unmarked fish) or if the clip nicked the body of the fish, then the fish was discarded and another was used;

- Fish were allowed to recover until all fish were oriented vertically in the buckets and swimming normally;
- Once recovered, fish were transferred into numbered, 1.3-ft diameter, 3/8-inch ace weave mesh cylindrical net pens using in-water transfer techniques to avoid injury; and
- Net pens were closed and floated on the 18-ft holding pool until testing. Pens were arranged within the pool to prevent folds or excessive overlap with other pens that could trap and injure fish.

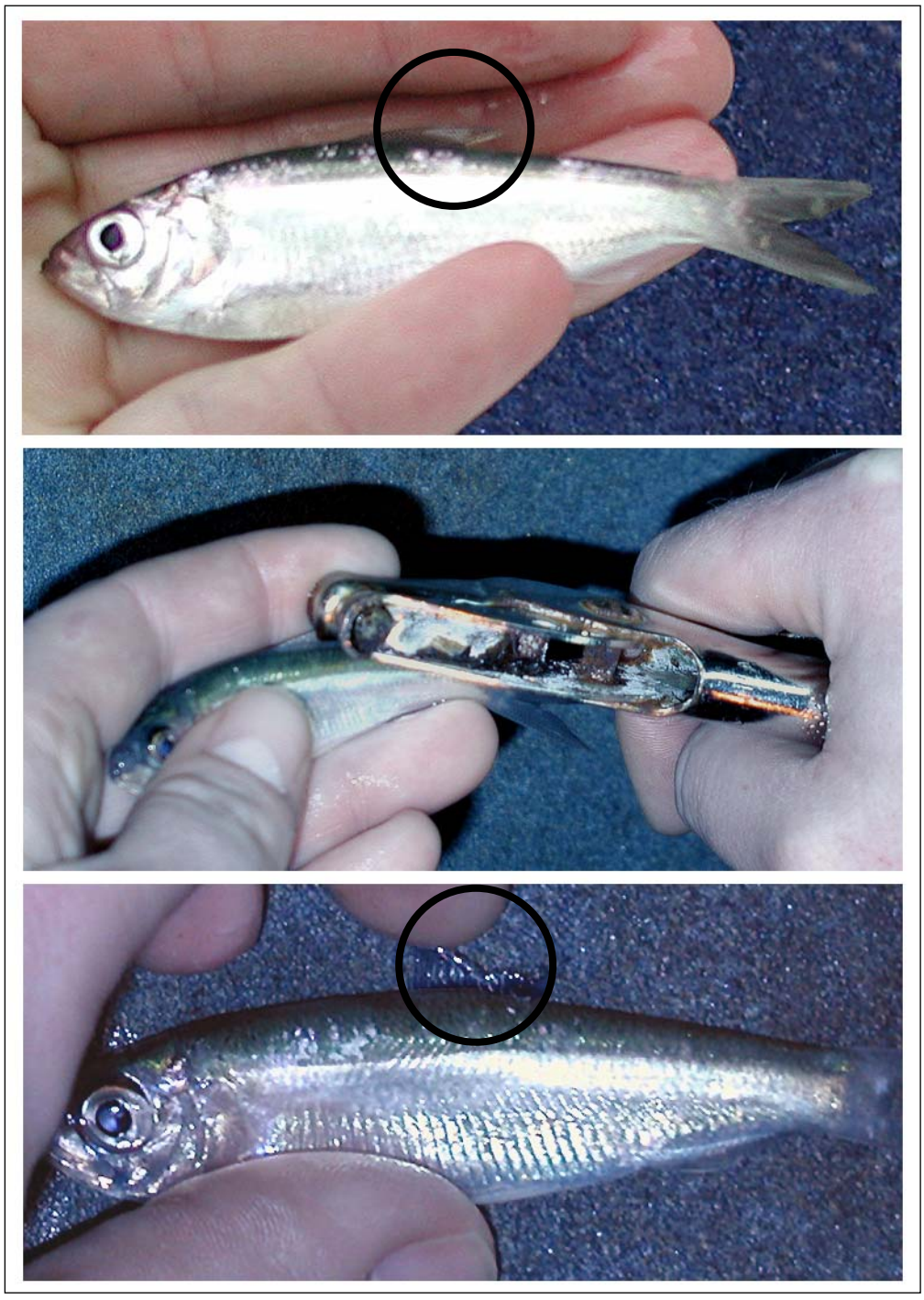


Figure 41. Alewife fin clipping: before (top), during (middle) and after procedure (bottom).

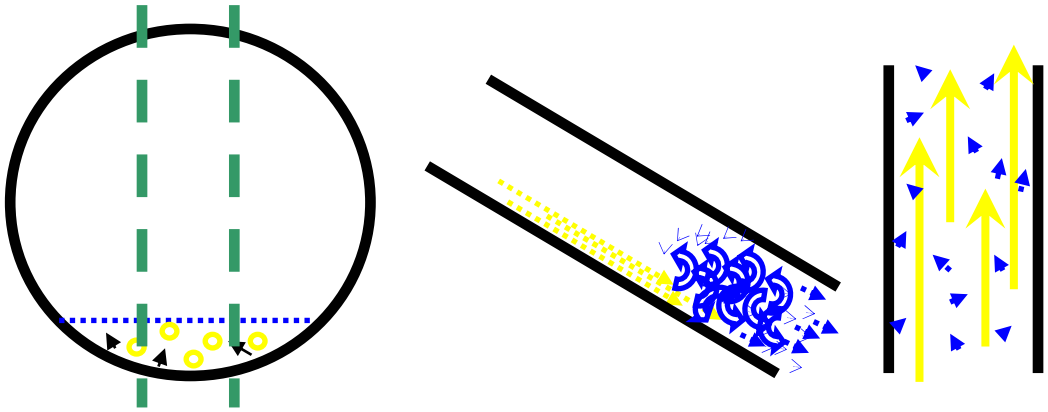
4.4. End-of-Pipe Testing

The CFD analyses of the existing fish return system indicated that a hydraulic jump occurs as flow enters the Delaware River in the 40-in. diameter discharge pipe. CFD analyses of alternative system designs indicated that bounded flows (*i.e.,* flows within the 40-in. return pipe) resulted in higher stressor levels than un-bounded flows (*i.e.,* freefall). CFD models of the existing EOP configuration and freefall conditions showed that with identical water velocities, hydraulic conditions were less turbulent and shear stresses lower in flows entering the river in a freefall.

Alden constructed a test facility to conduct fish survival experiments for both the existing condition and design Alternatives 1 and 2. A sectional design (described below) was used to replicate conditions within the EOP portion of the return system at the Salem. Alternative conditions were created by removing portions of the return trough to allow returning flows to freefall into the collection pool.

Sectional Design

The EOP analyses were conducted in a 12-in wide test section representing the center portion of the return pipe (Figure 42 [a]). The height of the test section was kept the same as the diameter of the return pipe at Salem, so the expanding flow in the lower portion of the pipe could develop over a similar distance compared to the "full-scale" flow at Salem. The flow expansion in the return pipe takes place primarily in a vertical plane (Figure 42 [b] and [c)]). By maintaining the proper expansion "diameter" and apportioning flow into the test section properly; a shear environment equivalent to the one in the return pipe at Salem was developed in the test section.



(a) Section (b) Profile (c) Plan

Figure 42. Schematic representations of flow in the existing EOP at Salem: (a) sectional view including water level – dashed lines indicate 12-in. section used for laboratory testing; (b) profile view of flow reentering the river; and (c) plan view of velocities within the EOP.

Using a test section rather than a full-pipe reduced the amount of flow (cfs) required for laboratory testing yet maintained hydraulic conditions similar to the existing Salem fish return system. Results of the HEC-RAS analysis indicated that a 5 cfs flow through a 12-in. wide test

section would produce similar hydraulic conditions to the existing 13 cfs flow exiting through the 40-in.pipe at Salem (Table 16).

Table 16. Results of a HEC-RAS analysis comparing the EOP at Salem to the sectional EOP facility at the laboratory.

Facility Description	Flow (cfs)	Trough to pipe transition		Pipe to pool transition		Pipe exit	
		Average Velocity (ft/sec)	Average Depth (ft)	Average Velocity (ft/sec)	Average Depth (ft)	Average Velocity (ft/sec)	Average Depth (ft)
Salem As-built	13.0	16.7	0.4	23.4	0.4	-	-
Alden Test Facility	5.0	18.8	0.3	23.0	0.2	-	-
Salem Alt 1	13.0	16.7	0.4	-	-	23.8	0.4
Alden Test Facility Alt 1	5.0	18.8	0.3	-	-	22.6	0.2
Salem Alt 2	13.0	16.7	0.4	-	-	18.0	0.4
Alden Test Facility Alt 2	5.0	-	-	-	-	18.8	0.3

4.4.1. Test Facility and Alternatives

As discussed previously, there are minor differences between the North and South discharge systems (See Figure 6 and Figure 7). The decision to model the North end discharge in the laboratory was based on the CFD and HEC-RAS models developed as part of stressor identification. Results of these analyses indicated that stressor levels were higher in the North end discharge than in the South end and, therefore, had higher potential to adversely impact fish. Details describing the calculated flow through both systems were compared to mortality data provided by PSEG and identified stressors. Hydraulic conditions in the return pipe change as the water level fluctuates with the tide. Results of the CFD models were used to determine which water level created the conditions with the greatest potential to injure to fish and it was determined that low tide conditions should be modeled in the laboratory.

The end-of-pipe and fish collection pool test facilities were designed to represent the hydraulic conditions of the existing configuration of Salem's fish collection and return systems. The EOP and FCP studies were conducted in an outdoor facility shown on Figure 43 and Figure 44. The test facility consisted of a steel tank, circulating piping, a 100-hp pump, EOP head tank and troughs, FCP head tank and troughs, and a 63,000 gallon concrete storage tank (Figure 45, Figure 46, Figure 47, Figure 48, and Figure 49 respectively). Flow in the test facility was set using a flow meter installed downstream of the pump discharge. The flow meter was equipped with a Rosemount Model 3051C Differential Pressure Transducer (DP cell). Power was supplied by a 200 hp generator with a variable frequency drive which varied the speed of the pump to set different flow rates. The EOP arrangements are discussed below. The FCP arrangements are discussed in Section 4.5.1.1.

4.4.1.1. End-of-Pipe

The EOP test arrangement is shown on Figure 50 (profile) and Figure 51 (plan). The 100-hp pump was used to circulate flow through the test facility. Water was withdrawn from the collection pool through an intake screen into a 10 in. diameter PVC pipe to the pump intake. The discharge of the pump was connected to a 10 in. diameter PVC pipe attached to the EOP head tank. A flow meter was installed between the pump and the EOP head tank to measure flows and the variable frequency driver was used to control and set flow rates by varying the speed of the pump. The flow meter consisted of an orifice plate installed in the 10 in. diameter pipe and differential pressure was measured across the orifice plate using the DP cell to determine flow rates. The EOP head tank was located on a wooden support platform approximately 20 ft above the ground. The head tank was constructed of steel and MDO plywood and was 8-ft long, 4-ft wide, and 4 ft-deep. A wooden trough extended from the EOP head tank to the collection pool and represented the as-built and proposed alternative conditions at Salem's fish return system.

The first EOP trough section from the EOP head tank was 13.8 ft long, was set at a downward slope of 41.7 %, and was 12 in. wide by 24 in. deep. The second EOP section was 10.4 ft long, was set at a slope of 18.7%, and was 12 in. wide by 24 in. deep. The last EOP section represents the as-built condition of Salem's North unit fish return pipe. This section was set at a vertical angle of 34 degrees, 12 in. wide and 40 in. deep and consisted of a steel frame with clear acrylic sheathing (Figure 52). The invert of the EOP trough exit was set at an elevation of 84 ft, with the bottom of the collection pool at an assumed elevation of 82.5 ft.

The EOP tests were conducted with a flow rate of 5 cfs to create hydraulic conditions that matched identically the calculated shear conditions at the exit of the fish return pipe at Salem under the normal flow rate of 13 cfs.

Two additional EOP configurations were tested to represent potential alternatives to the existing configuration of Salem's fish return system. Alternative 1 is shown on Figure 53. This alternative is similar to the initial EOP test facility with the last 12 ft of trough removed and with an exit trough invert set at an elevation of 89 ft (Figure 54). This exit condition created a 1.3-ft freefall. The second alternative is shown on Figure 55. This alternative is similar to Alternative 1 with an additional trough section removed set the invert elevation at 94.2 ft. This alternative mimics an exit condition where the returning flow would freefall 6 ft before entering the River (Figure 56).

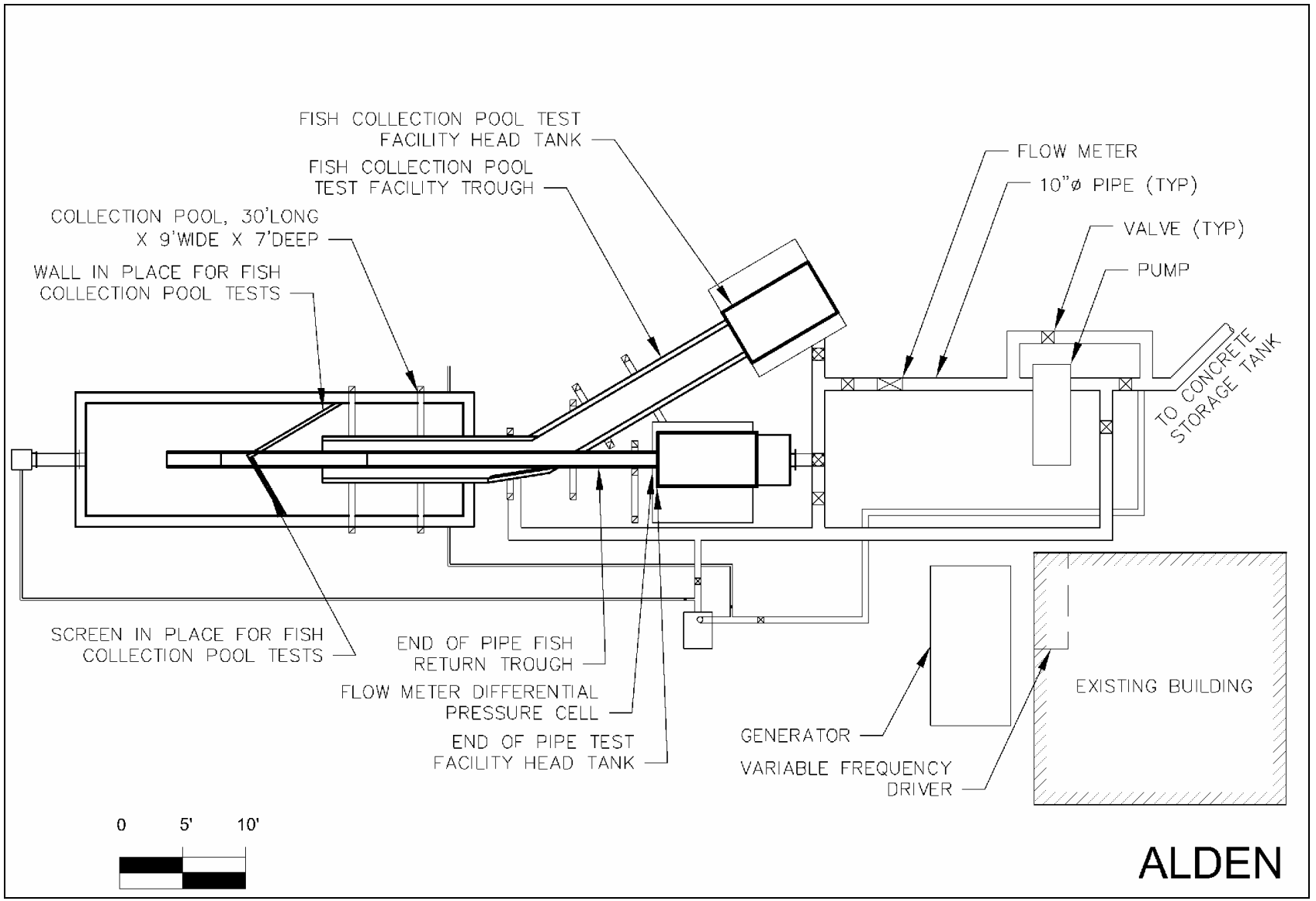


Figure 43. EOP and FCP test facility layout. Shown with the existing EOP trough and FCP spoon/walls in place.

Figure 44. EOP and FCP facility at Alden Research Laboratory. The 6-ft freefall condition is shown.

Figure 45. Steel fish collection pool during construction of the EOP and FCP test facility.

Figure 46. A portion of the 10-in. diameter piping used to fill the EOP and FCP test facility.

Figure 47. Installation of the EOP head tank at the Alden test facility.

Figure 48. Head tank for the FCP test facility.

Figure 49. North end (top) and inside view (bottom) of the 63,000 gallon concrete storage tank.

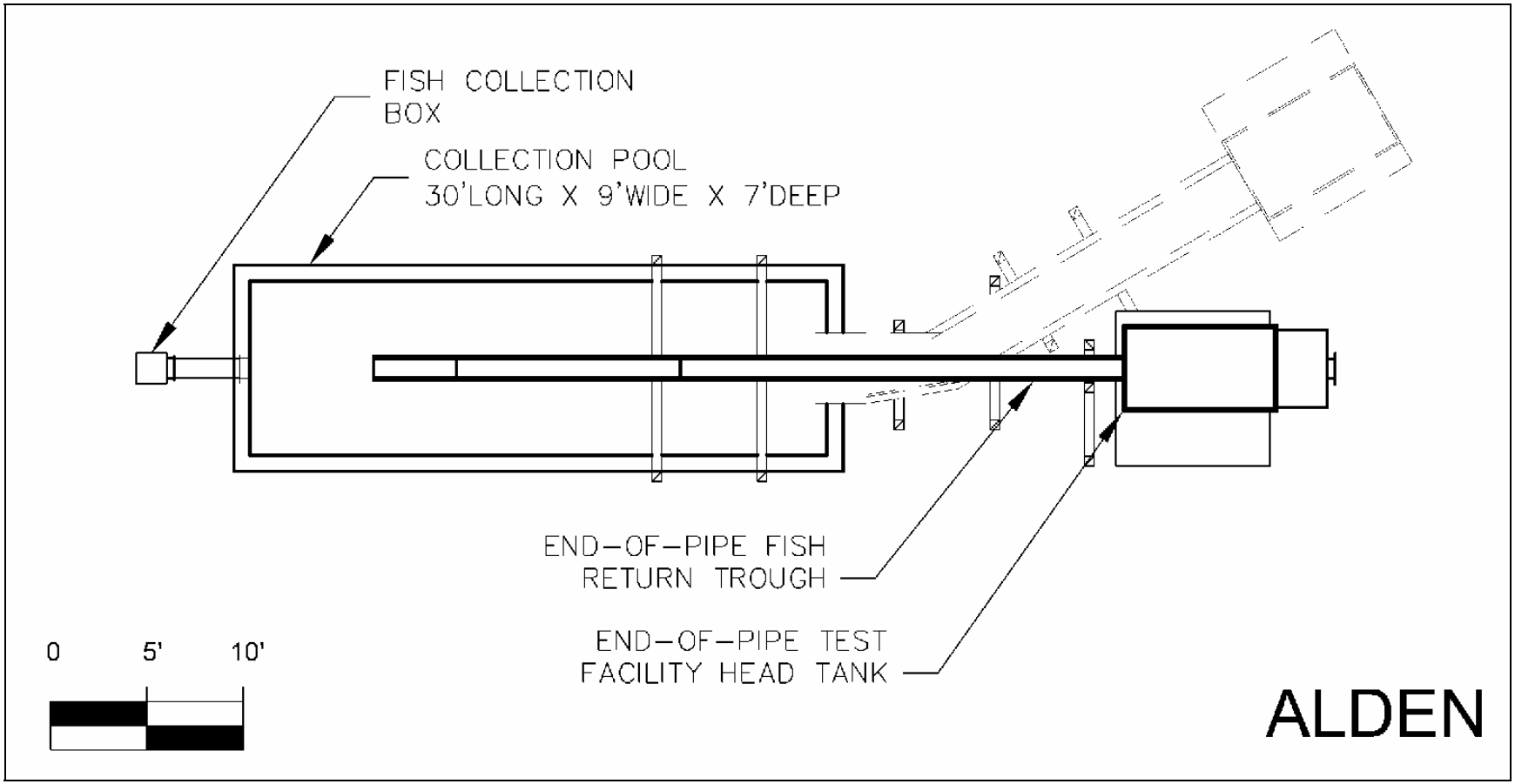


Figure 50. EOP test facility plan. Existing condition trough is in place.

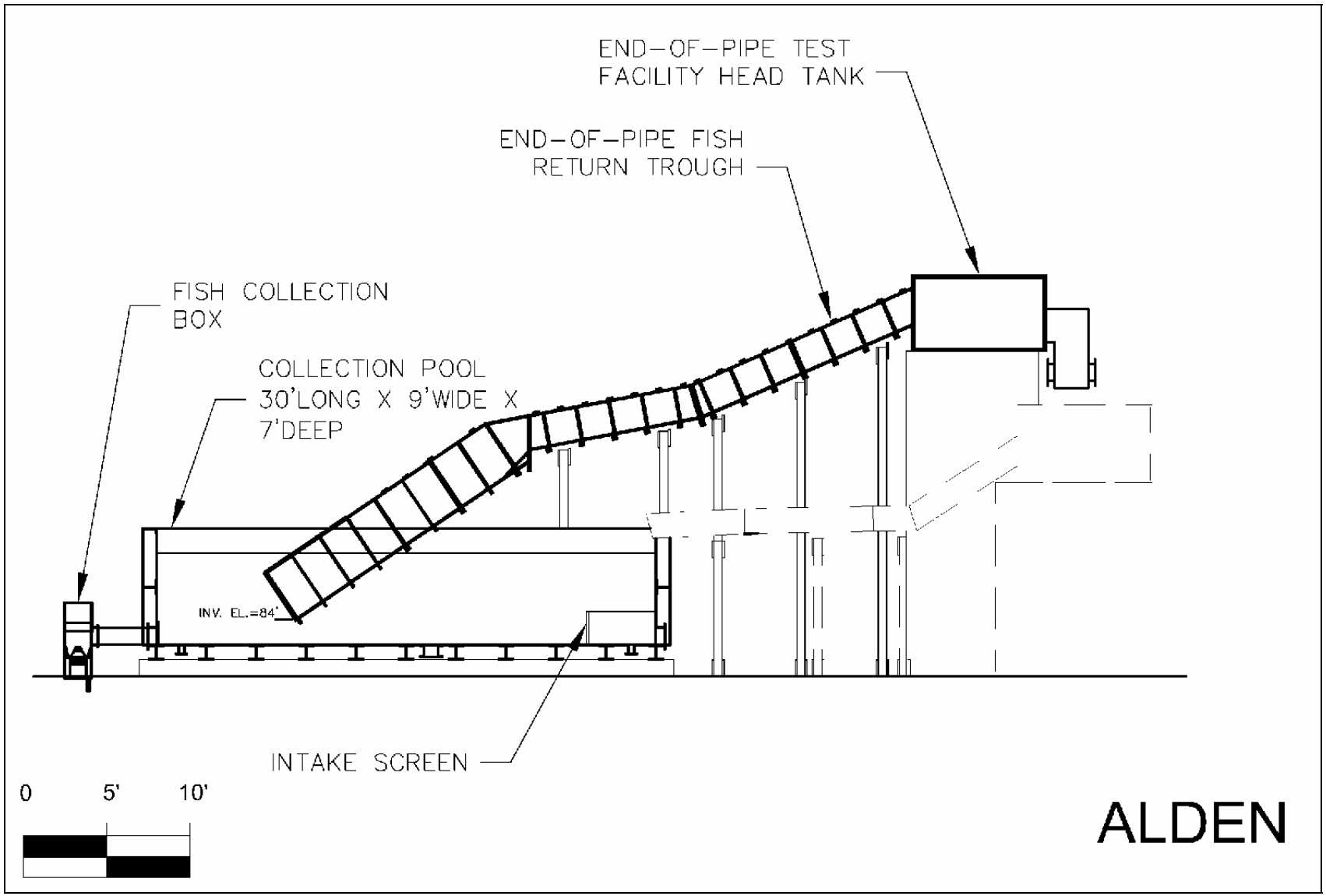


Figure 51. EOP test facility elevation. Facility is shown in the existing condition EOP configuration.

Figure 52. EOP test facility with troughs in place to simulate existing conditions at the North Salem fish return system.

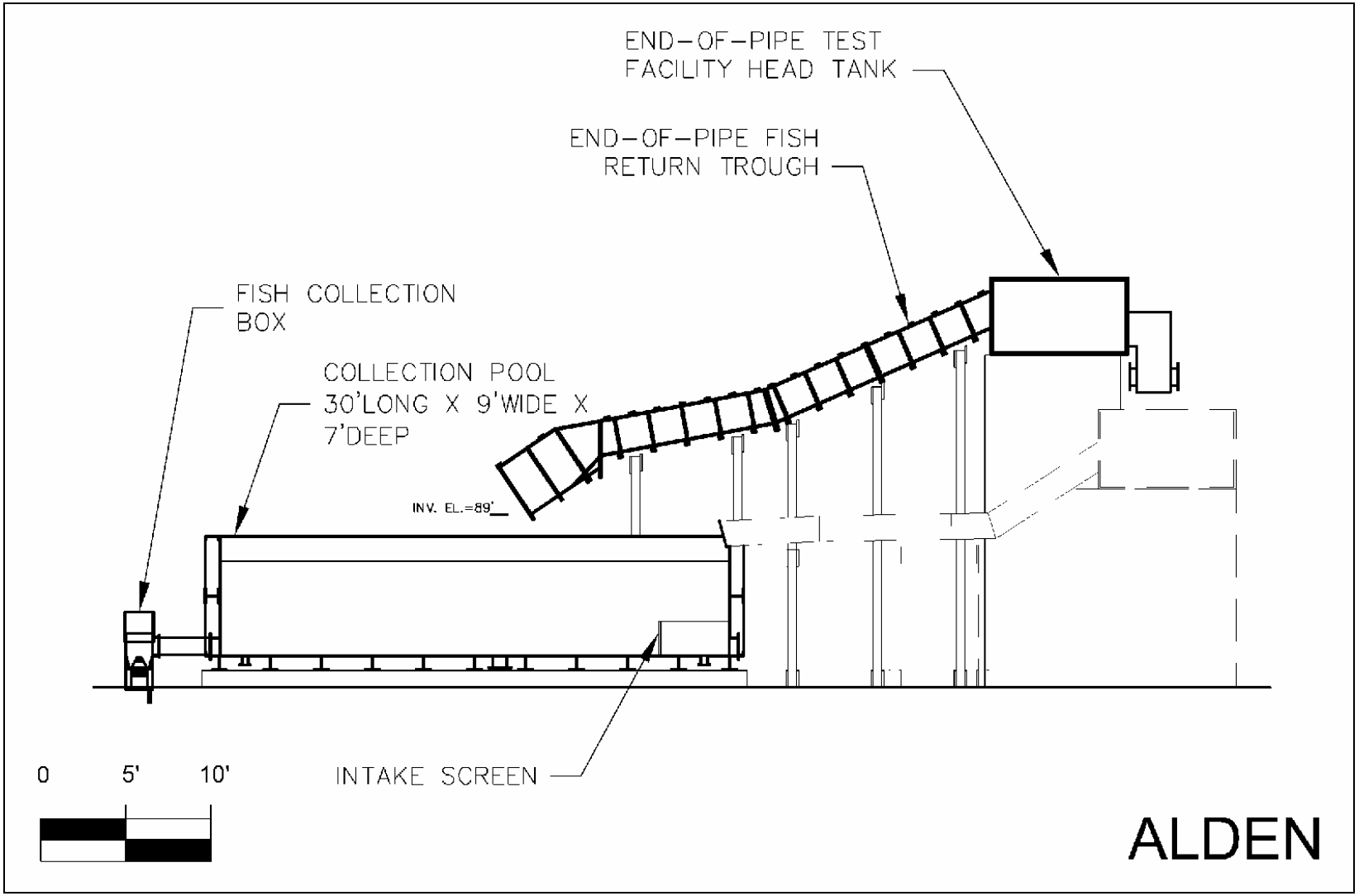


Figure 53. EOP Alternative 1 test facility elevation. Facility is shown in the 1.3-ft configuration.

Figure 54. EOP Alternative 1 test configuration. Facility is shown with a 1.3-ft freefall.

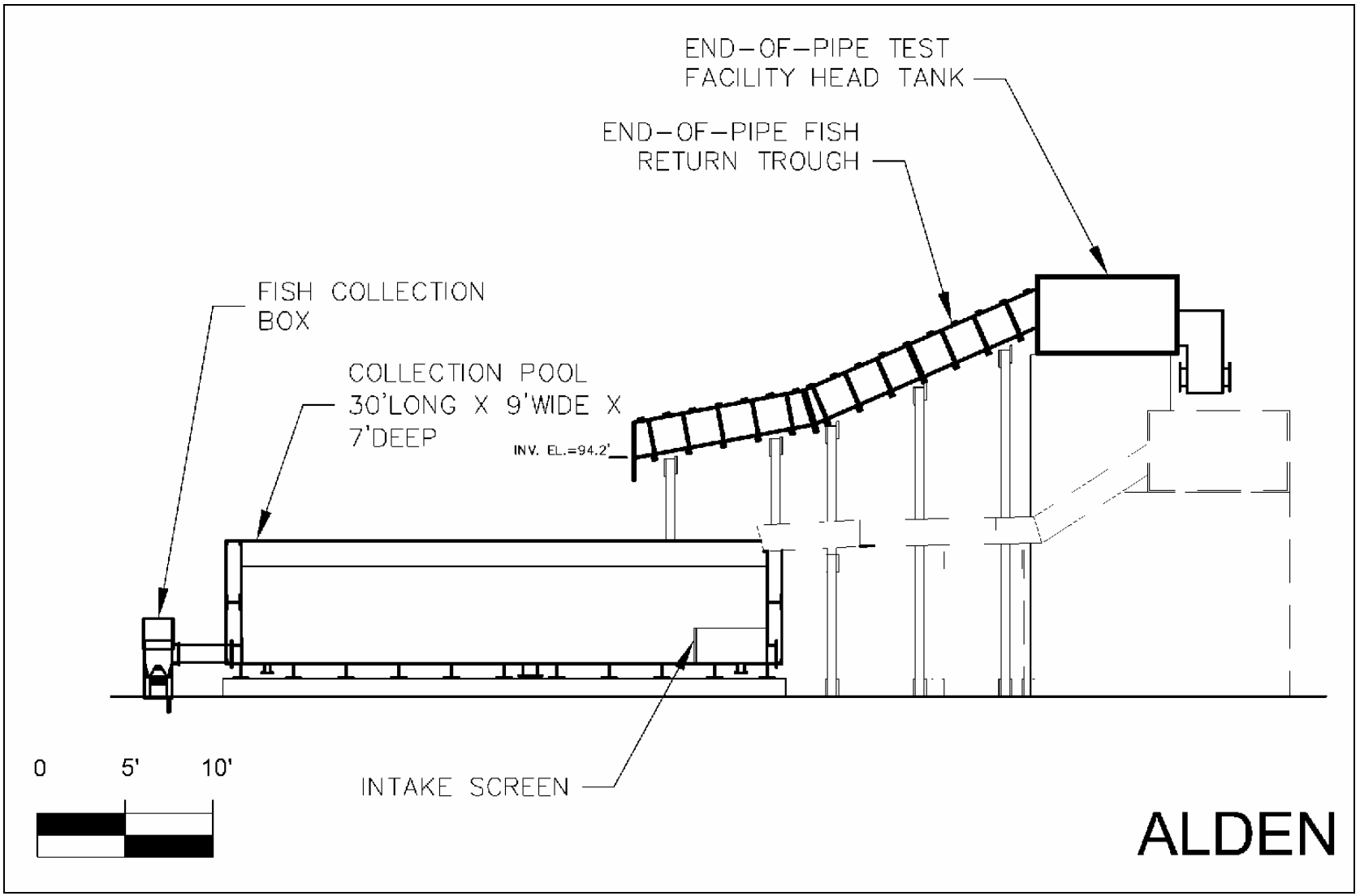


Figure 55. EOP Alternative 2 test facility elevation. Facility is shown in the 6-ft freefall configuration.

Figure 56. EOP Alternative 2 test configuration. Facility is shown with a 6-ft freefall.

4.4.2. Experimental Design

The experimental design was selected to determine the extent to which the existing EOP (containing the hydraulic jump) might be causing fish injury or mortality and to assess whether alternative designs might reduce such injury and mortality. Constructing the existing EOP in the laboratory provided a baseline of survival information to compare with survival of fish exposed to the two alternative designs. Selection of the study parameters was influenced by the analysis of the existing return system, CFD and HEC-RAS model results, and identification of practicable design alternatives for the Salem return system. Test procedures for evaluating the existing and alternative return pipe configurations are presented individually in Table 17 below.

Table 17. End-of-pipe testing scenario.

Condition	Configuration	Release Point	Number of Replicates	Number of Fish Per Replicate	Quantitative Analysis
Existing conditions Treatment Control	Salem	Head tank Collection pool	6	50	Percent survival
Alternative 1 Treatment Control	1.3-ft freefall	Head tank Collection pool	6	50	
Alternative 2 Treatment Control	6-ft freefall	Head tank Collection pool	6	50	

Results from each of the three conditions were compared against each other to determine if significant differences in survival were evident between treatments.

4.4.3. Test Procedures

Treatment (unclipped) and control (clipped) fish were transferred from 2-ft diameter net pens held in the fish holding pool into separate 5-gallon buckets or tubs and transported to the test structure (Figure 57). Prior to the introduction of test fish, the collection pool was filled to a depth of 5.5 ft and the valve settings were adjusted to create a closed recirculating system. The bottom edge of the trough was set at a depth of 4 ft for all tests of the existing system. The flow rate was calibrated to 5 cfs using the DP cell and flow meter described in Section 4.4.1. Once the system reached a steady state (*i.e.,* when the flow and water levels were constant), alewife were released into the test structure from two different points: treatment fish were released into an enclosure inside the head tank (Figure 58) and allowed to pass naturally down the sectional return trough and into the collection pool (Figure 59). Simultaneously, control fish were released into the collection pool in a calm portion of the tank located behind the EOP trough (Figure 60). Flow was stopped 3 minutes following the introduction of fish, and water was pumped out of the collection pool and back into the concrete reservoir tank. In the collection pool, the water level was dropped to 6 in. The alewife exhibited strong schooling tendencies allowing them to be cornered and removed with a flat net (Figure 61). Flat nets allowed the removal of fish while

minimizing fish-to-fish contact that can cause scale loss. This collection method was used throughout EOP and FCP testing (conducted at Alden or Salem) to minimize potential handling injury or mortality. Any dead fish were removed and measured. The remaining fish were removed from the testing structure were transferred to the latent survival holding facility. Fish were inspected immediately, 1-hour, 24-hours, and 48-hours after testing. Dead fish were removed, counted, measured, and recorded.

Figure 57. Fish holding facility with floating 2-ft diameter round and open top square net pens.

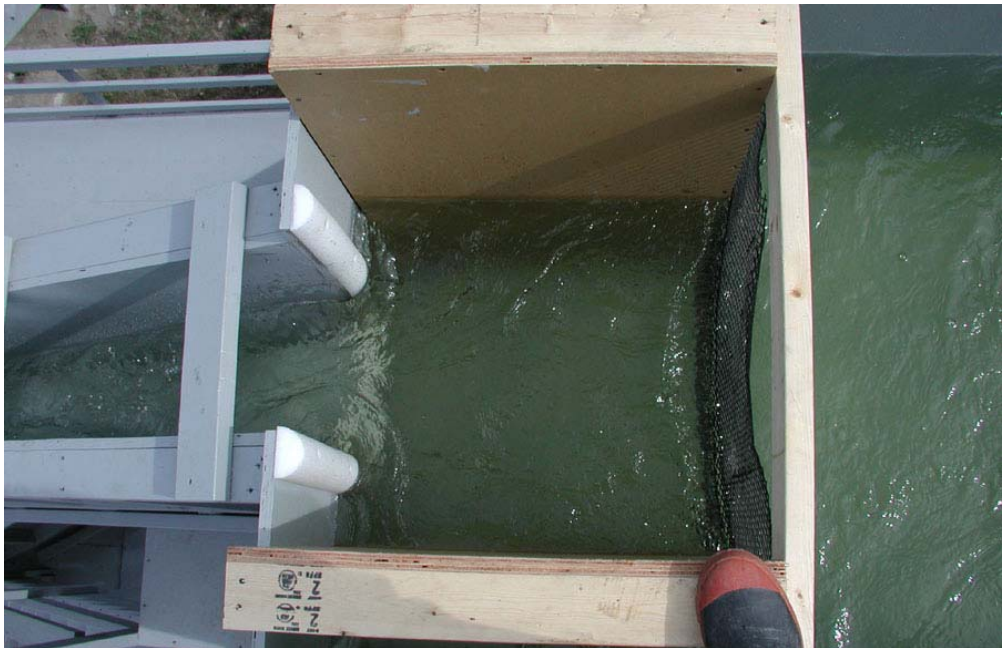


Figure 58. Top view of the head tank fish release structure for EOP testing.

Figure 59. Return trough and collection pool for EOP testing. Existing condition shown.

Figure 60. View of EOP sectional return trough looking downstream from the head tank. Control fish were released in the calm area behind return trough (next to red bucket).

Figure 61. Flat net collection method from the EOP collection pool.

Portions of the EOP test trough were removed to create freefalls of two different heights. These heights - 1.3 ft, and 6-ft (referred to as the 1.3-ft and 6-ft freefalls respectively) - reflect conditions that would be created at Salem should Alternative 1 or Alternative 2 be implemented. The 1.3-ft drop mimics the termination of the North return pipe at the existing sheetpile wall. Figure 62 is a profile drawing of the North return pipe at Salem with the pipe truncated at the sheetpile wall and Figure 63 is a photograph of the 1.3-ft drop configuration of the EOP at Alden. The 6-ft drop reflects the freefall that would exist if the North return pipe were re-set at a shallower angle (18.7° slope) to match the existing return trough angle. Figure 64 is a profile drawing of Alternative 2 for the North return pipe at Salem. Figure 65 is a photograph of the 6-ft drop configuration of the EOP at Alden. Once reconfigured, the alternative tests were conducted using the same methodology as described above for the existing return pipe testing.

4.4.4. Data Analysis

Analysis of EOP test results used raw data to develop survival estimates for each replicate-release. An analysis of variance (ANOVA), mean survival by treatment group, and the associated 95% confidence intervals were also reported.

The treatment design consists of three treatments:

- Existing conditions at Salem;
- 1.3-ft freefall; and
- 6-ft freefall.

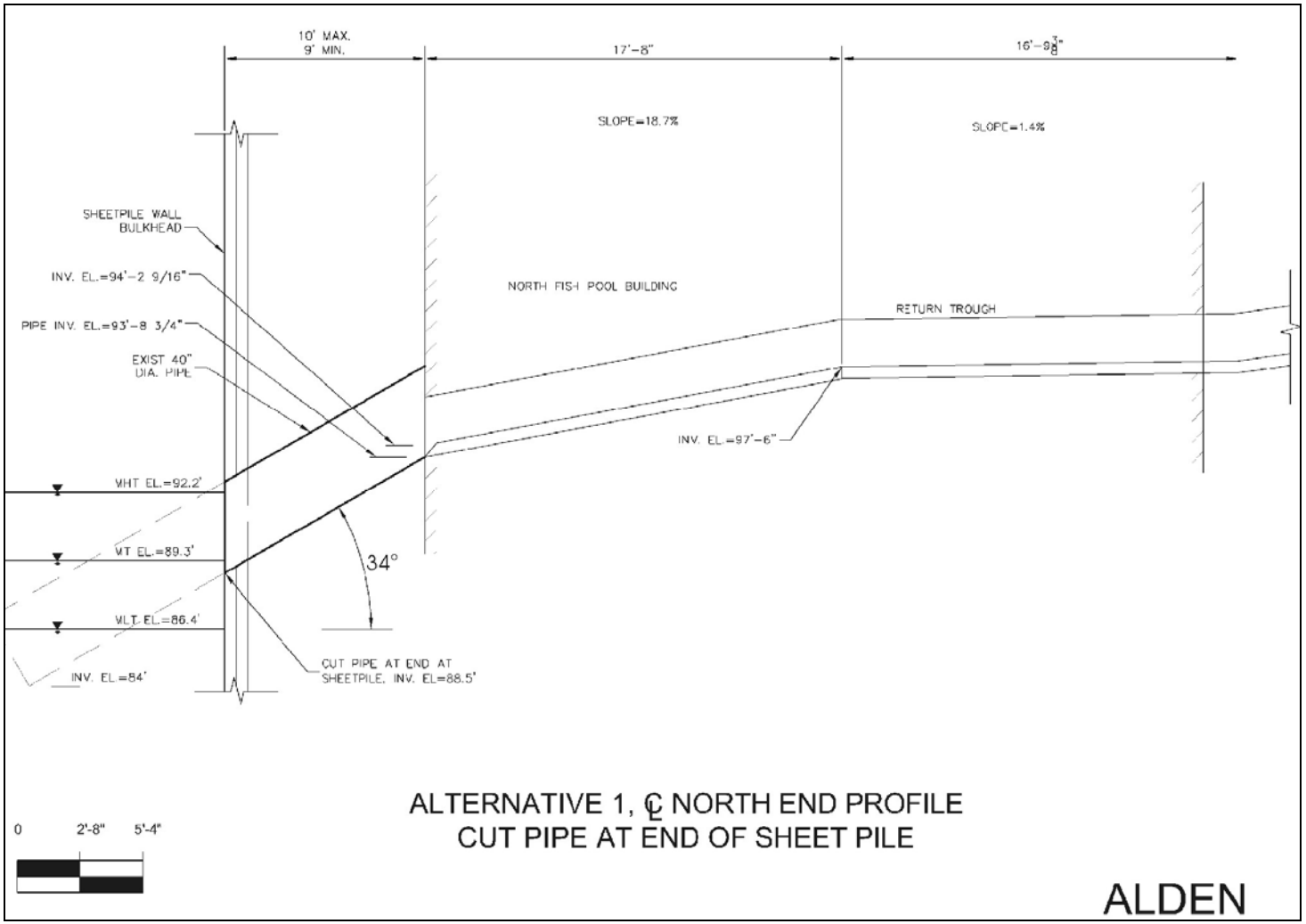


Figure 62. Profile of Alternative 1 for the North fish return system – 1.3-ft freefall. View extends from the sampling building to the Delaware River.

Figure 63. Front and side view of EOP laboratory testing – Alternative 1, 1.3 ft freefall condition.

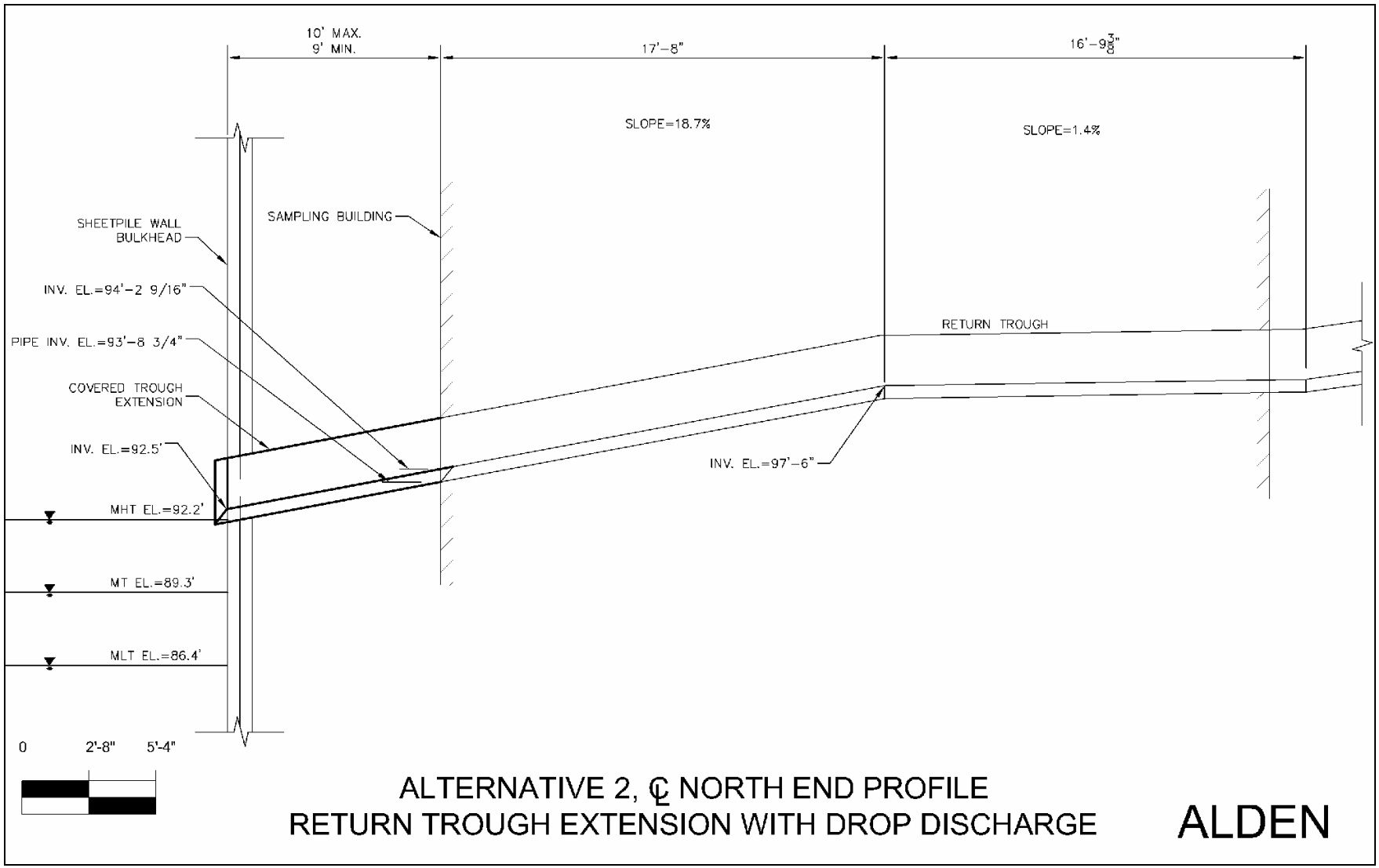


Figure 64. Profile of Alternative 2 for the North fish return system – 6-ft freefall.

Figure 65. Front and side views of EOP laboratory testing – Alternative 2, 6-ft freefall condition.

With each treatment, a corresponding release of control fish was used to characterize handling and recapture effects. The logistics of performing tests under the three configurations precluded the trials from being performed in an intermixed and random order. Hence, each treatment was conducted separately. As such, treatment comparisons may be confounded with time. Consequently, the study design is more correctly defined as a comparative observational study rather than a true experiment. Replicate trials under a specific test condition were performed. For a single trial, let:

R_C = number of control fish released (tank),
R_T = number of treatment fish released (trough),
c = number of control fish recovered alive to the end of the study,
t = number of treatment fish recovered alive to the end of the study.

The joint likelihood model describing the test results is then:

$$L = \binom{R_C}{c} S^C (1-S)^{R_C - c} \cdot \binom{R_T}{t} (SS_T)^t (1-SS_T)^{R_T - t}$$

where

S = probability a fish survives the handling process,
S_T = probability a fish survives passage through the pipe.

The maximum likelihood estimators for the above model then are

$$\hat{S} = \frac{c}{R_C}$$
$$\hat{S}_T = \frac{tR_C}{R_T c} \qquad (2)$$

with associated variance estimators

$$\widehat{Var}(\hat{S}) = \frac{\frac{c}{R_C}\left(1 - \frac{c}{R_C}\right)}{R_C}$$
$$\widehat{Var}(\hat{S}_T) = \hat{S}_T^2 \left[\frac{1}{t} - \frac{1}{R_T} + \frac{1}{c} - \frac{1}{R_C}\right]. \qquad (3)$$

For each trial, an independent estimate of $\hat{S}_T$ was computed along with its associated variance estimator.

A test of treatment differences was based on an F-test for a one-way ANOVA of the form:

Source	DF	SS	MS	F
Total	$3n$ *			
Mean	1			
$\text{Total}_{\text{Cor}}$	$3n-1$	SSTOT		
Treatments	2	SST	MST	$F_{2,3(n-1)}=\dfrac{\text{MST}}{\text{MSE}}$
Error	$3(n-1)$	SSE	MSE	

* n = number of replicate trials per treatment

The response variable in the analysis was $\ln \hat{S}_T$ which has an approximate variance of

$$\widehat{Var}\left(\ln \hat{S}_T\right)=\left[\frac{1}{t}-\frac{1}{R_T}+\frac{1}{c}-\frac{1}{R_C}\right].$$

If a weighted ANOVA is appropriate, the weights (w) should be inversely proportional to the variance where

$$W=\frac{1}{\widehat{Var}\left(\ln \hat{S}_T\right)}=\left[\frac{1}{t}-\frac{1}{R_T}+\frac{1}{c}-\frac{1}{R_C}\right]^{-1}. \qquad (4)$$

Adjusting the treatment survival $(\hat{S}_T)$ for the control survival rates $(\hat{S})$ should help account for confounding that may be exhibited through changes in fish viability and control handling mortality. It should be noted that this adjustment is based on the model assumption of multiplicative effects, *i.e.*,

$$E(t)=R_T\cdot S\cdot S_T.$$

Multiple comparisons using a Dunnett (1955) test (See Zar 1984:194-195) were used after the ANOVA to compare the existing configuration at Salem with the alternatives. One-tailed tests were performed of the form

$$\text{H}_\text{o}: \quad \hat{\bar{S}}_{\text{Exist}} \geq \hat{\bar{S}}_{\text{Ne}}$$

$$\text{H}_\text{a}: \quad \hat{\bar{S}}_{\text{Exist}} < \hat{\bar{S}}_{\text{Ne}}$$

for an existing and new treatment.

A $(1-\alpha)$ 100% confidence interval for mean survival was calculated from the ANOVA of the form

$$e^{\overline{\ln \hat{S}}\pm t_{3(n-1)}\sqrt{\frac{\text{MSE}}{n}}} \qquad (5)$$

for each treatment. Comparisons of confidence intervals for overlap can also be used to assess for statistical significance.

4.5. Fish Collection Pool Testing

4.5.1. Laboratory Studies

4.5.1.1. Description of Test Facility

The fish collection pool test facility was designed to represent the hydraulic conditions of the existing configuration of Salem's fish collection system. The FCP arrangements are discussed below.

The FCP test arrangement is shown on Figure 66 and Figure 67. The same 100 hp pump that was used to circulate flow through the EOP test facility was used to circulate flows through the FCP test facility. The pump was connected to the concrete storage tank by 10 in. diameter PVC pipe. The discharge of the pump was connected to the FCP head tank with 10 in. diameter PVC pipe and the same flow meter used for the EOP test installed between the pump and the FCP head tank. The FCP head tank was located on a wooden support platform approximately 12 ft above the ground (See Figure 48). The head tank was constructed of steel and MDO plywood and was 8-ft long, 4-ft wide and 4-ft deep. A wooden trough extended from the FCP head tank to the collection pool and represented the as-built condition at Salem's fish collection pool.

The FCP trough was made of MDO plywood and fiberglass. The first FCP trough section from the FCP head tank was 7-ft long at a downward slope of 55 % or 29 degrees. The second section from the FCP head tank extended 10 ft at a downward slope of 1.4 %. The third section from the FCP head tank turns 30 degrees from the alignment of the first two trough sections. The turn represents an open sampling gate which diverts water to the existing fish collection pool at the Salem Station. Figure 68 shows the mockup gate at the FCP test facility at Alden. Figure 69 and Figure 70 show the original and replacement gates (respectively) as they exist at Salem. The original gate was damaged the week before on-site testing and an acrylic surrogate structure was put in place to allow Salem FCP testing. The geometry and protrusions such as bolt heads and support brackets of Salem's sampling gate were incorporated into the FCP test facility design. The third trough section extended 5.5 ft at a downward slope of 5 %. The last section referred to as the spoon was 7 ft in length at a downward angle of 27.5 degrees. The trough was 2.5 ft wide and 2'-2" deep, with the last two sections identical to Salem's existing arrangement (Figure 71).

The FCP spoon section exited into the collection pool and was supported by a plywood floor which represented the existing fish collection pool elevation at Salem. A screen and wall was installed inside the collection pool orientated to represent the configuration of the existing screen and wall relative to the spoon section at Salem (Figure 72).

The FCP tests were conducted at a flow rate of 3 cfs (representative of the flow in the fish trough). Flow was withdrawn from the concrete storage tank and exited through the FCP test facility and into the collection pool.

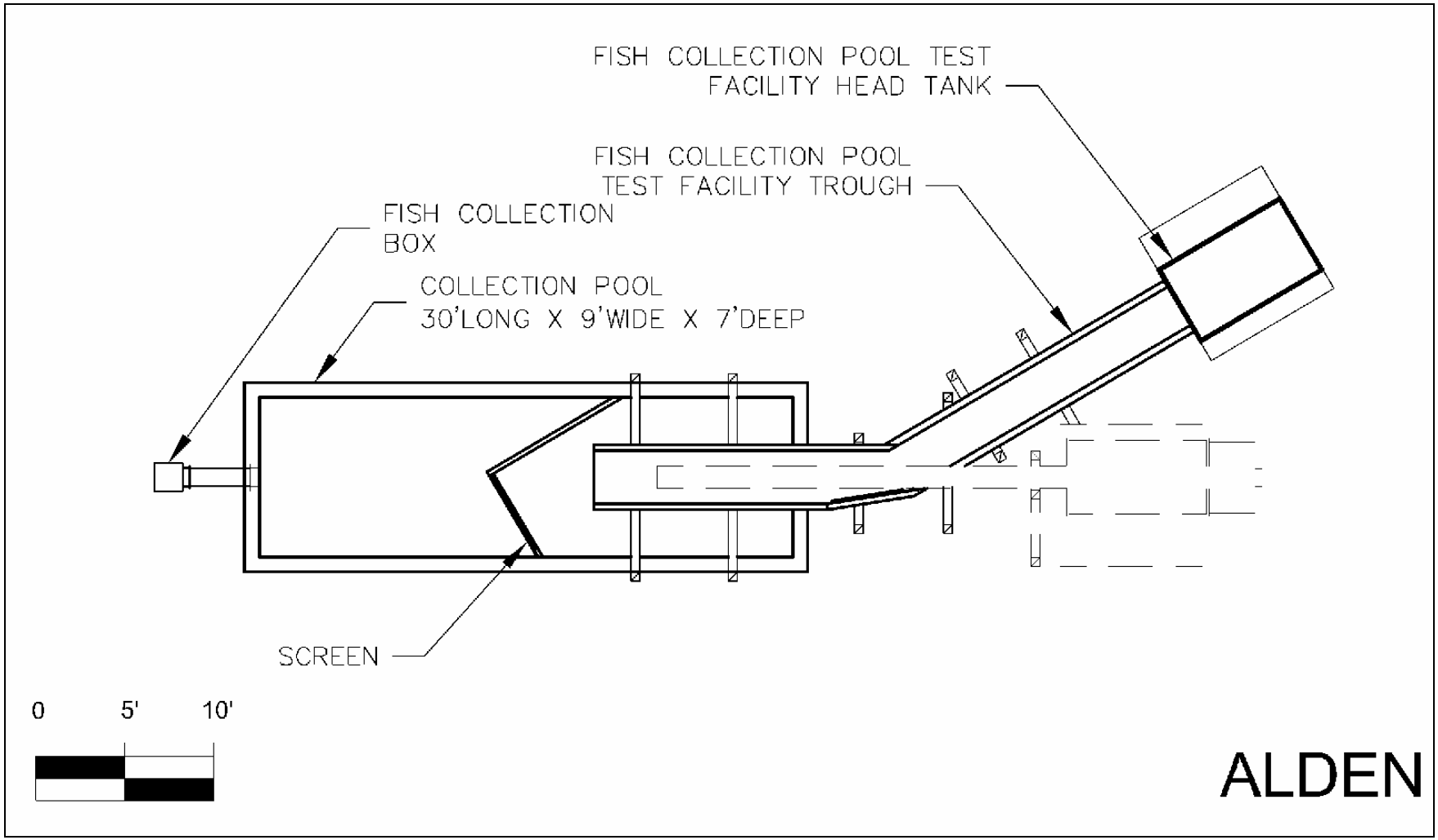


Figure 66. FCP test facility plan.

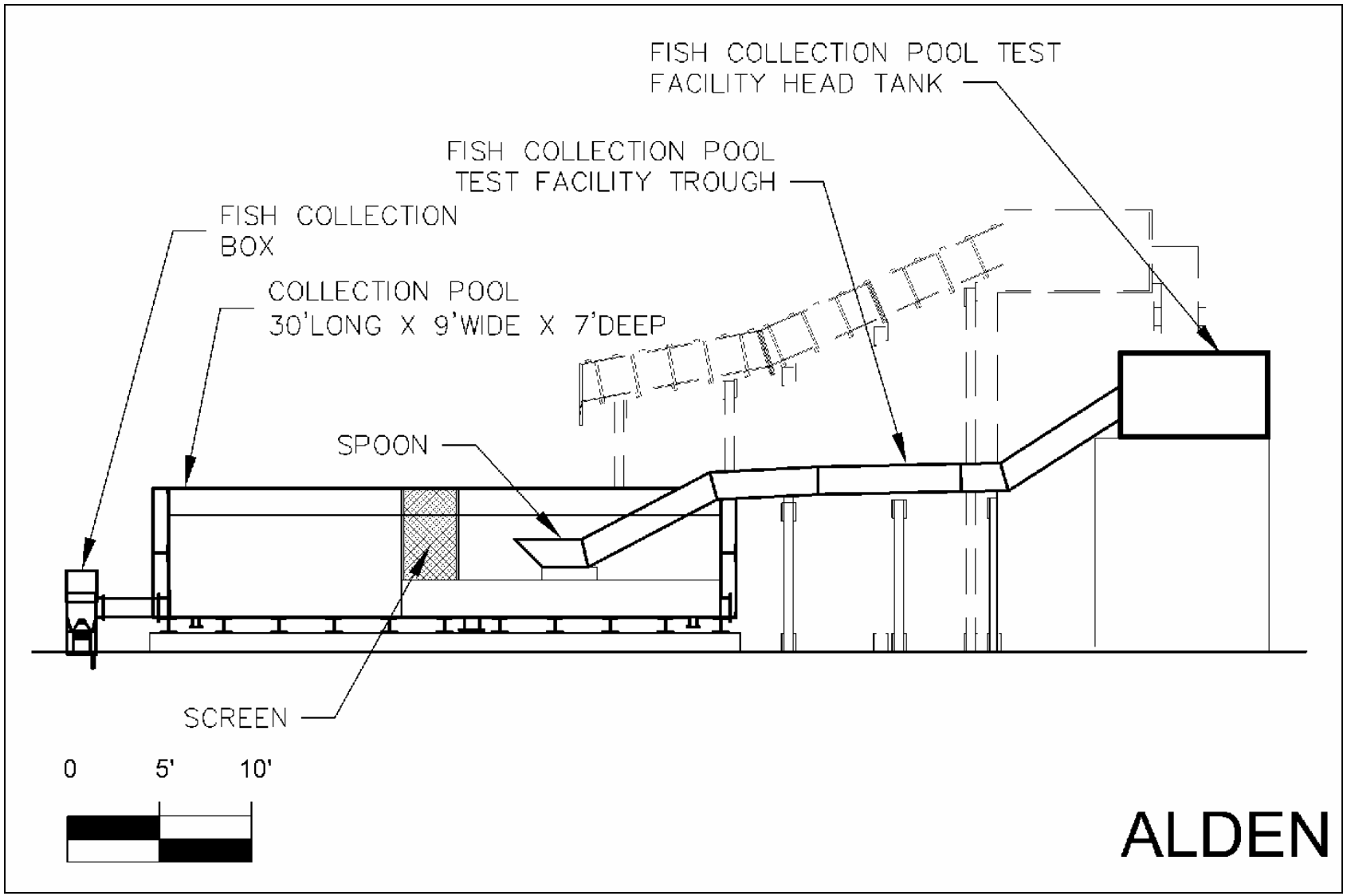


Figure 67. FCP test facility elevation.

Figure 68. The simulated sampling gate used for FCP testing. The 3 cfs condition is shown.

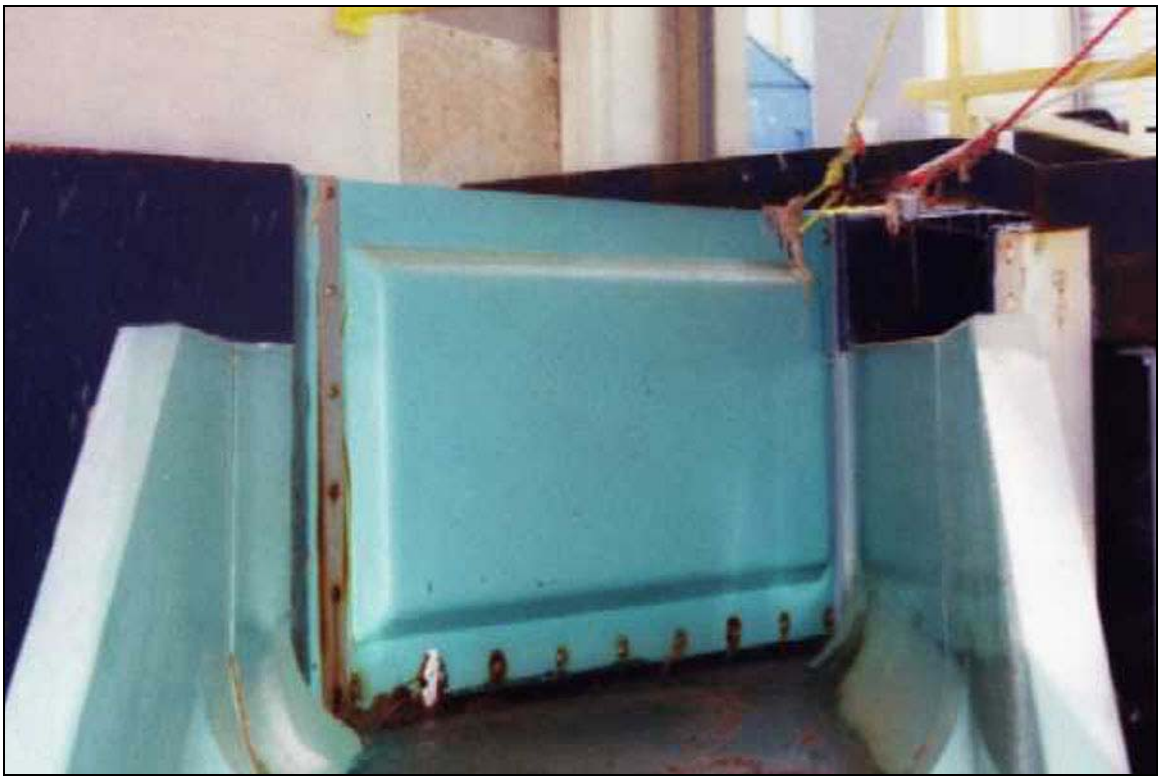


Figure 69. Original sampling gate in the north fish collection pool at Salem.

Figure 70. Two views of the replacement sampling gate in the South end fish collection pool at Salem. In the top image the gate is closed and the bottom gate is in sampling position. Both flow rates are 3 cfs.

Figure 71. The spoon portion of the FCP at Alden (left) and Salem (right).

Figure 72. The FCP test facility including solid and mesh wall sections. Sections match the orientation to the spoon at Salem.

The fish collection pool, including the trough upstream of the sampling gate, the gate itself, the spoon shaped trough leading into the pool, and the room that forms the collection pool, were investigated for stressors that could potentially harm fish. Potentially harmful stressors such as shear, abrasion and impact were identified the sampling gate and where the flow enters the spoon and spills into the collection pool. Specifically, observations, CFD modeling, and HEC-RAS simulations showed potential impact, abrasion, and shear stress at the point where the returning flow is diverted into the collection pool by the sampling gate (when in the sampling position). Fish being diverted into the flow may impact against the gate as the flow piles up against the gate and flows down toward the spoon. A hydraulic jump is created as the flow descends into the pool and meets the cushion water. Fish may also be exposed to impact and abrasion if they contact the wall, floor or screen once they enter the collection pool. Based on the analysis of the existing system and using the design criteria described in Section 3.2, three alternative FCP designs were developed.

Tests were conducted to investigate whether fish entering the collection pool were being killed under existing sampling conditions (25 cm of cushion water). In addition, tests using 50 cm of cushion water in the sampling pool were conducted to determine whether the addition of cushion

water would reduce mortalities. A full scale design (described below) was constructed and either 25 cm of water (used to replicate existing conditions within the FCP) or 50 cm of water (alternative FCP condition) was tested. Examples of each test condition were video taped for later visual comparison. Underwater footage was also taped to observe any fish injury or behavior immediately after entering the collection pool.

Laboratory test results were compared with the on-site Salem FCP testing to determine whether fish in the sampling pool have greater stress in situ where other factors are present that could influence the potential for survival (*e.g.,* predation, debris, flow volume, etc.).

4.5.1.2. Experimental Design

The experimental design was selected to determine what, if any, injury or mortality is caused by the existing FCP and to assess the potential for increased cushion water to reduced fish mortality in the fish collection pool. The goal was to develop baseline survival information for fish tested in a laboratory facility that mimicked the existing fish collection pool at Salem and compare it both to survival of fish exposed to alternative designs (increased cushion water) and in situ survival at Salem under identical hydraulic conditions. Selection of the study parameters was influenced by the analysis of the existing return system, CFD and HEC-RAS model results, and identification of practicable design alternatives for the Salem fish collection pool. The test designs for evaluating the existing and alternative fish collection pool configurations are presented individually below Table 18.

Table 18. Fish collection pool testing scenario.

Condition	Configuration and Cushion Water Depth	Release Point	Number of Replicates	Number of Fish Per Replicate	Quantitative Analysis
Existing condition Treatment Control	Salem - 25 cm	Below head tank Collection pool	6	50	Percent survival
Alternative 1 Treatment Control	Salem - 50 cm	Below head tank Collection pool	6	50	

Tests were conducted in a facility developed in tandem with the EOP test structure and used the same pump, support structure and collection pool. Fish were transferred from net pens in the fish holding pool to 5-gallon buckets. The buckets were transported to the structure and placed near the two introduction points: just below the FCP head tank for treatment fish (Figure 73) and in the back left-hand corner of the collection pool for control fish (See Figure 60). Testing began by draining down the collection pool into the concrete holding tank. When the water level reached 6 in., pumping was stopped and the valve settings were changed to direct flow to the FCP head tank (Figure 74). The 3 cfs flow rate was calibrated using the previously described DP cell. Treatment and control fish were introduced simultaneously when

Figure 73. A downstream view of the FCP facility. Arrow indicates the treatment fish release point.

Figure 74. View of the FCP head tank (left) and EOP head tank (right) while conducting an FCP test.

the water level in the collection pool reached 25 cm (or 50 cm in the case of alternative testing). Treatment fish were carried down the return trough where they encountered the simulated sampling gate (Figure 75). After passing the gate, fish dropped down the spoon portion of the trough and into the collection pool (Figure 76). Three minutes after introduction of the fish, flow was stopped, the collection pool was drained to a depth of about 6 in., and fish were crowded and removed from the tank using the flat-net method described in Section 4.4.3 (Figure 77). If present, dead fish were removed and measured before the remaining fish were transferred back to the holding facility for latent mortality observation. Fish were inspected immediately, 1-hour, 24-hours, and 48-hours after testing. Any dead fish were removed, counted, measured, and recorded. Conditions were identical between existing and alternative conditions except for the level of cushion water. Tests were conducted by alternating trials between existing and alternative conditions.

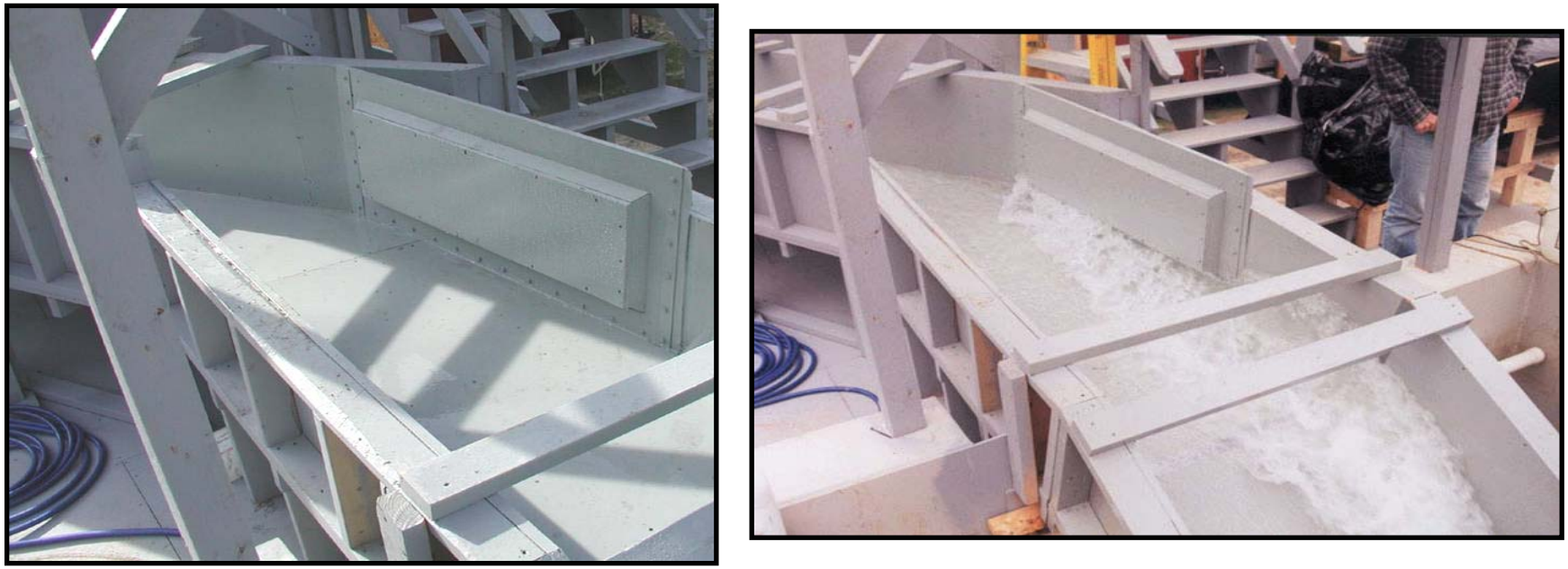


Figure 75. The simulated gate structure used for FCP testing at Alden with no flow (left) and 3 cfs (right).

Figure 76. Spoon portion of the Alden FCP return trough with no flow (left) and with 3 cfs (right).

Figure 77. Collecting alewife from the FCP using flat nets.

4.5.1.3. Data Analysis

Analysis of EOP test results used raw data to develop point estimates of survival by replicate-release. Analysis of variance table (ANOVA), and mean survival by treatment group were reported along with associated 95% confidence intervals.

The treatment design consisted of two treatments as follows:

25-cm cushion water; and
50-cm cushion water.

With each treatment, a corresponding release of control fish was used to characterize handling and recapture effects. The logistics of the study permitted the different treatment combinations to be intermixed in time. The data was analyzed as a randomized-block experimental design. Each trial within a block was composed of both a control (pool) release and a test (trough) release of fish. The test blocks were repeated seven times with the order of the treatments re-randomized in each block.

The measured responses for each trials were again of the following counts:

R_C = number of control fish released (pool),
R_T = number of treatment fish released (trough),
c = number of control fish recovered alive to the end of the study,
t = number of treatment fish recovered alive to the end of the study,
and were used to estimate survival of the test fish where:

$$\hat{S}_T = \frac{tR_C}{R_T c}$$

with associated variance estimator [Eq. (3)].

A test of treatment differences was based on an unweighted F-test using a two-way ANOVA of the form:

Source	DF	SS	MS	F
Total	$2n$*			
Mean	1			
$\text{Total}_{\text{Cor}}$	$2n-1$	SSTOT		
Blocks	$n-1$	SSB		
Treatments	1	SST	MST	$F_{3,3(n-1)} = \frac{\text{MST}}{\text{MSE}}$
Error	$(n-1)$	SSE	MSE	

* n = number of replicate trials for each treatment.

The response variable in the analysis was the $\ln \hat{S}_T$. Confidence interval estimation was based on Equation (4).

4.6. Testing at Salem Station

The opportunity arose to directly compare lab and field testing using the same flow, same species, same source of fish, same techniques, and same time of year. Differences include incoming flow patterns, replacement door design, presence of debris and water turbidity. In addition to testing conducted at 3 cfs, a set of six replicates was conducted at 13 cfs with 25 cm of cushion water.

4.6.1. Description of Test Facility

The North fish collection pool was undergoing repairs during the test period so on-site FCP testing was conducted using the South fish return system. Prior to testing, a fish holding facility was designed and constructed in a room adjoining the fish collection pool. The facility consists of a 450-gallon primary fish holding tank (Figure 78), sixteen 20-gallon post-test observation tanks (Figure 79), and filtration system (particle, biological, and UV sterilizer) (Figure 80). The total volume of the fish holding system is 770 gallons.

The direction of flow through the Salem fish return system alternates between North and South end depending on tidal direction. This system allows operators to return fish to the river in the same direction as the tidal flow. The current flushes fish away from the CWIS and reduces the possibility of reimpingement. Plant operators switch the direction of the return flow when the tide changes by opening and closing a set of gates on either end of the fish and debris return

troughs as they exit the screen house. The debris and fish return troughs can be operated separately such that one or both can be directed toward the North or South. To match the 3 cfs flow used during Alden FCP testing, the plant operators diverted only the debris trough flow (~10 cfs) to the North return system and left the fish return trough flowing in the southerly direction (~3 cfs). For the 13 cfs trials, the flow from both the fish and debris troughs were flowing into the South fish return system.

Figure 78. The 450-gallon primary fish holding tank at Salem.

Figure 79. Array of sixteen, 20-gallon latent mortality fish holding tanks at Salem.

Figure 80. Fish holding facility filtration system at Salem.

4.6.2. Experimental Design

The experimental design of FCP testing at Salem was similar to that used in the laboratory. These in situ tests were intended to determine what, if any, injury and mortality is being caused by the existing FCP and to assess the potential benefit of increased cushion water on fish survival. The goal was to develop baseline survival information to compare to laboratory results for both levels of cushion water. Unlike laboratory testing, on-site FCP tests had to be conducted in two parts with consecutive runs of treatment and control conditions. Also, on-site tests at 13 cfs were conducted to determine if flow volume had an effect on mortality. Test procedures for evaluating the existing and alternative fish collection pool configurations are presented individually below (Table 19).

Table 19. Fish collection pool testing scenario at Salem.

Condition	Configuration and Cushion Water Depth	Release Point	Number of Replicates	Number of Fish Per Replicate	Quantitative Analysis
Existing conditions Treatment	3 cfs/25 cm	Confluence of fish and debris troughs	6	50	Percent survival
Existing conditions Control	3 cfs/25 cm	collection pool	6	50	
Alternative 1 Treatment	3 cfs/50 cm	Confluence of fish and debris troughs	6	50	
Alternative 1 Control	3 cfs/50 cm	Collection pool	6	50	
Alternative 1 Control	13 cfs/25 cm	Collection pool	6	50	
Alternative 1 Control	13 cfs/25 cm	Collection pool	6	50	

At the beginning of testing, water quality data (temperature, DO, salinity, pH, hardness, alkalinity) were collected for the holding facility and the river water. Plant operators verified that all systems were operating properly including the number of screens in operation and the flow direction for the fish and debris troughs (South and North respectively). A mesh crowder (Figure 81) and scoop were used to concentrate fish and minimize handling injuries as they were transferred from the holding facility in 5-gallon buckets. Cushion water was diverted into the collection pool by opening the sampling gate (Figure 82). The collection pool was filled to nearly 25 cm or 50 cm depths depending on the trial (Figure 83). Once the pool was filled to the appropriate level, treatment fish were released just below the confluence of the fish and debris troughs, located upstream of the sampling gate (Figure 84),and control fish were released in a relatively quiescent section of the collection room located behind the spoon portion of the collection trough (Figure 85). For all 3 cfs trials, testing was conducted for 3 minutes before the gate was closed, and draining was initiated. For the 13 cfs trials, sampling time was limited to 1 minute because of the limited collection pool holding capacity. After the sample was complete, the collection pool was drained to a depth of about 1 ft and fish were collected using the previously described flat net method to minimize handling injury. Fish were transferred immediately to 20-gallon holding tanks for 48-hour observations (Figure 86). Any dead fish were removed, counted, measured and recorded. Fish were inspected immediately, 1-hour, 24-hours, and 48-hours after testing for latent mortality. Tested fish were held separately from untested fish. Three cfs trials were conducted by alternating treatment and control groups for existing and alternative conditions (*e.g.,* 25 cm treatment, 25 cm control, 50 cm treatment, 50 cm control). Also, treatment and control pairs were not split between test days. Treatment and control groups were also alternated during 13 cfs trials, all of which were conducted using the 25 cm cushion water condition.

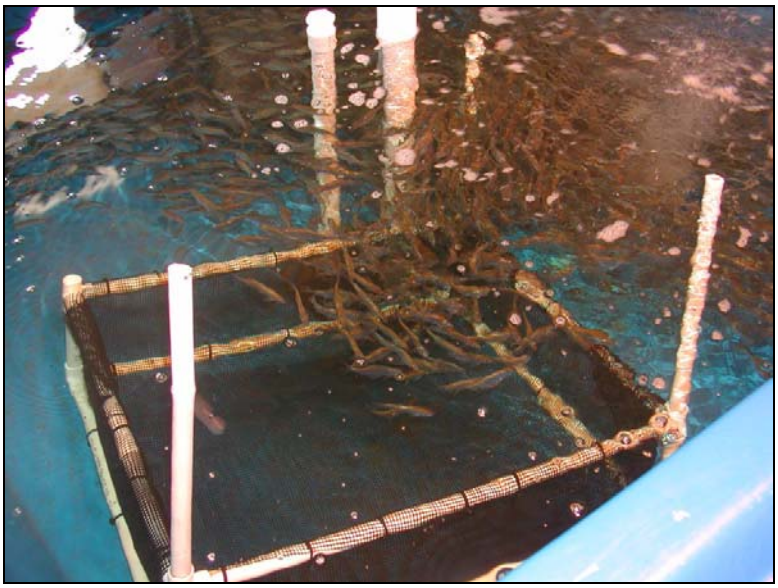


Figure 81. Plastic mesh crowding device used during Salem FCP testing to minimize handling stress.

Figure 82. Replacement gate on South end of Salem fish return system - closed position.

Figure 83. Fish collection pool at Salem filling to a cushion water depth of 50 cm - arrow indicates 50 cm mark on the pool wall.

Figure 84. The treatment fish release point for the fish collection pool facility at Salem.

Figure 85. The control fish release point for fish collection pool testing at Salem.

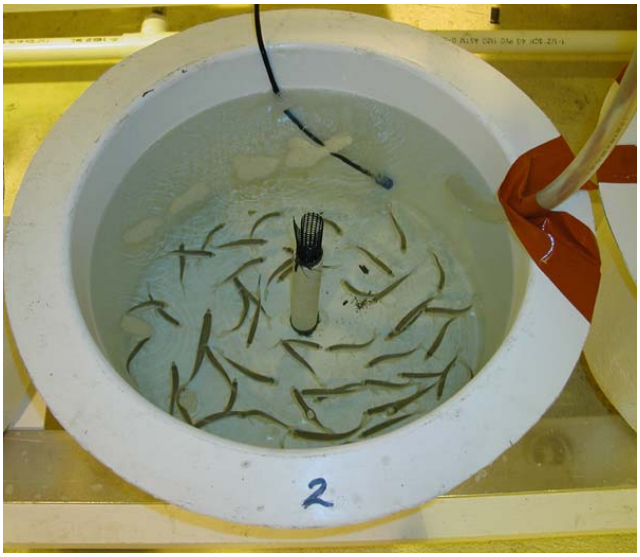


Figure 86. Twenty-gallon holding tank at Salem used for latent mortality monitoring. Note aerating stone and inflow hose.

4.6.3. Data Analysis

The treatment design consisted of three treatments as follows:

3 cfs flow and 25 cm cushion;
3 cfs flow and 50 cm cushion; and
13 cfs flow and 25 cm cushion.

With each treatment, a corresponding release of control fish was used to characterize handling and recapture effects.

The first two treatments (*i.e.,* 3 cfs flow with 25 or 50 cm cushion) were performed in a blocked design with 6 replicates. The third treatment was performed as a separate series of trials. The first two treatments were analyzed using a two-way ANOVA based on ln-transformed survival estimates. The ANOVA was of the form:

Source	DF	SS	MS	F
Total	$2n$*			
Mean	1			
$\text{Total}_{\text{Cor}}$	$2n-1$			
Blocks	$n-1$	SSB		
Treatments	1	SST	MST	$F_{1,n-1}=\frac{\text{MST}}{\text{MSE}}$
Error	$(n-1)$	SSE	MSE	

* n = number of replicate trials for each treatment.

The third treatment was summarized assuming the ln-transformed $\hat{S}_T$ were normally distributed. Confidence intervals for the first two treatments were calculated according to Equation (4). For the third treatment performed separately, the 95% confidence interval was calculated as follows:

$$e^{\overline{\ln \hat{S}} \pm t_{n-1}\sqrt{\frac{s^2}{n}}} \qquad (5)$$

where the t had $n-1$ degrees of freedom and s^2 calculated by the empirical variance among the replicate values of $\ln \hat{S}_T$. Because so many trials had 100% control and treatment survival, standard errors could not be computed and unweighted analyses performed.

Section 5
Study Results

Results are presented separately for each of the three different experiments concerning the fish return system at Salem Station.

5.1. End-of-Pipe Testing

Six replicate control-treatment releases were performed under each of three different test conditions: existing configuration and 1.3-ft and 6-ft freefalls. The release numbers, number of fish that died (48-hours), and estimates of survival are presented in Table 20 for each replicate trial. The results indicate that survival was nearly 100% under all conditions tested.

Table 21 and Table 22 provide unweighted ANOVA and mean survival data respectively. No significant difference in mean survival was found between existing condition and the two alternatives ($P = 0.3805$). Survival rates were ranged from 99.5% to 101.4% when adjusted for control mortality (Note: survival rates over 100% are the result of adjusting for control mortality that is higher than treatment mortality). Using the Dunnett (1955) test, neither the 1.3-ft nor the 6-ft freefall had significantly better survival than the existing condition despite larger point estimates of survival.

Maximum likelihood estimation of the treatment survival probabilities are provided in Table 23, where estimates are reported immediately, 1-hour, 24-hours, and 48-hours after collection. Survival estimates using this method of analysis ranged from 99.6% to 101%. The point estimates were derived after pooling the catch data across replicates. The reported standard errors are based on the variance formula (3).

The results indicate that mortality is minimal for alewife exposed to the existing hydraulic conditions in the EOP portion of the Salem fish return system.

Table 20. Forty-eight-hour survival data and survival estimates by replicate trial for the end-of-pipe test experiment.

Treatment or Control	Rep	Test Condition	Number of Fish Released	Number Dead at End of Observations	Alive/ Recovered	$\hat{S}_T$	$SE(\hat{S}_T)$
T	1	Exi	35	1	0.9714	0.9714	0.0282
C	1	Exi	40	0	1		
T	2	Exi	51	1	0.9804	0.9804	0.0194
C	2	Exi	51	0	1		
T	3	Exi	50	0	1	1	NA
C	3	Exi	60	0	1		
T	4	Exi	51	0	1	1	NA
C	4	Exi	49	0	1		
T	5	Exi	49	0	1	1	NA
C	5	Exi	51	0	1		
T	6	Exi	51	0	1	1.0208	0.021
C	6	Exi	49	1	0.9796		
T	1	1.3-ft	51	0	1	1.087	0.0453
C	1	1.3-ft	50	4	0.92		
T	2	1.3-ft	49	0	1	1	NA
C	2	1.3-ft	50	0	1		
T	3	1.3-ft	51	0	1	1	NA
C	3	1.3-ft	47	0	1		
T	4	1.3-ft	49	2	0.9592	1.0009	0.0422
C	4	1.3-ft	48	2	0.9583		
T	5	1.3-ft	51	0	1	1	NA
C	5	1.3-ft	49	0	1		
T	6	1.3-ft	49	0	1	1	NA
C	6	1.3-ft	51	0	1		
T	1	6-ft	53	0	1	1.0222	0.0225
C	1	6-ft	46	1	0.9783		
T	2	6-ft	51	0	1	1	NA
C	2	6-ft	49	0	1		
T	3	6-ft	52	0	1	1	NA
C	3	6-ft	48	0	1		
T	4	6-ft	51	0	1	1	NA
C	4	6-ft	49	0	1		
T	5	6-ft	48	0	1	1	NA
C	5	6-ft	51	0	1		
T	6	6-ft	50	0	1	1	NA
C	6	6-ft	49	0	1		

T = test
C = control
EXI = existing conditions
Rep = replicate

Table 21. Results of ANOVA analysis of the $\ln \hat{S}$ for the end-of-pipe experiment at 48-hours.

Source	DF	SS	MS	F	P-Value
$\text{Total}_{\text{Cor}}$	17	0.0088			
Treatments	2	0.0011	0.0005	1.0312	0.3805
Error	15	0.0077	0.0005		

Table 22. Estimates of mean survival and 95% confidence intervals by treatment for the end-of-pipe experiment at 48-hours.

Treatment	$\hat{\bar{S}}_T$	95% CI
Existing	0.9953	0.9759-1.0151
1.3-ft Freefall	1.0141	0.9943-1.0343
6-ft Freefall	1.0037	0.9841-1.0237

Table 23. Estimates of survival from the pooled replicates by treatment immediately following, 1-hour, 24-hours, and 48-hours post-collection for the end-of-pipe experiment. Standard errors are in parentheses.

Treatment	Immediate	1-Hour	24-Hours	48-Hours*
Existing	0.9965 (0.0035)	0.9965 (0.0035)	0.9965 (0.0035)	0.9964 (0.0059)
1.3-ft Freefall	1.0 (N/A)	1.0 (N/A)	1.0103 (0.0060)	1.0140 (0.0098)
6-ft Freefall	1.0 (N/A)	1.0 (N/A)	1.0 (N/A)	1.0034 (0.0034)

* Note the maximum likelihood estimates (MLE) differ slightly from the ANOVA results because the MLE pools the data differently across replicates and assumes no between-replicate variation.

EOP tests using weakfish

A limited number of weakfish (N = 178) were tested with existing conditions in the EOP test facility. Tests were conducted using the same methods as those used for alewife testing except that weakfish were not fin clipped so they were tested using an alternating treatment/control test protocol. The test results are provided in Table 24 below:

Table 24. Weakfish testing design and results with existing EOP conditions.

Condition	Treatment or Control	Replicate	Number of Fish Tested	Total Mortality After 48-Hours	Percent Mortality
Existing	Treatment	1	50	4	8.0
Existing	Control	1	50	1	2.0
Existing	Treatment	2	50	4	8.0
Existing	Control	2	28	3	10.7

When survival data were pooled and adjusted for control mortality, the mortality was 2.9%. While the sample size is limited, initial results suggest that weakfish mortality is also minimal for fish exposed to the existing hydraulic conditions in the EOP portion of the Salem fish return system.

5.2. Fish Collection Pool Testing

5.2.1. Laboratory Study

Seven replicate control-treatment releases were performed under each of two different test conditions: 25-cm and 50-cm cushion water levels. The release numbers, numbers of fish that died (48-hours), and estimates of survival are presented in Table 25 for each replicate trial. The results were subjected to an unweighted, two-way ANOVA. As shown in Table 26, no significant difference in mean survival probabilities was found between the two treatment conditions ($P = 0.3918$). Table 27 summarizes the mean survivals and their respective 95% confidence intervals at 48-hours. Table 28 provides estimates of survival also measured immediately following the trials, 1-hour, 24-hours, and 48-hours post-collection based on the maximum likelihood estimator (1) and variance (2).

Table 25. Forty-eight-hour survival data and survival estimates by replicate trial for the fish collection pool experiment. Survival estimates are adjusted for control mortality.

Treatment or Control	Rep	Test Condition	Total Fish Retrieved	Number Dead at End of Observations	Alive/ Recovered	$\hat{S}_T$	$SE\left(\hat{S}_T\right)$
T	0	25cm	51	0	1	1	NA
C	0	25cm	50	0	1		
T	1	25cm	62	9	0.8548	1.5994	0.2131
C	1	25cm	58	27	0.5345		
T	2	25cm	53	12	0.7736	1.2126	0.15
C	2	25cm	58	21	0.6379		
T	3	25cm	50	0	1	1	NA
C	3	25cm	50	0	1		
T	4	25cm	45	6	0.8667	1.1415	0.11
C	4	25cm	54	13	0.7593		
T	5	25cm	47	0	1	1.359	0.1118
C	5	25cm	53	14	0.7358		
T	6	25cm	51	1	0.9804	1.024	0.0375
C	6	25cm	47	2	0.9574		
T	0	50cm	47	0	1	1	NA
C	0	50cm	49	0	1		
T	1	50cm	46	19	0.587	0.6369	0.083
C	1	50cm	51	4	0.9216		
T	2	50cm	49	25	0.4898	1.1195	0.2454
C	2	50cm	48	27	0.4375		
T	3	50cm	51	8	0.8431	1.2399	0.1417
C	3	50cm	50	16	0.68		
T	4	50cm	48	2	0.9583	0.9787	0.0359
C	4	50cm	48	1	0.9792		
T	5	50cm	50	5	0.9	1.2162	0.117
C	5	50cm	50	13	0.74		
T	6	50cm	51	1	0.9804	1.1765	0.0794
C	6	50cm	48	8	0.8333		

Table 26. The ANOVA table associated with the analysis of the $\ln \hat{S}$ for the fish collection pool experiment at 48-hours.

Source	DF	SS	MS	F	P-Value
$\text{Total}_{\text{Cor}}$	13	0.5695			
Blocks	6	0.0917	0.0153	0.2192	0.9564
Treatments	1	0.0594	0.0594	0.8512	0.3918
Error	6	0.4184	0.0697		

Table 27. Estimates of mean survival and 95% confidence intervals by treatment for the fish collection pool experiment at 48-hours.

Treatment	$\hat{\bar{S}}_T$	95% CI
25-cm Cushion	1.1744	0.9200-1.4992
50-cm Cushion	1.0310	0.8076-1.3161

Table 28. Estimates of survival from the pooled replicates by treatment immediately following, 1-hour, 24-hours, and 48-hours post-collection for the fish collection pool experiment. Standard errors are in parentheses.

Treatment	Immediate	1-Hour	24-Hours	48-Hours*
25-cm Cushion	1.0 (N/A)	1.0 (N/A)	0.9994 (0.0104)	1.1643 (0.0358)
50-cm Cushion	1.0 (N/A)	1.0 (N/A)	1.0089 (0.0168)	1.0315 (0.0379)

* Note the maximum likelihood estimates (MLE) differ slightly from the ANOVA results because the MLE pools the data differently across replicates and assumes no between-replicate variation.

When survival data were pooled and adjusted for control mortality, the mortality ranged from 103.2% to 116.4% (Note: survival rates over 100% are the result of adjusting for control mortality that is higher than treatment mortality). Results suggest that fish mortality from hydraulic conditions that exist in the FCP portion of the Salem fish collection system is minimal.

5.2.2. Testing at Salem Station

Six replicate control-treatment releases were performed under each of three different test conditions: 3 cfs flow with 25 cm of cushion water, 3 cfs flow with 50 cm of cushion water, and 13 cfs flow with 25 cm of cushion water. The release numbers, number of fish that died

(48-hours), and the estimates of survival are present in Table 29 for each replicate trial. Survival was nearly 100 % under all conditions tested.

An unweighted analysis was performed because the sampling error could not be calculated for many of the replicates due to 100% survival of both treatment and control releases. An ANOVA could only be performed for the 3 cfs trials performed in a blocked design. There was no significant different in fish survival between the two 3-cfs treatments ($P = 0.3632$; Table 30). For the 3 cfs treatments, 95% confidence interval were calculated using Equation (4); for the 13-cfs treatment, the interval estimate was based on Equation (5). Inspection of the 95% confidence intervals for all three treatments indicates the 13 cfs/25 cm combination had significantly lower survival than the 3 cfs/50 cm combination ($P < 0.05$; Table 31). Estimates of survival by treatment group are also reported for immediately following each trial, and 1-hour, 24-hours and 48-hours post-collection (Table 32).

Table 29. 48-hour survival data and survival estimates by replicate trial for the on-site fish collection pool experiment.

Flow	Treatment or Control	Rep	Test Condition	Total Fish Retrieved	Immed Morts	1-Hour Morts	24-Hour Morts	48-Hour Morts	Number Dead at End of Observations	Alive/ Recovered	$\hat{S}_T$	$SE\left(\hat{S}_T\right)$
3 cfs	T	1	25cm	50	0	0	0	0	0	1	1	NA
3 cfs	C	1	25cm	50	0	0	0	0	0	1		
3 cfs	T	2	25cm	49	0	0	0	0	0	1	1	NA
3 cfs	C	2	25cm	50	0	0	0	0	0	1		
3 cfs	T	3	25cm	53	0	0	0	0	0	1	1	NA
3 cfs	C	3	25cm	48	0	0	0	0	0	1		
3 cfs	T	4	25cm	49	0	0	0	0	0	1	1	NA
3 cfs	C	4	25cm	51	0	0	0	0	0	1		
3 cfs	T	5	25cm	50	0	0	0	0	0	1	1.0204	0.0206
3 cfs	C	5	25cm	50	1	0	0	0	1	0.98		
3 cfs	T	6	25cm	53	1	0	0	0	1	0.9811	1.0012	0.0278
3 cfs	C	6	25cm	50	1	0	0	0	1	0.98		
3 cfs	T	1	50cm	51	0	0	0	0	0	1	1	NA
3 cfs	C	1	50cm	50	0	0	0	0	0	1		
3 cfs	T	2	50cm	51	0	0	0	0	0	1	1	NA
3 cfs	C	2	50cm	50	0	0	0	0	0	1		
3 cfs	T	3	50cm	40	0	0	0	0	0	1	1	NA
3 cfs	C	3	50cm	50	0	0	0	0	0	1		
3 cfs	T	4	50cm	47	0	0	0	0	0	1	1	NA
3 cfs	C	4	50cm	52	0	0	0	0	0	1		
3 cfs	T	5	50cm	50	0	0	0	0	0	1	1.0204	0.0206
3 cfs	C	5	50cm	50	1	0	0	0	1	0.98		
3 cfs	T	6	50cm	50	0	0	0	0	0	1	1.0204	0.0206
3 cfs	C	6	50cm	50	1	0	0	0	1	0.98		

Table 29. (Continued)

Flow	Treatment or Control	Rep	Test Condition	Total Fish Retrieved	Immed Morts	1-Hour Morts	24-Hour Morts	48-Hour Morts	Number Dead at End of Observations	Alive/ Recovered	$\hat{S}_T$	$\widehat{SE}\left(\hat{S}_T\right)$
13 cfs	T	1	25cm	50	0	0	0	0	0	1	1	NA
13 cfs	C	1	25cm	44	0	0	0	0	0	1		
13 cfs	T	2	25cm	49	0	0	0	0	0	1	1	NA
13 cfs	C	2	25cm	52	0	0	0	0	0	1		
13 cfs	T	3	25cm	47	0	0	0	0	0	1	1	NA
13 cfs	C	3	25cm	43	0	0	0	0	0	1		
13 cfs	T	4	25cm	47	0	0	0	0	0	1	1	NA
13 cfs	C	4	25cm	50	0	0	0	0	0	1		
13 cfs	T	5	25cm	50	1	0	0	0	1	0.98	0.98	0.0198
13 cfs	C	5	25cm	50	0	0	0	0	0	1		
13 cfs	T	6	25cm	51	0	0	0	0	0	1	1	NA
13 cfs	C	6	25cm	49	0	0	0	0	0	1		

Table 30. A two-way ANOVA table for the on-site fish collection pool experiment using $\ln \hat{S}_T$ at 48-hours.

Source	DF	SS	MS	F	P-Value
$\text{Total}_{\text{Cor}}$	11	0.000907			
Blocks	5	0.000727	0.000145	4.8318	0.0544
Treatments	1	0.000030	0.000030	1.0000	0.3632
Error	5	0.000150	0.000030		

Table 31. Estimates of mean survival and 95% confidence intervals by treatment for the on-site fish collection pool experiment at 48-hours.

Treatment	$\hat{\bar{S}}_T$	95% CI
3 cfs flow/25 cm cushion	1.0036	0.9978-1.0094
3 cfs flow/50 cm cushion	1.0068	1.0010-1.0126
13 cfs flow/25 cm cushion	0.9966	0.9931-1.002

Table 32. Estimates of survival from the pooled replicates by treatment immediately following, 1-hour, 24-hours, and 48-hours post-collection for the on-site fish collection pool experiment. Standard errors are in parentheses.

Treatment	Immediate	1-Hour	24-Hours	48-Hours*
3 cfs/25 cm	1.0034 (0.0058)	1.0034 (0.0058)	1.0034 (0.0058)	1.0034 (0.0058)
3 cfs/50 cm	1.0067 (0.0047)	1.0067 (0.0047)	1.0067 (0.0047)	1.0067 (0.0047)
13 cfs/25 cm	0.9966 (0.0034)	0.9966 (0.0034)	0.9966 (0.0034)	0.9966 (0.0034)

* Note the maximum likelihood estimates (MLE) differ slightly from the ANOVA results because the MLE pools the data differently across replicates and assumes no between-replicate variation.

When survival data were pooled and adjusted for control mortality, the mortality ranged from 99.6% for fish exposed to the 13 cfs hydraulic conditions to 100.7% for the 3 cfs/50 cm condition (Note: survival rates over 100% are the result of adjusting for control mortality that is higher than treatment mortality). Results suggest that mortality is minimal for fish exposed to the existing hydraulic conditions in the FCP portion of the Salem fish return system. Results from on-site FCP tests appear to validate the results of laboratory FCP tests.

Section 6
Spraywash Pressure Testing

In addition to the EOP and FCP testing, a special test program was conducted to examine potential causes of injury or mortality prior to fish entering the return system troughs at Salem. This study examined the high-pressure spraywash system used to remove debris from the traveling water screen baskets. The complete report on this test program is presented in Appendix A. Below is a summary of the study rationale, methods and results.

6.1. Rationale

The high-pressure debris spraywash system has been identified as a potential source of injury and mortality. Fish collected in the ascending traveling screen baskets move up over the head sprocket and are exposed to low-pressure (5-20 psi) sprays designed to wash fish into the fish return trough. Fish and debris not removed by the low-pressure wash typically fall past the fish trough flap seal and encounter the high-pressure spraywash system located directly below the fish collection trough. This spraywash system operates at pressures between 80 and 120 psi and has the potential to cause injury directly by striking the fish with the high-pressure spray, or indirectly as the spray pushes the fish into the housing cover. A study conducted by PSEG (PSEG 2001d) investigated whether there was differential mortality between fish collected in the fish return trough and those collected from the debris return trough. The results indicated that for some species, during some months, there were higher mortality rates for fish collected from the debris trough. This report is included as Attachment 1. This spraywash pressure study was designed to determine if the high-pressure spraywash may be contributing to fish mortality for the portion of fish getting past the low pressure spraywash system.

6.2. Methods

A pilot-scale version of a Salem traveling screen was constructed at the Alden Fish Testing Facility. This fully functioning screen was equipped with fish and debris spraywash headers, used 4-ft wide sections of baskets from Salem and could be rotated at the same speed ranges as the Salem system. To examine spraywash pressure effects, Alden installed a high-pressure debris spraywash system capable of up to 100 psi pressures, added a fish return trough and a debris return trough, and re-created the Salem configuration of spray headers, troughs, spray housing (for the debris spraywash trough), and debris flap seal.

Fish were introduced into the traveling screen baskets (set at a speed of 6 ft per minute) and allowed to pass over the head sprocket, past the fish collection trough, and down to the debris flap seal and trough. Fish were exposed to seven separate conditions in an effort to develop a predictive relationship between spraywash pressures and fish survival (Table 33). Tests were conducted using alewife delivered from the same source that provided fish for the EOP and FCP tests.

Table 33. Debris spraywash pressure testing scenario.

Condition	Description	Number of Replicates	Number of fish per replicate
0 psi (handling control)	Fish were brought from the holding facility, placed directly in the debris return trough and collected immediately.	6	50
0 psi (basket control)	Fish were poured into the ascending basket and allowed to pass over the crest and into the debris return trough where they were collected.	6	50
20 psi	The spraywash header system was brought up to the selected pressure prior to fish being introduced. Once at the appropriate pressure, fish were introduced into two ascending baskets (25 fish per basket) and then were collected from the debris return trough via a fish collection flume located in the bottom of the trough (water levels in the trough were set to 9 in. reflecting the minimum water level measured at Salem).	6	50
40 psi		6	50
60 psi		6	50
80 psi		6	50
100 psi		6	50

6.3. Results

The results from six replicate tests conducted with each condition are presented in Table 34. Survival estimates and 95% confidence limits are presented in Table 35.

Table 34. Results of debris spraywash testing. Data from replicate trials are pooled for each condition.

Test Condition	Number of Fish Released	Number of Fish Collected*	Total Mortalities After 48-Hours	Percent Mortality	Percent of Fish Recovered
handling control	299	292	2	0.7	97.7**
0 psi (basket control)	300	284	3	1.1	94.7
20 psi	300	299	-	0.0	99.7
40 psi	300	300	-	0.0	100
60 psi	300	300	-	0.0	100
80 psi	300	300	-	0.0	100
100 psi	300	300	3	1.0	100

* Fish that passed by the debris trough flap seal were not included as mortalities.
** During a single replicate of the handling control, the net pen slipped partially off of the collection trough. Seven fish escaped into the test flume. If this trial is excluded from recovery calculations, the handling control recovery rate is 100%.

Table 35. Mean survivals by treatment level and corresponding 95% confidence intervals for the spraywash pressure testing .

Treatment	$\hat{\bar{S}}_T$	95% CI
0 psi	0.9969	0.9892-1.0047
20 psi	1.0074	0.9996-1.0152
40 psi	1.0074	0.9996-1.0152
60 psi	1.0074	0.9996-1.0152
80 psi	1.0074	0.9996-1.0152
100 psi	0.9972	0.9895-1.0049

6.4. Conclusions

No substantial mortality occurred for any of the six test conditions. The lowest mean survival that occurred was for the 0 psi control condition (99.7%). Based on the results of the spraywash pressure tests conducted with alewife, it is unlikely that spraywash pressures at Salem of 100 psi or lower are injurious to fish.

Section 7
Discussion

7.1. Summary of Findings

An extensive evaluation of the Salem fish return and collection pool systems has provided valuable information about the role that the system has on fish injury and mortality. For EOP tests, freefall distance did not have a substantial effect on survival. For FCP tests, cushion water depth and flow volume (3 or 13 cfs – Salem testing only) did not have a substantial effect on survival. A discussion of the results of the literature review, CFD and HEC-RAS analysis, and live fish testing as they apply to the Salem fish return system is given below.

7.1.1. Literature Review

Based on the literature review, Alden concluded that pressure-related stress is not a factor for fish moving through the Salem fish return system. The system also meets criteria developed for fish return and bypass systems to minimize injury and mortality associated with abrasion. Water velocities within the EOP portion of the return system are lower than those cited in published reports as being injurious or causing fish mortality (about 30 fps). Little information is available on turbulence mainly due to its complex nature and logistical difficulties with monitoring and quantifying stressor metrics. Velocity is a factor that directly influences the magnitude of other stressors such as abrasion, impact, turbulence, and shear. In summary, the literature indicates that the Salem fish return system is designed and operates within recommended limits.

7.1.2. Hydraulic Investigations (CFD and HEC-RAS Analyses)

1. The study by Nietzel et al. (2000) provides sufficient information to re-create the study methods and develop accurate CFD models of the critical portions of Salem fish return system.
2. Shear levels within the EOP and FCP systems were below levels cited as causing major injury or death.
3. Shear stress levels identified in the existing EOP portion (*i.e.*, enclosed area of the pipe) of the fish return system are more intense within the bounded area than when alternative freefall condition were established.
4. Hydraulic conditions similar to those in the existing Salem fish return system could be created for laboratory testing using a sectional test facility (EOP).
5. For laboratory testing of the fish collection pool, a full scale reproduction of the fish collection gate, spoon, and collection pool was constructed.

7.1.3. End-of-pipe Laboratory Tests

1. Fish exposed to hydraulic conditions that simulated the existing EOP system at Salem experienced a pooled mortality rate of 0.7%. Control mortality was 0.3%.
2. Tests with the 1.3-ft freefall alternative EOP configuration provided a pooled mortality rate of 0.7%. Control mortality was 2.3%.
3. Tests with the 6-ft freefall alternative EOP configuration provided a pooled mortality rate of 0%. Control mortality was 0.3%.
4. When adjusted for control mortality, existing and alternative test conditions produced survival rates of 99.5% for the existing EOP, 101.4% for the 1.3-ft freefall alternative, and 100.4% for the 6-ft freefall alternative. (Note: survival rates over 100% are the result of adjusting for control mortality that is higher than treatment mortality).

7.1.3.1. Analysis – EOP Tests

Alden's analysis of the potential effect of shear on fish passing through the existing EOP demonstrated that conditions within the pipe are not a significant source of mortality for alewife. Based on the results of EOP testing, we conclude that fish exiting the Salem fish return system experience minimal injury and mortality associated with the EOP portion of the fish return system (99.5% survival). There was no discernable difference in survival potential between the existing and alternative conditions. Therefore, there appears to be no biological justification for modifying the existing EOP system at Salem.

7.1.4. Laboratory and Salem Fish Collection Pool Tests

7.1.4.1. Laboratory FCP Tests

1. Based on the results of laboratory FCP testing, Alden concludes that fish experience minimal injury and mortality associated with entering the fish collection pool portion of the Salem fish return system.
2. Mortality rates for tests with the existing FCP conditions (25 cm cushion water) ranged from 0-22.6%. Control mortality was 0-46.6%.
3. Mortality rates for tests with the alternative FCP conditions (50 cm cushion water) ranged from 0-51.0%. Control mortality was 0-56.3%.
4. When adjusted for control mortality, laboratory tests of existing and alternative test conditions produced minimal mortalities. Survival rates with the existing FCP conditions were 117.44% and 103.10% for the alternative FCP conditions. (Note: Survival rates over 100% are the result of adjusting for control mortality that is higher than treatment mortality).
5. There was no statistically significant difference between existing and alternative test condition mortality rates when adjusted for control mortality.

7.1.4.2. Salem FCP Tests

1. Mortality rates for tests with the existing FCP conditions at a flow rate of 3 cfs ranged from 0-1.9%. Control mortalities ranged from 0-2.0%.
2. Mortality rates for tests with the alternative FCP condition (50 cm cushion water) at a flow rate of 3 cfs were 0%. Control mortalities ranged from 0-2.0%.
3. For tests conducted with the 13 cfs flow, mortality rates for tests with the existing conditions (25 cm cushion water) ranged from 0-2.0%. There were no control mortalities.
4. Adjusted for control mortality, results from on-site test of existing and alternative test conditions indicate minimal mortality. For tests with the existing conditions with a flow of 3 cfs there was a survival rate of 100.4%. For the alternative condition with a flow of 3 cfs survival was 100.7%. For existing condition tests conducted with a flow of 13 cfs the survival rate was 99.7%. There was no statistically significant difference between mortality rates for the two test conditions at 3 cfs (25 cm and 50 cm cushion).
5. Survival rates for the 50 cm/3 cfs condition were significantly higher than survival for the 25 cm/13 cfs tests (100.7% and 99.7%, respectively, $P<0.05$).
6. Based on the results of on-site FCP testing, we conclude that fish experience minimal injury and mortality associated with entering the fish collection pool portion of the Salem fish return system at either 3 cfs or 13 cfs flow conditions.

7.1.4.3. Analysis – Laboratory and Salem FCP Tests

Alden's analysis of the potential effect of impact and shear for fish encountering the FCP sampling gate and entering the fish collection pool indicated that the FCP is not a significant source of mortality for alewife when either 25 or 50 cm of cushion water is in place at the time of sampling. There was no significant difference between the 25 and 50 cm cushion survival rates (117.4% and 103.3%, respectively) during laboratory testing. On-site FCP tests supported the laboratory results. Estimates of mean survival were 100.4% for the 25 cm of cushion water (the existing sampling protocol for Salem) and 100.7% for tests conducted with 50 cm of cushion water. Increased flow (from 3 cfs to 13 cfs) also did not have a substantial effect on survival (99.96%). On the other hand, survival rates were significantly lower for the 25 cm/13 cfs condition than for the 50 cm/3 cfs condition ($P<0.05$). However, although significant, these differences were not biologically meaningful. In all, 6 of 1776 fish tested at the Salem fish collection pool were killed. All but one of these fish were killed by blue crabs and stranding in the collection pool during the netting process. If these fish are excluded from consideration, the raw mortality (48-hr) for fish tested at the Salem is 0.06%.

7.2. Conclusions and Recommendations

The evaluations and studies conducted as required by G.2.b.ii of the Salem Permit have yielded strong evidence that the existing Salem fish return system and fish collection pool do not create stressor conditions that are injurious to fish. In particular, existing EOP and FCP hydraulic conditions did not cause substantial injury or mortality to alewife – a species that is considered to be fragile to handling, stress, and injury. Therefore, there does not appear to be a biological justification for changing the existing design or operation of the fish return and collection systems at Salem.

Bibliography

American Society of Civil Engineers (ASCE). 1982. *Design of Water Intake Structures for Fish Protection*.

Abernethy, C. S., B. G. Amidan and G. F. Cada. 2001. Laboratory studies on the effects of pressure and dissolved gas supersaturation on turbine-passed fish. U. S. Department of Energy, Idaho Operations Office. DOE/ID-10853.

Bell, M. C. and A. C. DeLacy. 1972. A compendium on the survival of fish passing through spillways and conduits. U. S. Army Corps of Engineers, Portland, OR.

Cada, G. F. 1990. A review of studies relating to the effects of propeller-type turbine passage on fish early life stages. North American Journal of Fisheries Management 10: 418-426.

Cada, G. F., C. C. Coutant, and R. R. Whitney. 1997. Development of biological criteria for the design of advanced hydropower turbines. U.S. Department of Energy, Idaho Operations Office.

Cook, T. C., G. E. Hecker, H. B. Faulkner, W. Jansen. 1997. Development of a more fish tolerant turbine runner. Advanced hydropower turbine project. ARL Report No. 13-97/M63F.

Dunnett, C. W. 1955. Multiple comparison procedure for comparing several treatments with a control. Journal of the American Statistical Association 50: 1096-1121.

Electric Power Research Institute (EPRI). 1999. Fish Protection at Cooling Water Intakes: Status Report. EPRI. Palo Alto, CA. TR-114013

ESSA Technologies Limited (ESSA). 2000. Review of portions of the New Jersey pollutant elimination system (NJPDES) renewal application for the Public Service Electric & Gas (PSE&G) Salem Generating Station: Final Report. Prepared for the New Jersey Department of Environmental Protection Division of Water Quality, Bureau of Point Source Permitting – Region II. Trenton, NJ. June 14, 2000.

Flow Science. 2002. FLOW-3D User's Manual – version 8.0k. Los Alamos, NM.

Graser, L. F., P. A. Hackney, L. B. Starnes, and J. J. Hogue. 1979. Investigations of dynamics and fate of larval fish in the vicinity of the John Sevier Steam-Electric Plant. Tennessee Valley Authority.

Hirt, C.W. and B. D. Nichols. 1981. Volume of Fluid (VOF) Method for the Dynamics of Free Boundaries. Journal of Computational Physics 39:201.

Groves, A. B. 1972. Effects of hydraulic shearing actions on juvenile salmon (summary report). Northwest Marine Fisheries Service, National Oceanic and Atmospheric Administration.

Hirt, C.W., J. M. Sicilian. 1985. A Porosity technique for the definition of obstacles in rectangular cell meshes. Proc. Fourth International Conference on Ship Hydrodynamics. National Academy of Science. Washington, DC.

Keevin, T. M., S. R. Adams, and K. J. Killgore. 2000. Effects of pressure changes induced by commercial navigation traffic on mortality of early life stages of fish. U. S. Army Corps of Engineers. Interim Report. ENV Report 34.

Nietzel, D. A., M. C. Richmond, D. D. Dauble, R. P. Mueller, R. A. Moursund, C. S. Abernethy, G. R. Guensch, and G. F. Cada. 2000. Laboratory studies on the effect of shear on fish: final report. U. S. Department of Energy, Idaho Operations Office. DOE/ID-10822.

Odeh, M. 2001. Evaluate effects of hydraulic turbulence on the survival of migratory fish, design and construction of experimental apparatus to sturdy the potential effects of turbulence on fish. U. S. Department of Energy, Bonneville Power Administration. Project No. 2000-057-00.

Pardue, G. B. 1983. Habitat suitability index models: alewife and blueback herring. U.S. Department of Interior Fish and Wildlife Service. FWS/OBS-82/10.58.

Public Service Electric and Gas (PSE&G). 1999. PSE&G Salem Station NJPDES Permit Renewal Application: Alewife (*Alosa pseudoharengus*) Attachment C-7.

PSEG Services Corp. (PSEG). 2001a. Ranking of RIS Vulnerability. D. Garchow to R. McDowell, letter dated October 30, 2001. EEP01381

PSEG Services Corp. (PSEG). 2001b. Special Study Report, Salem Generating Station. Estimated Latent Impingement Mortality Rates: Updated Pooled Estimates Using 1995, 1997, 1998, 1999 and 2000 Data. Prepared by PBS&J, Beltsville, MD. June 2001.

PSEG Services Corp. (PSEG). 2001c. Analysis of Data on Factors Affecting Estimates of Mortality Rates for Fish Exposed to the Fish Return System. Prepared by PBS&J, Beltsville, MD. August 2001.

PSEG Services Corp. (PSEG). 2001d. Salem Generating Station. Analysis of Data on Factors Affecting Estimates of Mortality Rates for Fish Exposed to the Fish Return System. Prepared by PBS&J, Beltsville. MD. October 2001.

Ruggles, C. P. and D. G. Murray. 1983. A review of fish response to spillways. Canadian Technical Report of Fisheries and Aquatic Sciences No. 1172. Freshwater and Anadromous Division, Fisheries Research Branch, Department of Fisheries and Oceans.

Stone and Webster Engineering Corporation (SWEC). 1975. Studies to alleviate potential fish entrapment problems. Final report. Prepared for Niagara Mohawk Power Corporation, Nine Mile Nuclear Power Station – Unit 2

Turnpenny, A. W. H., M. H. Davis, J. M. Fleming, and J. K. Davis. 1992. Experimental studies relating to the passage of fish and shrimps through tidal power turbines. Fawley Aquatic Research.

United States Army Corps of Engineers (USACE). 1991. Revised compendium on the success of passage of small fish through turbines. North Pacific Division.

Zar, J. H. 1984. *Biostatistical Analysis*. Second Edition. Prentice-Hall, Inc. Englewood Cliffs, NJ.

Appendix A
Special Study 2002 – Spraywash Pressure Testing

Salem Generating Station
NJPDES Permit No. NJ0005622

Special Study
2002 Spraywash Pressure Testing
Final Report

Prepared for:
PSEG Services Corporation
Estuary Enhancement Program

Prepared by:
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December 2002

Attachment 1
Salem Generating Station. Analysis of Data on Factors Affecting Estimates of Mortality Rates for Fish Exposed to the Fish Return System