PRELIMINARY RESEARCH PROPOSAL
SUBMITTED TO THE U.S. ARMY CORPS OF ENGINEERS UNDER THE ANADROMOUS FISH EVALUATION PROGRAM
2007 PROJECT YEAR

I. BASIC INFORMATION

A. TITLE

Smolt Responses to Hydrodynamic and Physical Characteristics of Forebay Flow Nets Upstream of Surface Flow Outlets

B. PROJECT LEADERS

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C. STUDY CODES

SBC-W-06-01

D. ANTICIPATED DURATION

1 Jan 2007 – 31 Dec 2007

E. DATE OF SUBMISSION

August 2006

II. PROJECT SUMMARY

A. GOAL

The goal of this field study is to provide fisheries managers and engineers with general design guidelines on hydraulic and physical conditions that are conducive to passing juvenile salmon at surface flow outlets (SFOs), such as sluiceways and removable spillway weirs (RSWs). This information will aid transfer of successful SFO technologies from one site to another. Considerable variety exists in the physical characteristics of existing SFO entrances, and our focus will be to identify entrance characteristics that facilitate smolt passage (i.e., minimize delays), without the need to build prototype test facilities. The relationship between entrance conditions and fish responses within about 20 m of SFOs is a critical uncertainty in the widespread development of successful SFO technology.

B. OBJECTIVES

1. Using new empirical data on fish swim paths and water velocities from remote sensing techniques, examine statistical relationships between juvenile salmonid movements and hydraulic variables at RSW entrances at Lower Granite and Ice Harbor dams.

2. Describe and compare fish movements and forebay hydraulic signatures of SFOs, including the Ice Harbor RSW, Lower Granite RSW, Bonneville Dam B2 Corner Collector, the B1 Sluiceway, and The Dalles sluiceway.
3. Determine if there is a threshold in water acceleration or related variables during approach to a SFO that results in juvenile salmonids rejecting the entrance.
4. Recommend guidelines on hydraulic and physical conditions that provide for efficient passage of juvenile salmonids at dam SFOs.

We propose sampling RSW flow nets at Lower Granite Dam (LGR) and Ice Harbor Dam (IHR) in 2007 with at least one DIDSON acoustic camera and a standard footprint Acoustic Doppler Current Profiler (ADCP). Comparative fish tracking data collected with the same methods are available from studies of the Bonneville Second Powerhouse Corner Collector (B2CC) in 2004 (Ploskey et al. 2005), The Dalles Dam sluiceway in 2004 and 2005 (Johnson et al. 2005), and the Bonneville First Powerhouse (B1) sluiceway in 2005 (In preparation). The Ice Harbor and Lower Granite RSWs we propose to sample have high discharge (ca. 6,000 cfs) relative to the discharge of 500 cfs at the B1 sluiceway entrances, 1500 cfs at the TDA sluiceway, and 5,000 cfs at the B2CC. Weir shapes also differ. The B1 sluiceway has a sharp crested weir, the B2CC and TDA sluiceway entrances have broad crested weirs, and the RSWs have shaped weirs and side walled entrances for controlling acceleration. The range of discharges and differences in shapes will allow for an investigation of a wide range of relations between fish behavior and hydraulic conditions. Fish sampling and tracking methods were extensively developed in 2004 and 2005 studies. These methods are mature and ready to be applied at new locations to increase the diversity of the SFO data base. Hydraulic data collection methods are also well-known. However, methods to collect fish movement and hydraulic data simultaneously are not well-established. Thus, we will merge and analyze fish movement and environmental datasets to determine which variables have the greatest effect on entrance efficiency and characteristics of fish movements at the SFO entrances. Performance comparisons will include entrance efficiencies at all locations. These data will be applied in recommendations for general guidelines on SFO entrance conditions.

C. METHODOLOGY

We plan to sequentially sample RSWs at LGR and IHR dams, three times in spring and three times in summer. Every time a site is visited, movements of fish and flow approaching within about 20 m of each entrance will be sampled for 24-h per day for 3 consecutive days so that about 216 hours of data will be acquired each season. The first step each season will be to identify the entrainment zone, where fish can no longer avoid being entrained by identifying a contour of 7 ft / s velocity upstream of the opening based upon ADCP sampling. The next step will be to identify the zone of 100% entrance efficiency by observing hundreds of approaching fish with dual-frequency-identification sonar (DIDSON). Sampling upstream of the entrainment zone is important because fish have no choice after they are entrained, and we do not want to compare the entrance efficiency of entrained fish at one site with that of un-entrained fish at another site or explore relations between fish tracks and hydraulic variables after fish are committed to passing. Defining the entrainment zone and sampling just upstream of it provides a common denominator for comparing results among surface flow outlet sites with different structural configurations and hydraulic conditions. Sampling will consist of simultaneous recording of movements of approaching fish and water velocity. A DIDSON will be used to sample 2D movements of fish and a standard-footprint acoustic Doppler Velocimeter (ADCP) will sample average water velocity within 0.5-m strata from the instrument. Both instruments will be mounted on the same plate, which will be moved by a programmable stepper motor. The stepper motor will be programmed to aim the instruments to sample each of six 30° wide, 12° deep zones for 10 minutes every hour. All zones will be upstream of the entrainment zone so we do not expect structure to interfere with ADCP sampling. Three of the adjacent horizontal zones will be as close to the water's surface as possible and the other three zones will be immediately below the near-surface zones. We propose sampling zones because previous attempts at

actively tracking individual or schools of fish did not result in a large pool of long complete tracks for analysis because most fish were lost even by the most diligent tracker.

We also will perform a pilot study to derive water velocity estimates immediately around fish using a particle image velocimetry (PIV) method on DIDSON image data. If this method proves useful, we will have the capability to make water velocity measurements in the immediate vicinity of fish for the first time. The methods from a successful 2007 pilot study of DIDSON PIV could be applied routinely in future studies.

We will estimate metrics designed to assess the acceptability of entrances to smolts and enter the metrics into a data base so that they can be compared to similar statistics compiled from field trips to sample other SFOs. Entrance acceptability data from all different surface routes will be analyzed to rank the routes based upon entrance efficiency, which is the first step in determining what smolts prefer. The probability that a smolt will enter an SFO will be calculated using a Markov chain analysis of fish tracks (Johnson et al. 2004). The Markov analysis does not require complete tracks to predict an entrance probability. The second, more important step will be to analyze independent variables describing the hydraulic and physical environment of the flow net to each SFO entrance to assess the relative importance of those factors on entrance efficiency and smolt movements. The primary independent variable in this analysis will be the "fish behavior" vector, which is obtained by subtracting the flow vector from the observed fish movement vector. This study will involve descriptive statistical methods to examine associations and correlations, not cause and effect, between fish movements and environmental variables.

D. RELEVANCE TO THE BIOLOGICAL OPINION

UPA Measures: Hydrosystem Substrategy 1: Mainstem Juvenile Passage Improvements. There also are several Reasonable and Prudent Alternative (RPA) Actions in the 2000 Biological Opinion that apply to this proposal. Action 86 states that the Corps shall continue to investigate a way to increase entry rates of fish approaching surface bypass/collector entrances. Action 85 states that the Corps shall continue to develop and evaluate improved fish-tracking technologies and CFD modeling. The ability to integrate these technologies and fluid dynamics shall be assessed as a potentially improved means of determining fish responses to forebay hydraulic conditions. Action 61 states that the Corps shall complete the ongoing prototype powerhouse system surface collection evaluation at Bonneville First Powerhouse in 2000. The prototype surface collector evaluation is now complete, but given projected cost of construction, other surface bypass alternatives are being examined. This research supports those efforts.

III. PROJECT DESCRIPTION

A. BACKGROUND

Development of surface routes to safely pass juvenile salmon through hydroelectric dams in the Pacific Northwest has been underway for over thirty-five years. In the 1970s and early 1980s, researchers showed that sluiceways at Bonneville, Ice Harbor, and The Dalles dams passed a relatively high proportion of smolts in a relatively low proportion of the flow (Willis and Uremovich 1981; Johnson et al. 1982; Nichols and Ransom 1981, respectively). Sluiceway operations for juvenile fish passage have been employed ever since, although the sluice route is not sufficient as a stand-alone bypass. In 1995, a major Corps program to develop surface flow outlets was initiated. Work in 1995 and subsequent years included prototypes at Bonneville, Ice Harbor, John Day, Lower Granite, and The Dalles dams. Surface flow outlet research was summarized and synthesized by Johnson et al. (1997) and Dauble et al. (1999) for the region as a whole, by Johnson and Giorgi (1999) and Johnson and Carlson (2001) for Bonneville Dam, and by Anglea et al. (2002) for Lower Granite Dam. A common concern expressed in these

reviews was, despite many years of research, information was lacking on the relationship between fish behavior and flow-field features, especially in the zone within about 20 m of SFO entrances.

Surface flow outlets are intended to create a flow field in the forebay that juvenile salmon can discover and utilize to move downstream. Although they generally follow the bulk flow downstream through reservoirs, fish sometimes meander when they encounter slow water in the forebays of dams (Adams et al. 1998). Assuming smolts discover the SFO flow net, a key point is whether they will react positively or negatively, i.e., will they enter or avoid the entrance? Thus, discovery of a SFO flow net is only half the battle; the other half is for the fish to actually follow the flow field and pass into the entrance.

The development of acoustic camera technology is what makes this proposed study possible. The Dual-Frequency Identification Sonar (DIDSON) is an ideal assessment tool for this study because it is highly portable, requires minimal site preparation to deploy repeatedly, and does not rely on fish tagging. With the DIDSON, we can distinguish fish from other targets, observe their behavior unobtrusively, and track their movements. The DIDSON was developed by the Applied Physics Laboratory (APL) at the University of Washington for the Space and Naval Warfare Systems Center harbor surveillance program (Belcher et al. 1999). The DIDSON was designed to bridge the gap between existing sonar, which can detect acoustic targets at long ranges but cannot record the shapes or sizes of targets like optical systems, which can videotape fish in clear water but are limited at low light levels or when turbidity is high. The DIDSON has a high resolution and reasonable frame rate designed to allow it to substitute for optical systems in turbid or dark water. The images within about 18 m of the device are clear enough to reveal fish undulating as they swim and for users to measure fish and to tell the head from the tail. This is important because one of the dependent variables characterizing behavior will be fish orientation throughout their approach and whether they turned and swam downstream at some point.

The DIDSON is not as sensitive to entrained air as are the 6–10 degree beams that are typically used for hydroacoustic sampling. The clarity is possible because the field of view is composed of 96 different 0.33 × 8.5-degree beams operating at 1.8 MHz and 48 different 0.6 × 8.5-degree beams operating at 1 MHz. These narrow beams individually have much better signal to noise ratios than does a 6-degree hydroacoustic beam. The DIDSON can sample up to 12 frames per second and has a 29-degree field of view. The multiple beams allow image processing that produces a movie of fish movements. Unlike single and split-beam hydroacoustic transducers, the acoustic camera has multiple narrow beams that allow it to be aimed oblique to a flat surface and still record fish swimming very near the surface. At Bonneville and The Dalles dams during 2001 and 2002, the acoustic camera proved to be a useful tool to evaluate fish movements in turbid water very near structures. Details provided by a single frame from an acoustic-camera file can be seen in Figure 1, but the strength of the method is the ability to record swimming movements of fish.

This proposed study will use standard methods across multiple sites to designate the near-field zone relative to the point at which fish are entrained, estimate entrance efficiency, and estimate other fish response characteristics relative to physical conditions. Entrance efficiency is the proportion of fish that pass into an entrance out of the total number available within some specific distance immediately upstream of the entrainment zone. We refer to this area of availability as the near-field zone. Over the years, different researchers using different methods have estimated entrance efficiency based upon arbitrary designations of the near-field zone, and this produced estimates that could not be directly compared. Nevertheless, entrance efficiency is a valuable concept because it reflects fish responses to environmental conditions in SFO flow nets.

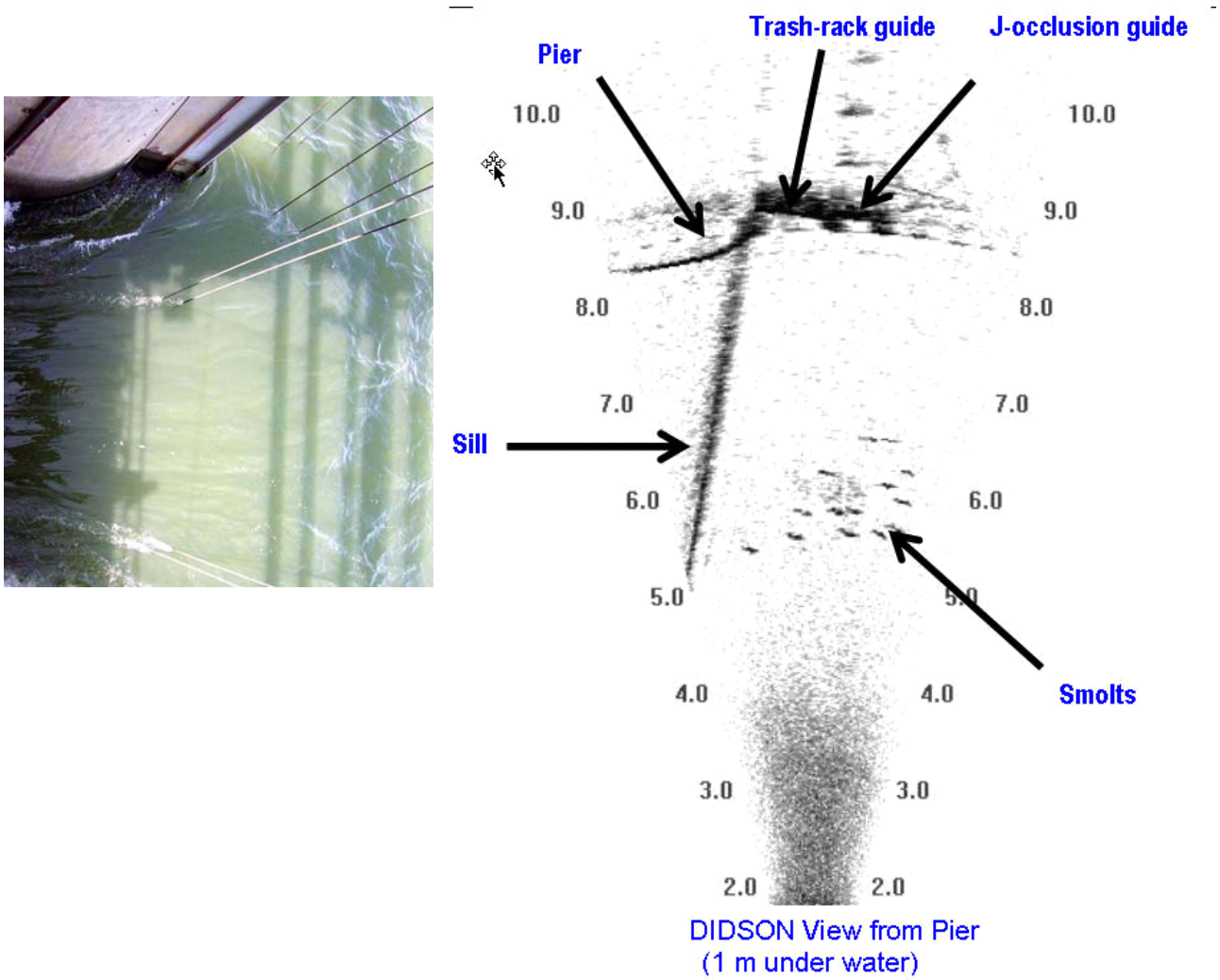

Figure 1. Photograph taken from the top of the pier at Main Unit 1 at The Dalles Dam looking down on a sluiceway entrance (left) and an image from the acoustic camera deployed 1-m deep on the same pier and aimed horizontally across the sluiceway entrance (right).

Metrics in this study cannot be converted to estimates of fish guidance efficiency (FGE) or fish passage efficiency (FPE) because only the entrance area will be sampled. It is true that a high FGE or FPE does not require high entrance efficiencies, because fish may ultimately pass even after rejecting the entrance multiple times previously. However, it also is likely that SFOs with high entrance efficiencies and limited hesitation by smolts also will have high guidance or passage efficiencies provided the entrance is located in a good place for smolts to discover it.

Information from our study will be useful to fisheries managers and engineers seeking to transfer SFO technologies from one site to another. We are aware this has been and always will be a difficult proposition because site-specific features can affect fish behavior in unexpected ways. As Mike Erho said in Johnson et al. (1996, p. A-18), "It may be difficult to determine universal biological design criteria for surface flow bypass because of the uniqueness of each site...there is no magic engineering formula for SFB…certainly much can be learned by experience and information from other sites, but ultimately one needs to thoroughly assess each individual project and determine what's best for it." Our study is

designed to at least partially transcend this limitation because it will include diverse sites, use standard assessment methods, occur over similar times, and collect data in situ. Thus, while we retain Erho's skepticism about "a magic engineering formula", we are optimistic that the potential exists to discover overarching principles of fish response to flow fields that would lead to guidelines on hydraulic and physical conditions that are conducive to facilitate juvenile salmon passage at surface routes at dams.

Finally, we think that a significant value of this study will be derived from directly and simultaneously observing fish behavior in SFO flow nets. As envisioned, we expect to track thousands of fish at each site, and sample sizes should provide for a robust analysis of effects of physical characteristics. However, from a strictly descriptive viewpoint, the study will provide valuable insight into fish behavior that should also be useful for bioengineers.

Table 1. Summary of features at proposed and previously sampled study sides.

Site	**Owner**	**Route**	**Discharge per Entrance (cfs)**	**Dimensions (WxH ft)**	**Description**
Ice Harbor	CENWW	Removable Spillway Weir*	~6,000	50 X 10	Smooth, specially shaped entrance
Lower Granite	CENWW	Removable Spillway Weir*	~6,000	50 X 10	Smooth, specially shaped entrance
Bonneville Dam	CENWP	B1 Surface entrance **	~500	21 X 4	Vertical gate (sharp crested weir)
Bonneville Dam	CENWP	B2 Corner Collector **	~5,000	15 x 22	Sharp crested weir
The Dalles Dam	CENWP	Sluiceway entrance **	~1,500	21 X 7	Broad crested weir

* Proposed for sampling in 2007
**Previously sampled

B. OBJECTIVES

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2. Describe and compare fish movements and forebay hydraulic signatures of SFOs, including the Ice Harbor RSW, Lower Granite RSW, Bonneville Dam B2 Corner Collector, the B1 Sluiceway, and The Dalles sluiceway.
3. Determine if there is a threshold in water acceleration or related variables during approach to a SFO that results in juvenile salmonids rejecting the entrance.
4. Recommend guidelines on hydraulic and physical conditions that provide for efficient passage of juvenile salmonids at dam SFOs.

C. METHODOLOGY

Site Preparation

In early spring, we will securely anchor a pontoon barge upstream and off to one side of each RSW entrance similar to the way that a barge was anchored at the B2CC in 2004 (Figure 2). All anchors, deployment, and safety protocols will be worked out with the respective Projects. Proper permissions and access procedures will be obtained ahead of time. During each site visit (three times in spring and three in summer), the electronic equipment package (DIDSON, ADCP, stepper motor and cables) will be

moved to each barge and deployed by staff, either by crane or by boat. However, nobody will be on the barges during data acquisition.

Figure 2. Two views of a pontoon barge anchored upstream of the B2CC in spring and summer 2004.

Sampling Schedule

The objective is to successively sample two RSWs within one week of each other three times in spring and three times in summer. The upstream to downstream order of sampling was selected primarily for logistical reasons, but it may provide for greater similarity in species composition within blocks. Sampling of each of the six zones will be continuous so that diel effects on behavior can be evaluated.

Description of Activities during a Site Visit

Preliminary activities. Upon arrival at LGR or IHR, the equipment package will be transferred to the anchored barge either by boat or crane, and technicians will get everything up and running so that sampling can be controlled from a trailer on the spillway. A weather instrument and light meter for continuously measuring wind speed, direction, air temperature and ambient light also will be deployed on the barge. A water sample will be taken to measure temperature and turbidity. The ADCP and DIDSON will be panned over the entire area upstream of the entrance to ensure that everything is functional before technicians leave the barge.

Fish Sampling. The first task at each site will be to identify the extent of the entrainment zone (EZ) and the zone of 100% entrance efficiency (100%EE). Sampling immediately upstream of the EZ is important to establish a common denominator for comparing results among sites with different shapes and hydraulic conditions. We do not want to compare the entrance efficiency of entrained fish at one site with that of un-entrained fish at another site or explore relations between fish tracks and hydraulic variables after fish are entrained and cannot alter their fate. First, velocity contours > 7 fps will be plotted to define the EZ, where all fish are involuntarily entrained. Second, recorded swim paths of fish will be used to identify the 100%EE zone, where 100% of fish pass into an entrance by choice or because they are entrained. The extent of 100%EE zone may be ≥ the extent of the EZ. A DIDSON in low-frequency mode will be used to sample 2D movements of fish and a standard-footprint acoustic Doppler Velocimeter (ADCP) will sample average water velocity within 0.5-m strata from the instrument. Both instruments will be mounted on the same plate, which will be moved by a programmable stepper motor. The stepper motor will be programmed to aim the instruments to sample each of six 30° wide, 12° deep pie-slice shaped volumes for 10 minutes every hour (Figure 3). The zones will overlap slightly in the horizontal plane (~ 3 deg). All zones will be upstream of the EZ so we do not expect structure to interfere with ADCP sampling. Three of the adjacent horizontal zones will be as close to the water's surface as possible and the other three zones will be immediately below the near-surface zones. We propose sampling fixed volumes because previous attempts at actively tracking individual or schools of fish did not result in a large pool of long complete tracks for analysis because most fish were lost even by the most diligent tracker. In addition, tracking and water velocity estimates within the field of view are much more accurate when the instruments are not moving. Finally, the Markov-chain analysis that will be used to estimate the probability of fish entering does not require complete tracks. Every frame of recorded data will include the aiming coordinates of the DIDSON rotator and the lateral position of the fish in the DIDSON field of view. We also will note the number and locations of predators in the vicinity of entrances during sampling so that those observations can be included in the data bases and referenced to flow and smolt behavior.

Species Composition

Although the acoustic camera cannot identify species, we will differentiate subyearling Chinook salmon from resident fishes in summer based on size, silhouette, and behavior. We will supplement acquired data with species composition data from the juvenile bypass systems. Measured lengths of targets should allow us to classify many targets as steelhead or yearling Chinook salmon in spring and as subyearling Chinook salmon and other larger fish such as American shad in summer.

Fish Track Data

Accuracy. The DIDSON detects fish positions accurately in two dimensions, i.e., in range from the device and across the fan of 96 0.3-degree wide beams but can only estimate position in the depth

dimension perpendicular to the fan of beams to within 12 degrees. For a deployment with the fan of 48 beams oriented horizontally and the camera aimed across an entrance as proposed in this study, the DIDSON will provide very accurate estimates of fish position (within 50-75 mm) across the opening and in the upstream-downstream direction. However, we will have to estimate depth by assuming that the fish are in the center of the 12° deep beams and calculate fish depth as follows:

$$\text{Fish depth} = CD + (R \times \text{Tan}(RA_{BH}/2)) \times 2,$$

where CD = camera depth, R = range from the acoustic camera, Tan = tangent; and RA_{BH} = rotator angle below horizontal. Therefore, the error in estimates of fish depth will be range dependent (i.e., ± Tan(12º/2) x R). In the low-resolution mode, with a fan of 48 beams oriented horizontally, the DIDSON provides high resolution 2D position information based upon range from the instrument and location among the beams. With the same orientation, the vertical resolution of fish position is less accurate. It is ± 0.52 m at 5 m of range, ± 1.05 m at 10 m, and ± 1.6 m at 15 m.

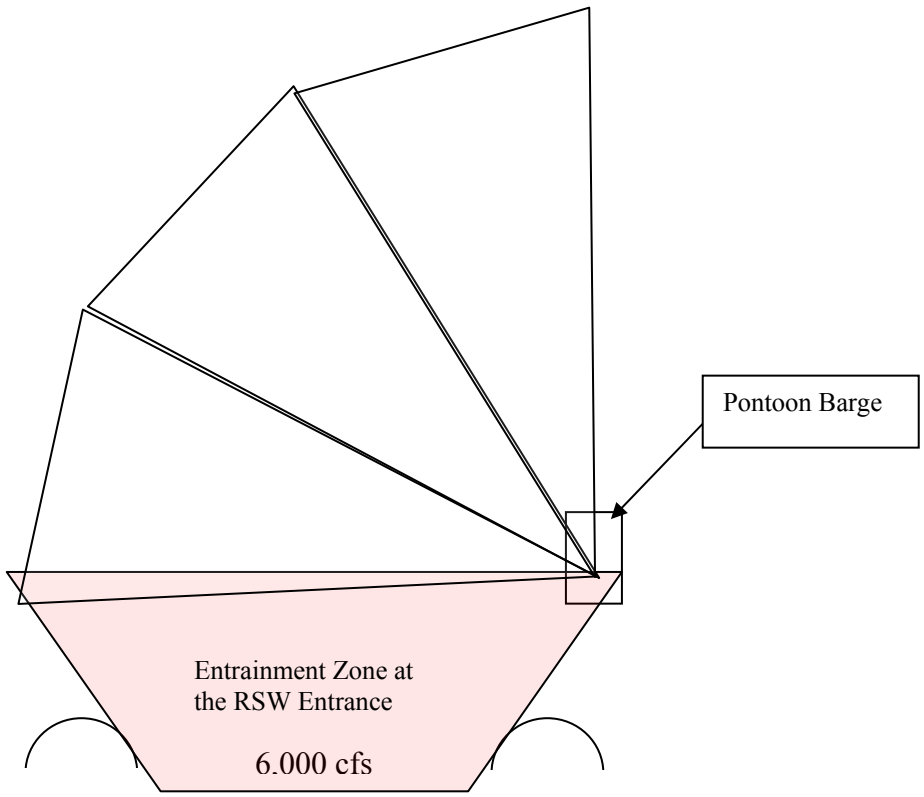

Figure 3. Plan view diagram showing three near-surface 30º-wide, 12º-deep zones for sampling fish movement with a DIDSON. Three additional zones will be 12º deeper than the surface zones visible in this plan view.

Processing. Processing of DIDSON fish-image data into a time series of 3D coordinates will be done with a DIDSON autotracker developed in 2005. Automated processing will provide substantial cost savings over manual tracking that had to be used in 2004. Processing DIDSON data to fish tracks is tedious and time-consuming. Tracks obtained from the autotracker and a manual tracker are very similar, but the autotracker is much faster. The autotracker will process the data on a frame-by-frame basis for maximum resolution of fish positions through time and will automatically associate time and rotator coordinates with each fish position.

Observation-Specific Metrics. Characteristics of completed tracks will provide a host of metrics for comparing fish behavior at different sites and for relating fish behavior to hydraulic and physical

conditions. These include but are not limited to variables listed in Table 2. Because these metrics are fish-specific, the sample size for determining effects of independent variables such as flow or time of day (Table 2) will be much larger than the sample size for comparing entrance efficiencies among sites or times.

Table 2. Dependent and independent variables for the analysis of entrance conditions at surface passage routes.

Type	Variable
Header	Location (field site)
	Julian date
	Time start observation segment
	Time end observation segment
	Day/night
	Zone
	Distance from the entrance that fish are entrained (i.e., the start of nearest zone for estimating entrance efficiency
Dependent Variables	
Primary Metric	Fish behavior vectors (see Data Analysis section)
	Entrance efficiencies by range from SFO entrance
Observation Metrics	Orientation (rheotaxis)
	Change in orientation
	Behavior category (e.g., swimming d/s, holding, searching)
	Direction of movement
	Residence time
	Fish Length
	Position (X, Y, Z)
	Number of fish in school
	Swim path length relative to the distance to the entrainment point
	Lateral displacement after first detection
	Speed
	Mean track duration (seconds) and variation therein
	Track directivity = distance from first detection to last detection / total track length (Fish that go in a straight line will have a track directivity approaching 1)
Supplemental	Specific composition by date from the closest juvenile bypass system

Hydraulic Data

Physical data will be primarily hydraulic, although data on entrance dimensions, shape, water temperature, water turbidity, ambient light, wind, and presence of adjacent structures also will be collected. Dam operations data will be obtained from the operations personnel at each site. We will need hourly data on operations for each turbine unit, spill bay, as well as total powerhouse, sluiceway, and spillway discharges and forebay elevations.

A standard foot-print (28°) ADCP (RDI, Inc. 600 kHz) will be used to obtain water velocity data while we collect the acoustic camera data. Note that the ADCP provides an averaged velocity over the area of the foot print and thus is much larger area than occupied by a fish. The ADCP will be mounted on the same plate as the DIDSON and will sample the same zone as the DIDSON at the same time. Standard

processing techniques will be used to estimate water velocity by range through time and a common GPS clock of time will ensure that time lines for fish tracks and water velocities are synchronized.

We also will conduct a pilot study to see whether we can derive water velocity estimates using a particle image velocimetry method (PIV) on DIDSON images. The potential for successful development of a 2D DIDSON PIV will be determined in the narrowly defined and funded lab study. Since its establishment in the last decade, PIV has overcome the limitation of the traditional single-point velocity measurement techniques and become a state-of-the-art, non-intrusive, whole-flow-field technique, providing instantaneous velocity vector measurements in a whole plane. The use of a stereoscopic PIV approach permits instantaneous measurement of all three velocity components, providing a means to characterize real-time three-dimensional flow structures for areas of interest, such as around the body of a fish. We will compare 2D velocity estimates derived from DIDSON images collected at high and low frequency modes with estimates from stereoscopic images processed with a 3D high-speed digital PIV system that PNNL acquired in 2003. The 3D system was used to characterize flows around fish in a tank (Deng et al. 2004). Those measurements showed unsteady vortex shedding in the wake, and very high vorticity and high stress regions around the head of fish, with the highest in the pectoral area (see Figure 4). We anticipate using and modifying the existing PIV software for extracting estimates of water velocity and for quantifying flow features from DIDSON images using the PIV technique.

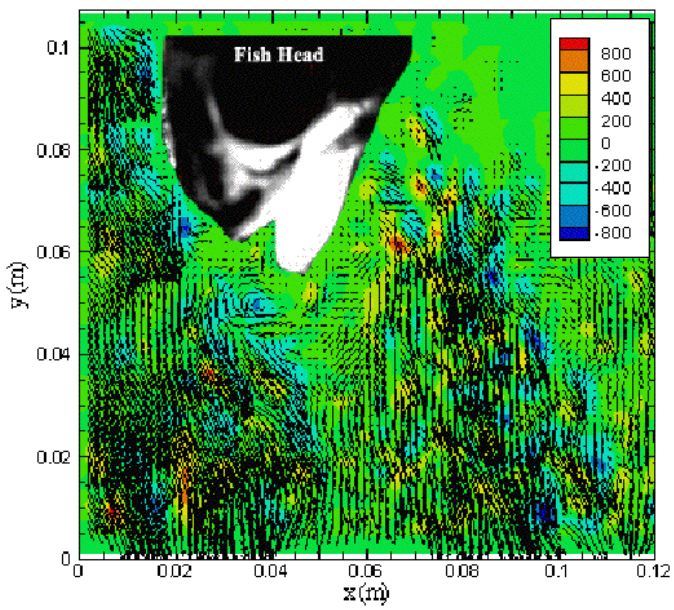

Figure 4. Example contour plot of instantaneous vorticity field around fish head held in a water jet, in (m/s)/m, overlapped with instantaneous velocity vectors measured using the PNNL PIV system.

Processing DIDSON images to describe real-time flow characteristics will require a special subtask by Drs. Smith and Liou at the University of Idaho and Dr. Marshall Richmond (PNNL) to make use of the advanced microelectronics already packaged into the DIDSON. They will develop imaging processing techniques to extract real-time velocity vector fields in close proximity to fish being tracked from DIDSON images. Once the velocity fields are known, other hydraulic quantities such as vorticity and shear rate can be estimated. Of special interest is the use of spatial correlations to identify flow structures (Nezu and Nakagama 1993). We anticipate that flow structures with scales ranging from a fraction to multiple fish body lengths can be quantified using the DIDSON data. There has been considerable research in the development of image processing techniques associated with Particle Image Velocimetry (PIV) (Adrian 1991, Westerweel 1993, Raffel et. al., 1998, Hart 1999, 2000). This body of knowledge to a great extent is applicable and will be used to process the DIDSON images. This subtask will consist of

a combination of laboratory and field segments designed to develop methods to use the DIDSON camera to characterize flow field conditions. Field data will be acquired from the forebay within 20 m of the lower Granite RSW. Laboratory flumes at either Washington State University or the University of Idaho will be used to calibrate DIDSON images against known flow features. Trials will be run in which the water will be seeded so that the "target strength" of particles entrained are within the range measured on the Columbia River. The image processing has five steps:

1. Divide two adjacent (in time) images with known elapse time into sub-regions.
2. Perform cross-correlation or minimum quadratic difference operations between two corresponding sub-regions to establish the sub-region average velocity vector. Repeat the same for all sub-region pairs.
3. Apply super-resolution algorithm to obtain sub-pixel resolution
4. Perform local and global filtering
5. Smooth the resulting velocity vector fields.

Several commercial and public-domain software packages for PIV are available to convert images from PIV hardware to velocity vector fields. We will first apply the software system currently used with the PNNL 3D PIV system. Issues particular to DIDSON, such as non-homogeneous seeding and non-uniform thickness of the view field will be investigated. The achievable spatial and temporal resolutions of the velocity vector fields from DIDSON images will be quantified as a function of frame rate, and the view field's position and size. Software that converts the velocity information into vorticity and strain rates will be developed. In conclusion, if the DIDSON PIV method is successful, we will have the capability to make water velocity measurements in the immediate vicinity of fish in the field for the first time.

Merging of Biological and Physical Data

The ADCP data on water velocity and associated hydrodynamic characteristics such as acceleration and rate of strain will be merged with the fish data for specific times and three-dimensional positions. The universal coordinate system for this study will be Oregon south for IHR and LGR referenced to the NAD27 horizontal datum and the NGVD vertical datum. This is the same as for previous studies at Bonneville and The Dalles dams. A reference position at each study site will be established. The measured fish position data and the measured ADCP data will be transformed to the universal coordinate system. Once the master biological and environmental data sets are ready, they will be merged. Merging allows the sequential positions and associated behaviors of ensonified fish obtained by the acoustic camera to be related to hydraulic data for each sequential fish location.

Data Analysis

Data analysis for the three study objectives is interrelated (Figure 5). For the 2007 IHR and LGR study sites, fish movement data from the DIDSON samples will be merged with concurrent hydraulic data from the ADCP. These data will be analyzed to determine fish/hydraulic relationships (Objective 1). The fish and hydraulic data sets will also be summarized to compare with other similar data from SFOs at BON and TDA we collected in 2004-2005 (Objective 2). Pertinent data from all sites will be integrated to determine if there is a threshold in water acceleration during approach to a SFE that results in juvenile salmonids rejecting the entrance (Objective 3). This section of the proposal describes data analysis methods for the three study objectives.

Relationships between Fish Movements and Hydrodynamic Conditions (Obj. 1)

Observed fish movements are a combination of passive advection and active swimming. The active swimming component reflects fish behavior and is fundamental to the understanding of fish response to hydrodynamic conditions. To extract the active swimming component from the observed fish movement data, we will assume passive advection is represented by the ambient water velocity vector and subtract this vector from the observed fish movement vector.

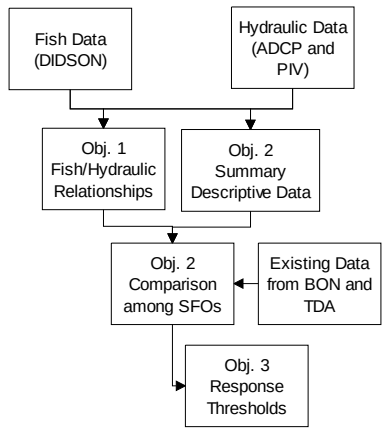

Figure 5. Flow of Data Analysis for Interrelated Study Objectives

Johnson et al. (1998) and Scheibe and Richmond (2002) used this approach, conceptualized as follows:

$$\overrightarrow{Fish}_{behavior} = \overrightarrow{Fish}_{observed} - \overrightarrow{Water}_{observed}$$

That is, for a given time increment, the vector difference between the displacements of fish and water is the active swimming or fish behavior component (Figure 6).

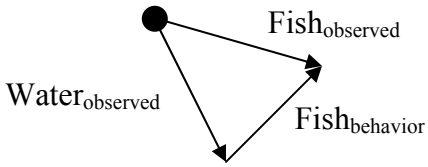

Figure 6. Observed Fish and Water Vectors and the Resulting Fish Behavior Vector.

For the analysis of fish/hydrodynamic relationships, the fish behavior vector will be the basic dependent variable and hydrodynamic and other environmental conditions will be the independent variables. Water acceleration and related variables (e.g., strain) are thought to influence fish behavior (Goodwin 2004), along with other environmental conditions such as the presence of predators, water temperature, and pressure. Thus, independent variables will likely include:

1. Total water velocity
2. Total water acceleration
3. Longitudinal component of water acceleration
4. Transverse vertical component of water acceleration
5. Transverse horizontal component of water acceleration
6. Water temperature

7. Hydrostatic pressure

We will explore the data initially using frequency histograms, bivariate scatterplots, and correlation analyses. Because of the non-linear and complex nature of these types of data sets, we propose to apply multivariate statistical methods (Sokal and Rohlf 1981) to examine relationships between the dependent and independent variables. For example, a Principle Components Analysis will reveal any variables or combinations of variables that explain a majority of the variability (> 50%) in the dependent variable being analyzed.

We performed such an analysis on DIDSON fish movement data and CFD hydrodynamic data collected at The Dalles Dam in 2004 (unpublished data). An example scatterplot of the first principle component versus the second in this particular analysis (Figure 7) shows that there is some pattern in the data, but does not itself define this pattern. Subsequent analyses revealed the hydrodynamic variables most strongly distinguished by the principle components were those related to acceleration, especially the transverse acceleration variables. We propose analyses similar to this to meet Study Objective 1.

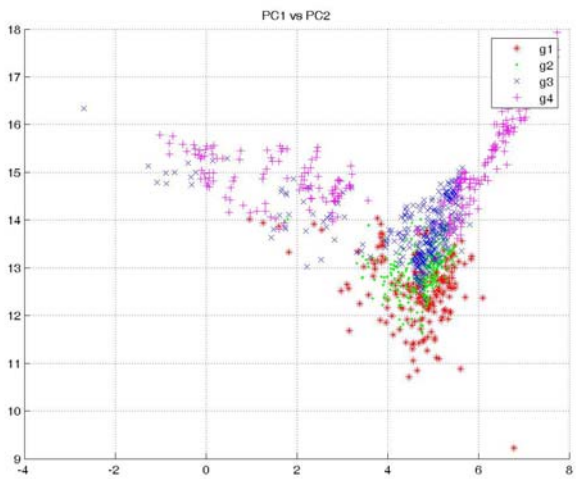

Figure 7. Scatter plot of Principal Components #1 versus #2 for The Dalles 2004 DIDSON Sluiceway Study. Color coding represents observation groupings identified by cluster analysis applied to the first four principal components. Unpublished data.

Summary Descriptive Data and Comparison of Fish/Hydraulics among Multiple SFOs (Obj. 2)

Hydraulic Signatures

The ADCP data we systematically collect at each study site will be analyzed to describe the hydraulic conditions in the forebay of each. The temporal and spatial variability in water velocity, acceleration, and other hydrodynamic variables will also be described. Contour plotting will be used to visualize the hydraulic signatures of the SFOs (Figure 8).

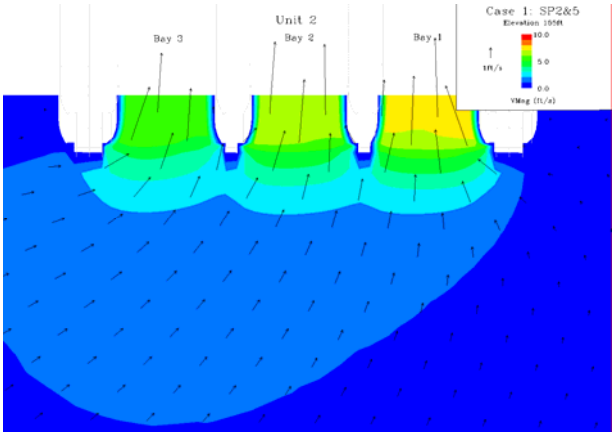

Figure 8. Example Contour Plot of Hydraulic Signature of a SFO. (Data are from CFD performed by PNNL at TDA in 2005.)

Fish Movement Data

Descriptive results from the DIDSON data sets will be useful to characterize fish movements in general and to foster comparison among sites. Typical descriptive data include the mean and standard deviations of observed fish velocities and computed fish swimming velocities. These data will be partitioned by time season, period within season, and day/night and, if appropriate, region of the forebay. The sampling volume will also be divided into cells to describe fish movements, as shown in the example in Figure 9.

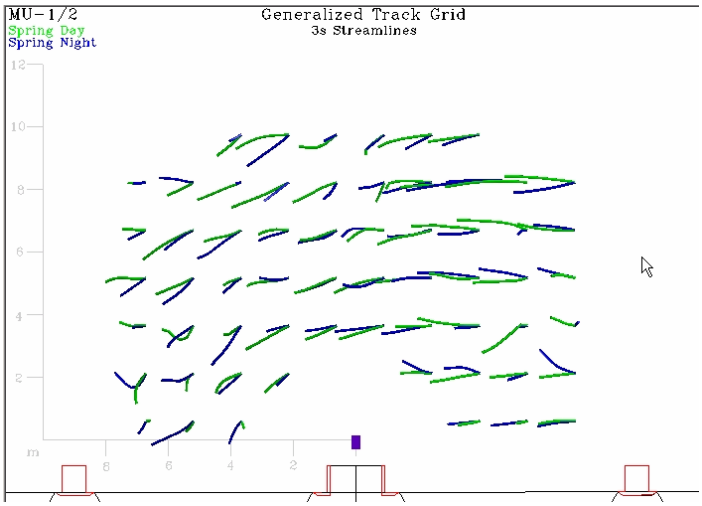

Figure 9. Descriptive DIDSON Data on Mean Observed Fish Velocities (from The Dalles Dam 2004).

Descriptive data will also involve quantification of the zones of entrainment and entrance efficiencies at the subject SFOs. We propose to apply a Markov Chain analysis of the DIDSON fish movement data (Johnson et al. 2004). This analysis will describe the probability of fish passing into the SFO entrance by location in the nearfield of the SFOs (Figure 10).

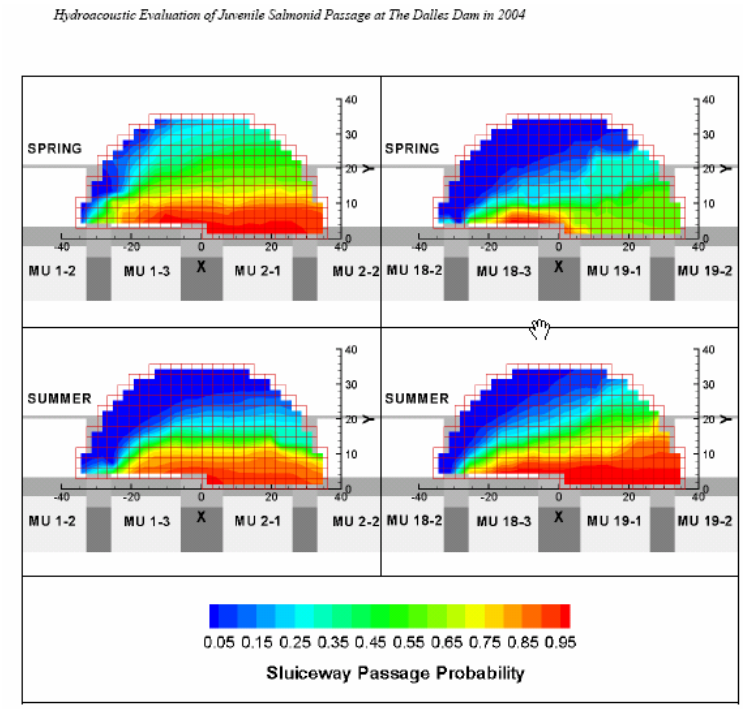

Figure 10. Example Descriptive Data on Zones of Entrainment and Entrance Efficiencies. (Data are from TDA 2004).

Comparison of Fish/Hydraulics among Multiple SFOs

Data on entrainment zones and entrance efficiencies can be integrated to compare descriptions among sites (Figure 11). The data describing the zones of entrainment and entrance efficiencies will be compared statistically (methods to be determined based on the nature of the data).

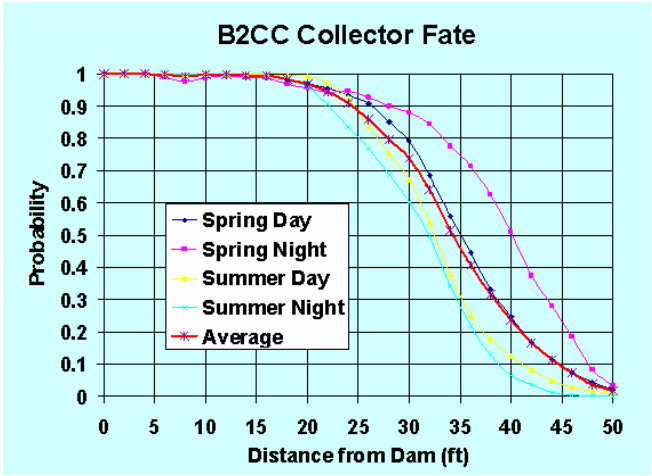

Figure 11. Example Descriptive Data Comparing Zones of Entrainment among Conditions. (Data are from BON 2004).

SFO Rejection Response Threshold (Obj. 3)

Null Hypotheses

We tentatively plan statistically test the following null hypotheses, which will be finalized after consultation with the Science Review Work Group:

1. At a given distance from the SFO entrance, water acceleration (substitute other independent variables) is not related to entrance efficiency.
2. Water acceleration (substitute other independent variables) is not related to the size of the entrainment zone.
3. Smooth-shaped entrances do not affect entrance efficiency (or zone of entrainment).
4. There is no relationship between hydrodynamic variables (insert variable of interest) and fish behavior in the SFO flow nets.
5. SFO discharge is not related to the extent/size of the SFO zone of entrainment.
6. Fish behavior does not differ among the different SFO entrances.
7. Entrance efficiency does not differ among the different SFO entrances.
8. Zone of entrainment does not differ among the different SFO entrances.

Quality Control and Assurance

Quality control and assurance practices will be used throughout the study. Technicians will be on site at least 8-h per day to verify that all equipment is operating to specifications and that acquired data are useful. After the DIDSON and ADCP data have been processed and analyzed, we will examine the data for anomalies and quality. We plan on the following QA/QC steps:

- Pre- and post-season calibration of all instruments
- Review of equipment set-up by a manufacturer's representative
- Use silicon rubber or other material to electrically isolate the ADCP and acoustic camera from their mounts
- Identification of detections of big fish and manual examination of those records to identify potential predators or fallback of adult salmonids
- Manual tracking of 1% of the tracked fish data to verify autotracker performance
- Obtain spatial closure
- Computer time clocks will be synchronized continuously by a common GPS clock.

Reporting Schedule

A preliminary summary of spring data will be provided to the Corps of Engineers by 31 August and spring and summer data summaries will be provided by 31 October. A formal presentation will be made at the Corps of Engineers Anadromous Fish Evaluation Program review, and a draft final report will be completed by 31 December 2007.

D. FACILITIES AND EQUIPMENT

The following list of equipment will be necessary for this study. Most of it will be transported between the study sites on a routine basis.

- DIDSON (one owned by PNNL and another by the CE)
- ADCP: 600 kHz, standard footprint (owned by CE and PNNL)
- PIV: a 3D stereoscopic system including laser and software (owned by PNNL)
- Programmable stepper motor and cables (owned by the CE)
- Vehicle (2 leased from GSA)
- Crane support (CE or commercial)

E. IMPACTS

When available, project assistance in the form of riggers and crane support will be used to deploy the equipment package to the barge. When unavailable, we will subcontract with a private company for crane support.

F. COLLABORATIVE ARRANGEMENTS AND PROJECT DUTIES

The PNNL will subcontract with Drs. John Skalski (University of Washington) and John Hedgepeth (Tenera, Inc.) for assistance with statistical analyses and the Markov Chain analysis, respectively. PNNL also will subcontract with the University of Idaho to work on the particle imaging velocity task.

IV. LIST OF KEY PERSONNEL AND PROJECT DUTIES

Gene Ploskey, PNNL	Co-principal Investigator and all elements of acquisition,
Gary Johnson, PNNL	Co-principal Investigator and all elements of acquisition,
Marshall Richmond, PNNL	Co-principal Investigator (Hydrodynamics)
David Smith and Chry Pyng Liou (U of I), and Z. Deng	Development of flow estimates from DIDSON images
John Skalski (UW)	Statistical design and advice
John Hedgepeth (Tenera)	3D Data Analysis
Technicians	Data acquisition

V. TECHNOLOGY TRANSFER

All results will be formally documented and disseminated to interested parties in the public and private sectors. The principal means of technology transfer will be presentations and reporting. A presentation will be made at the Corps' annual Anadromous Fish Evaluation Program Review. A final report will be published in 2007. Technology transfer activities may also include presentation of research results at regional or national fisheries symposia, or publication of results in a scientific journal.

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VII. BUDGET

A detailed budget will be provided under separate cover.