A Study to Estimate Salmonid Survival through the Columbia River Estuary using Acoustic Tags, 2002

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EXECUTIVE SUMMARY

In 2001, the National Marine Fisheries Service and Battelle Pacific Northwest National Laboratory initiated a study to assess survival of juvenile Pacific salmon *Oncorhynchus* spp. through the lower Columbia River below Bonneville Dam and in the estuary. The study proposed development of a microacoustic transmitter tag small enough for implant into subyearling chinook salmon, with survival estimates based on detections at a stationary acoustic receiver array located near the Columbia River mouth. This report describes results from the first two years of study, which covered feasibility evaluations, tag design, and initial testing of the prototype microacoustic tags and dedicated receiver node. Development of the receiver array and microacoustic tag was conducted simultaneously.

During the feasibility phase, evolution of the acoustic receiver array considered detection probabilities required for accurate survival estimates as well as positioning requisites, tagged smolt intercept maximization, accessability for deployment and retrieval of array elements, acoustic disruption, and economy. Acoustic signal models derived from physical data acquisition indicated that the proposed array was achievable, though maximum receive range would be about 274 m in the presence of a salt water/fresh water interface.

A receiver design array configuration study examined alternatives for hydrophone configuration, node deployment (non-cabled, individually deployed on separate cables or sequentially deployed along a single cable), transect location, signal conditioning, data transmission, cable type, and data recovery and storage. This study identified the most practicable receiver configuration as a bottom-mounted array cabled to shore stations for power and data recovery. A transect from West Sand Island to Clatsop Spit was selected as the most advantageous route for the proposed array.

Tag design criteria focused on size (small enough to place in 92 mm subyearling chinook salmon), tag weight, tag volume, and tag life. A minimum tag life of 30 d was considered necessary to allow slower-moving individuals to migrate through the estuary to the detection array and to allow a reasonable period for estuarine residence.

Differential phase-shift encoding of the 416.7-kHz signal in the proposed design represented a compromise to meet the size criteria and maximize the number of unique codes. An interim umbilical prototype tag was assembled to assess acoustic and electronic component performance without concern for power restrictions. Range testing suggested a maximum range of about 150 m for detection, but effective range for code

discrimination from the transmitted signal was only about 100 m. Discrimination generally increased with tag depth, suggesting surface-related multipath corruption of the signal.

An autonomous, non-functional prototype tag was also constructed for use in preliminary evaluations of the biological effects. These evaluations included biological assessment of the conformal encapsulation material proposed for use as an external coating for the tag. Results of comparisons among control, sham-tagged and acoustically-tagged fish groups indicated that the encapsulation material had no effect on growth (length and weight) or survival over a 30-d evaluation period.

Field evaluations of compatibility between the prototype umbilical microacoustic tag and detection array were conducted at Jones Beach, Oregon (Columbia River kilometer 75). Detection ranges achieved during field evaluations were similar to those observed during initial testing. Software and hardware problems in the prototype receiver node delayed further testing pending retrieval and repair of the system.

Though the receiver and prototype tag appear to function as designed, more testing is needed to determine maximum range for the tag, and evaluations should include assessment of the cause of lower detection ranges than predicted by models.

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INTRODUCTION

Mortality in the estuary and ocean comprises a significant portion of the overall mortality experienced by salmonids throughout their life cycle, and seasonal and annual fluctuations in salmonid mortality in the estuary and marine environments are a significant source of recruitment variability (Bradford 1995). In response to potential for estuaries to influence overall survival, recent studies have attempted to evaluate effects of estuarine conditions on salmon.

Simenstad et al. (1982) suggest that estuaries offer salmonids three primary advantages: productive foraging, relative refuge from predators, and a physically intermediate environment in which the animal can transition from freshwater to marine physiological control systems. Thorpe (1994) reviewed information from three genera of salmonids (*Oncorhynchus, Salmo,* and *Salvelinus*) and concluded that salmonids are characterized by their developmental flexibility and display a number of patterns in estuarine behavior. He found that stream-type salmon migrants (some chinook, coho, sockeye, and Atlantic salmon) move through estuaries and out to sea quickly compared to ocean-type salmon migrants.

Most of our knowledge of how salmonids utilize estuaries is limited to smaller systems that can be more readily sampled. For example, Beamer et al. (1999) assessed the potential benefits of different habitat restoration projects on the productivity of ocean-type chinook salmon in the Skagit River, Washington. They concluded that restoration of freshwater habitats (peak flow and sediment supply) to "functioning" levels "would provide limited benefits unless estuary capacity or whatever factor that limits survival from freshwater smolt to estuary smolt is also increased." They used productivity and capacity parameters to estimate that estuarine habitat restoration could produce up to 21,916 smolts/ha. Reimers (1973) found that subyearling chinook salmon *O. tshawytscha* in the Sixes River, Oregon, used diverse estuary rearing periods and strategies.

Little information is available describing historical use of the Columbia River estuary. Rich (1920) found that 36% of juvenile yearling and subyearling chinook salmon collected from 1914 to 1916 demonstrated extensive rearing in the estuary. As many as 70% of the fish sampled had resided in the estuary from 2 to 6 weeks, and subyearling chinook salmon attained 20 to 66% of their fork length while in the estuary.

In contrast, in more recent times where hatchery fish dominate the juvenile population, Schreck and Stahl (1998) found mean migration speed of radio-tagged yearling chinook salmon was highly correlated with river discharge, and averaged approximately 2 mph from Bonneville Dam to near the mouth of the Columbia River.

Movement in the lower estuary was influenced by tidal cycles, with individuals moving downstream on the ebb tide and holding or moving upstream during the flood tide. They reported a high proportion of tagged animals were lost to piscivorous bird colonies located on dredge disposal islands.

Ledgerwood et al. (1999) also found that travel speed of fish marked with passive integrated transponder (PIT) tags from Bonneville Dam (rkm 235) to Jones Beach (rkm 75) was highly correlated with total river flow. They also observed significant differences in travel time between spring/summer chinook salmon released at Lower Granite Dam to migrate inriver and cohorts transported and released below Bonneville Dam. Inriver migrants detected at Bonneville Dam had significantly faster travel speeds (98 km/d) than their cohorts released from a transportation barge below Bonneville Dam (73 km/d). These recent studies provide a cursory assessment of estuarine migration behavior.

Physical processes in the estuary and thus estuarine habitat are shaped by two dominant factors, channel bathymetry and flow. River flow is controlled by climate variation and anthropogenic effects such as water storage, irrigation, withdrawals, and flow regulation. The Federal Columbia River Power System (FCRPS) has altered the hydrology of the Columbia River estuary through flow regulation, timing of water withdrawals, and irrigation, which have affected the average flow volumes, timing, and sediment discharge (Bottom et al. 2001; NRC 1996; Sherwood et al. 1990; Simenstad et al. 1992; Weitkamp 1994). Annual spring freshet flows are approximately 50% of historical levels, and total sediment discharge is roughly one-third of levels measured in the 19th century. The direct effects of these changes to the estuary from FCRPS operations on migrant salmonids have not been evaluated.

The potential for delayed mortality on fish that migrate through the hydropower system is also a concern to fisheries managers and regional decision makers. Recent quantitative model studies have assessed the importance of survival downstream from Bonneville Dam to the overall life cycle, and sensitivity analyses have identified the life stages where management actions have the greatest potential to influence annual rates of population change, and priorities for research (NMFS 2000). A reduction in mortality in the estuary/ocean and during the first year of life had the greatest effect on population growth rates for all spring/summer chinook salmon stocks when a 10% reduction in mortality in each life stage was modeled.

These analyses suggest that salmonid recovery efforts will require an understanding of the important linkages between physical and biological conditions in the Columbia River estuary and salmonid survival. Indeed, Kareiva et al. (2000)

concluded that modest reductions in estuarine mortality, when combined with reductions in mortality during the first year of life, would reverse current population declines of spring/summer chinook salmon. Emmett and Schiewe (1997) concluded that survival must be separated between the freshwater, estuarine, and ocean phases to be able to answer these management questions.

Given the high proportion of mortality occurring below Bonneville Dam, the potential positive response in population growth rates from changes to survival in this area, and the uncertainty over the causal mechanisms of hydropower system delayed mortality, there is a need for detailed studies to evaluate juvenile salmonid survival and behavior through the lower Columbia River and through the Columbia River estuary.

This is particularly true for subyearling chinook salmon, which may utilize portions of the estuary for extended periods as rearing and transition habitat. However, these fish are smaller than yearling chinook salmon smolts, with approximately 85% of the subyearling fish ≥92 mm (3.5 in) fork length (FL) at Bonneville Dam. Three technologies have the potential for marking (tagging) individual fish of this size to assess survival through estuaries. These include radio tags, passive integrated transponder (PIT) tags, and acoustic tags.

Since radio signals are quickly attenuated in salt or brackish water, radio tags cannot be used over significant portions of the study area. PIT tags are appropriate for implant into small salmonids and function in salt water environments. Unfortunately, maximum detection range for PIT tags is only about 610 mm (2 ft), making this technology suitable for sites where fish can be concentrated into a small sampling volume, such as in fish passage facilities at hydroelectric projects. Acoustic technology alone offers the combination of transmission range and transmission medium independence suitable for tagging small fish migrating through fresh and saline conditions. The drawback however, is that at this time, acoustic tag vendors only offer tags small enough for implant into smolts larger than about 120 mm FL.

In 2001, NOAA fisheries, in partnership with the Pacific Northwest National Laboratory, initiated a multi-year project to address the need for a microacoustic transmitter (tag) for implant into smaller fish. Development was begun to engineer a miniaturized acoustic tag and attendant detection array to be used to estimate salmonid smolt survival through the lower Columbia River and estuary. This report details progress during the first two years of that effort, and addresses the following objectives:

1) Develop an acoustic receiver array for use in the Columbia River estuary capable of detecting microacoustically tagged migrating salmonid smolts.

2) Develop a microacoustic transmitter tag small enough for implant into subyearling chinook salmon with sufficient working life to be functional passing the acoustic detection array.

3) Conduct field evaluations of prototype microacoustic tag and detection array compatibility.

OBJECTIVE 1: Develop an Acoustic Receiver Array to Detect Microacoustic-Tagged Salmonid Smolts Migrating through the Columbia River Estuary

The planned approach was to integrate the main components of the acoustic detection system (receiver array design and tag signal design) to maximize detection probabilities at the mouth of the Columbia River. The work is being completed in three phases, beginning with feasibility assessment and design parameter definition during the first year (2001). Over the second year of the study, efforts focused on development of the detection array and prototype tag, and on evaluating compatibility and range between these two components. The final stage will include field deployment and initiation of survival estimates.

Design and feasibility studies for the detection array and microacoustic transmitter proceeded in unison, with both efforts directed toward producing detection probabilities sufficient to meet the statistical requirements of the single-release survival model. For design purposes, minimum acceptable detection probability was set at 0.60, with precision estimates within ±0.10 of the mean survival estimate.

Estimates of expected precision were developed by simulating detection probabilities for release group sizes from 100 to 500 fish in 50-fish increments (Appendix Table A1). These simulations considered survival values from Bonneville Dam to the primary array (primary survival) ranging from 0.50 to 0.95 and between the primary array to the secondary array ranging from 0.50 to 1.00 for each primary survival scenario.

From the simulations, a minimum release group of 250 fish was found to be the minimum sample size required to obtain confidence intervals of ±0.10 or less where both arrays met the minimum detection probability criterion of 0.60. Using release groups of 250 fish, the lowest acceptable detection probability modeled (with approximately 0.10 precision about the survival estimate) was 0.60 on both arrays, where survival to the first array was 0.60 and survival from the primary to the secondary array was at least 0.80.

In addition to detection probability criteria, physical design and positioning requisites for a primary array transect included interception of as many migrating smolts as possible, reasonable accessability for deployment and retrieval of array elements, minimal acoustic disruption, and economy. As a critical first step, environmental and acoustic characterization data were acquired within the target area prior to validation of an analytical acoustic characterization model.

Characterization tests were carried out in two phases: phase I evaluated the acoustic environment and selected test sites. Phase II collected acoustic data necessary to validate an analytical model. During phase I, test sites were selected to represent the worst-case acoustic conditions through the target deployment area, and a test date was selected to provide maximal tidal variability. Seven sample locations (waypoints), defined by global positioning system (GPS) coordinates (Table 1), were selected to cover the range in bathymetry over the target area (Figure 1). Conductivity, temperature, and depth (CTD) profile data were collected at each waypoint using a Sea-Bird SBE 911 CTD instrument.[1]

Four CTD casts were completed at each of the 7 waypoints during the flood tide on 5 May 2001. All 7 waypoints were sampled consecutively as a block, with approximately 1 h between blocks, before repeating the process. Sound velocity profiles were computed for each cast using the algorithm developed by Chen and Millero (1977). The resulting CTD data and sound velocity profile plots (Appendix Figure A1) were evaluated by contract personnel. Waypoints 3 and 4 were selected for testing during phase II as having exhibited worst-case acoustic conditions among the seven sites.

Phase II testing occurred 22-23 May 2001. This process involved calibration tests to provide baseline source levels, followed by physical data collection to validate modeled environmental characterization.

Calibration tests established in-water signal levels over a 1-m distance using 110, 130, 150, and 200 kHz signal generators. The resultant signal data provided a basis for determining the reference source level and receive system gain. Transmit and receive test equipment was optimized for signal reception, and settings for both transmitter and receiver electronics were logged for reference.

Characterization tests were conducted using two vessels tethered together at a known distances (Figure 2). The larger (electronics) vessel was anchored at a waypoint, and the smaller (support) vessel was allowed to drift at the end of the tether. A hydrophone suspended from the smaller vessel received signals produced by an acoustic projector (transducer) suspended from the larger vessel. The hydrophone was connected to signal processing equipment on the larger vessel by a cable running along the tether between the two craft.

[1] Use of trade names does not imply endorsement by the National Marine Fisheries, NOAA.

Table 1. Geodetic waypoint positions located using a global positioning system (GPS) instrument.

Waypoint	Latitude	Longitude
1	46°15.919' N	124°03.682' W
2	46°15.842' N	124°02.491' W
3	46°15.887' N	124°01.739' W
4*	46°15.470' N	124°00.905' W
5	46°15.238' N	124°01.963' W
6	46°15.022' N	124°01.173' W
7	46°14.840' N	124°00.490' W

* Waypoint 4 was initially at 46°15.552' N, 124°01.659' W during phase-I characterization evaluations using the CTD instrument. The waypoint was moved approximately 275 m east during phase II operations because the original point was located within an active navigation channel.

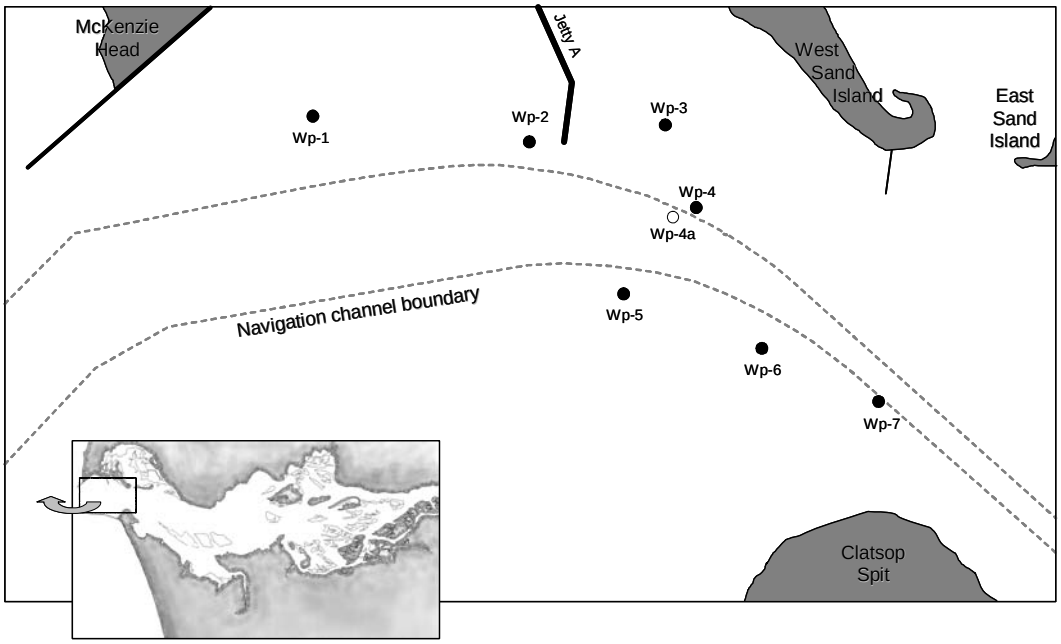


Figure 1. Sample waypoints selected for conductivity, temperature, and depth (CTD) profile sampling to provide data used in development of an acoustic characterization model of the Columbia River estuary during acoustic receiver array development, 2001.

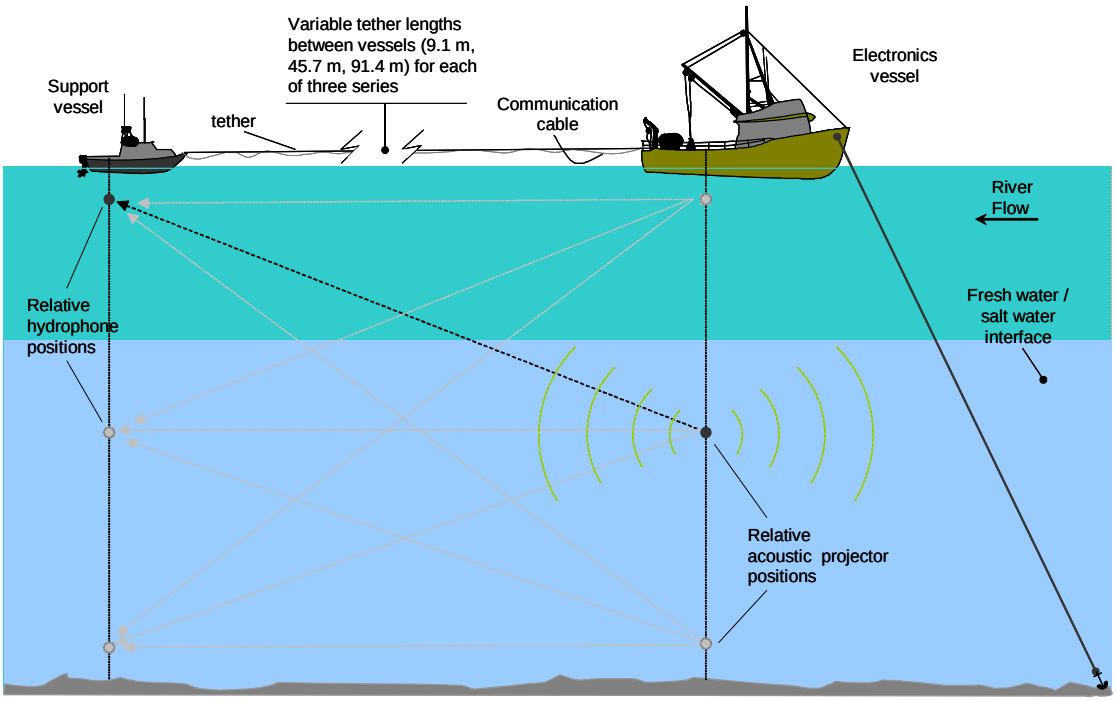


Figure 2. Relationship between positions of vessels and test equipment during acoustic characterization evaluation in the Columbia River estuary, 21-23 May 2001.

The transducer deployed from the larger vessel and hydrophone deployed from the smaller boat were lowered to predetermined depths dependent on the existing sound velocity profile. The sound velocity profile was determined by CTD instrument deployments from the smaller vessel before and periodically during the test sequence. Acoustic signals were generated at the pre-selected frequencies and levels determined during the system calibration stage. The separation distance between the transducer and hydrophone was calculated by multiplying the observed propagation delay time (m/sec) by the average velocity of sound in the direct acoustic path. Signals were stored by the receiving signal processor to determine signal propagation loss in the water during later analysis. Tests were repeated in combinations of transducer depths, hydrophone depths, and test vessel separation distances at the pre-selected waypoints (Table 1).

Of 61 test events, 52 had data of sufficient quality for analysis (transmitted pulses verified to be direct path). Based on analyzed data, a predictive model of the Columbia River estuary acoustic environment was conducted using the Gaussian Ray Bundle (GRAB) of the U.S. Navy Comprehensive Acoustic Simulation System. GRAB is a ray-based propagation simulator specifically designed for acoustic modeling in shallow-water, high-frequency systems. Over 63% of the measured data agreed with model predictions to within 3 dB. The majority of data over 3 dB from the GRAB prediction was due to insufficient signal-to-noise ratios for accurate measurement. The largest variation from the GRAB prediction was 7 dB in one event.

The GRAB model predicted several possible sources of signal disruption in the estuary environment. Propagation loss plots of direct path signals based on sound velocity profile data indicated focusing discontinuities resulting from ray bending. This focusing creates the potential for simultaneous arrival of a propagated signal at the receiver from several directions due to surface refraction, called the multipath effect. Since these simultaneous arrivals impinge on each other, the multipath phenomenon results in corruption of encoded information. The GRAB model further indicated that salt water intrusion into the estuary would be a major factor in signal loss at ranges over 91 m (100 yds) due to absorption of the signal.

Table 2. Transducer depths, hydrophone depths, and test vessel separation distances at pre-selected waypoints during physical acoustic characterization tests in the Columbia River estuary, 2002.

Test date	Time	Waypoint (test location)	Transducer depth (m)	Hydrophone depth (m)	SVP[a] layer depth (m)	Transducer to hydrophone range (m)
21 May 01	16:40	[b]4	mid column	mid column	N/A	[c]1.03
22 May 01	08:30	4	4.88	3.66	10.67	27.07
22 May 01	09:00	4	4.88	15.24	10.67	22.77
22 May 01	09:26	4	4.88	19.81	10.67	29.99
22 May 01	09:55	4	15.24	4.57	5.79	25.69
22 May 01	10:05	4	15.24	20.42	5.79	35.11
22 May 01	10:47	4	21.34	20.42	5.79	28.53
22 May 01	10:53	4	21.34	10.06	5.79	20.39
22 May 01	11:08	4	21.34	4.57	5.79	20.94
22 May 01	12:38	4	21.34	9.14	surface	40.51
22 May 01	12:38	4	2.13	2.44	surface	40.51
22 May 01	14:27	[d]3	3.05	3.05	mixed	26.43
22 May 01	14:55	3	6.01	6.01	mixed	26.61
22 May 01	15:16	3	6.01	6.01	mixed	44.71
22 May 01	15:18	3	6.01	6.01	mixed	67.67
23 May 01	07:56	4	near bottom	1.83	mixed	33.65
23 May 01	08:34	4	near bottom	[e]19.81	5.49	33.65
23 May 01	09:03	4	near bottom	[e] 9.14	12.19	37.22
23 May 01	10:48	4	mid column	mid column	N/A	[c]1.03

a SVP: Sound velocity profile
b Waypoint 4: 46°15.470' N, 124°00.905' W
c on calibration fixture
d Waypoint 3: 46°15.887' N, 124°01.739' W
e approximate

A ray-path plot of direct path signals (Figure 3) based on sound velocity profiles suggested that ray bending produced shadow zone effects which will significantly reduce detection range for any receiver suspended in the water column or near the surface. Ray path plots predict a signal detection limitation of less than 274 m (300 yds) when large volumes of fresh water are present over salt water.

Information from field sampling, data analysis, and acoustic modeling was used to provide a basis for a study to determine the most advantageous receiver array configuration. At this stage of receiver design, specific configuration parameters for the acoustic tag had not been finalized. Therefore, assumptions were made concerning tag function based on initial tag design specifications so that receiver development could continue. Specifically, source level output for the tag was placed at 150 dB re μP to overcome anticipated signal-to-noise ratio concerns, and a target operating frequency was assumed to lie between 105 and 150 kHz. The lower frequency range was selected to minimize effects of absorption loss, which increases with increasing frequency. Also, pulse position modulation (PPM) was chosen as the most probable tag code encryption method, as being more resistant to multipath effects than other strategies and less difficult to implement. A list of other parameters and associated values used for range calculations during the configuration study is presented in Appendix Table A2.

The receiver array configuration study also considered alternatives for hydrophone design, node deployment (non-cabled, individually deployed on separate cables or sequentially deployed along a single cable), transect location, signal conditioning, data transmission, cable type, and data recovery and storage (Figure 4).

Since the ray-bending model predicted reception reductions associated with shadow zones for receivers suspended in the water column or near the surface, the trade study focused on bottom-mounted array configurations. The final design recommended for prototype development was a bottom-mounted linear array of hydrophone nodes connected sequentially along a cable. The cable was designed to supply power to the nodes and furnish a data conduit to a shore station for data recovery and storage. In addition, the cable was engineered to provide a strength member for serial deployment and retrieval of the receiver nodes.

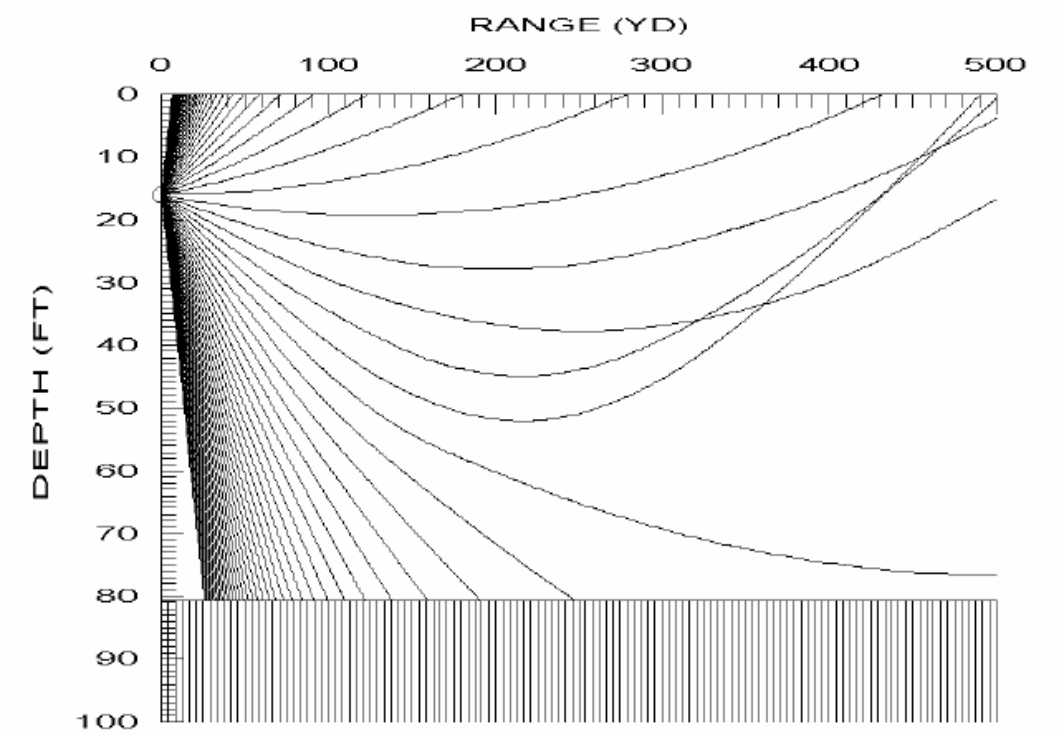


Figure 3. Gaussian Ray Bundle (GRAB) model ray-path plot of freshwater over salt-water condition in the Columbia River estuary data. Ray paths are plotted plus and minus 40° in one-degree increments from a source located 15 ft (4.6 m) below the surface.

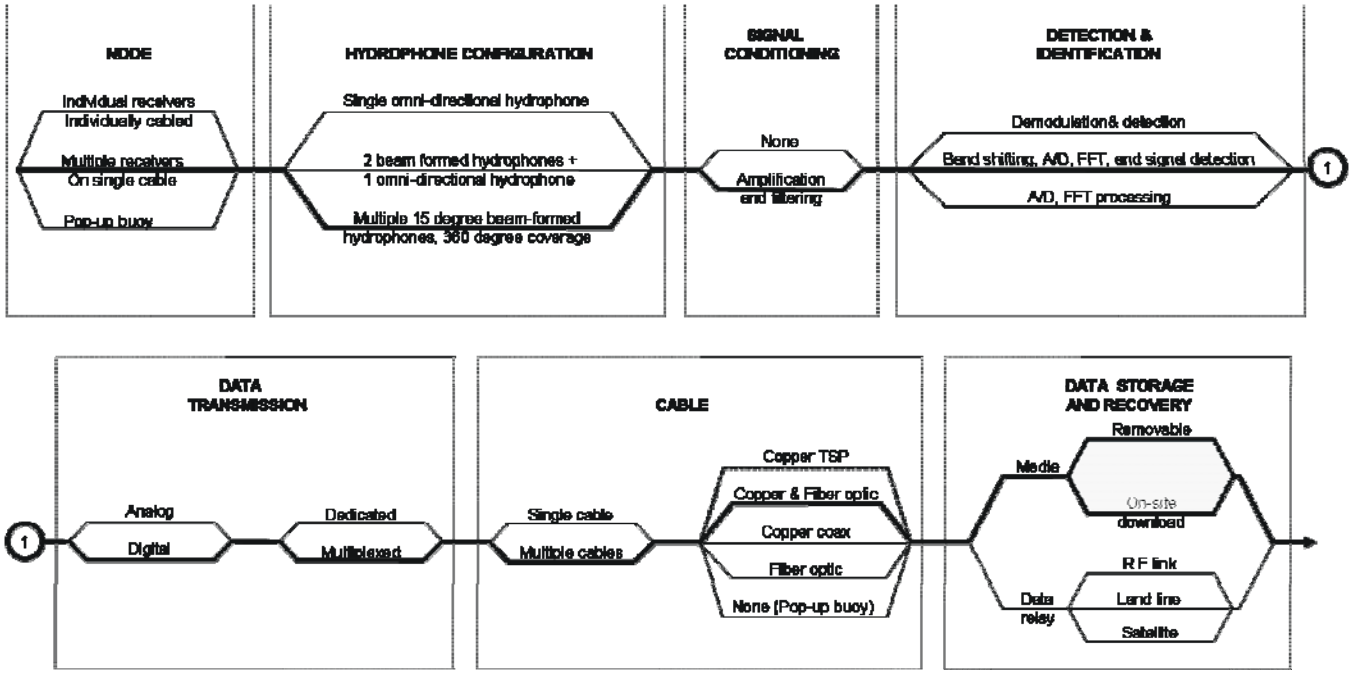


Figure 4. Schematic diagram of options considered during a study of alternate configurations for a bottom-mounted acoustic receiver system for the Columbia River estuary. Heavy lines represent the current selection path. Dotted lines represent options which were initially selected but later abandoned.

The final consideration of the configuration study was a transect route for the array across the estuary. This process involved consideration of fish travel routes through the lower estuary, shoaling, small boat and shipping traffic, acoustic detection range limitations, and economy (length of cable and number of nodes required for coverage along a proposed transect). After consultations with the U.S. Coast Guard, it was considered ill-advised to place detection nodes in the Columbia River commercial ship channel.

Several possible sites at the downstream end of the estuary were identified, ranging from 4 to 6 km upstream from the river mouth. Of the transects examined, the preferred route ran from West Sand Island to Clatsop Spit. To avoid the ship channel, the proposed transect was divided into two smaller arrays connected by cable: one extended from the northern border of the ship channel to a power and communications station on the south end of West Sand Island; the other extended from the southern border of the ship channel to Clatsop Spit (Figure 5).

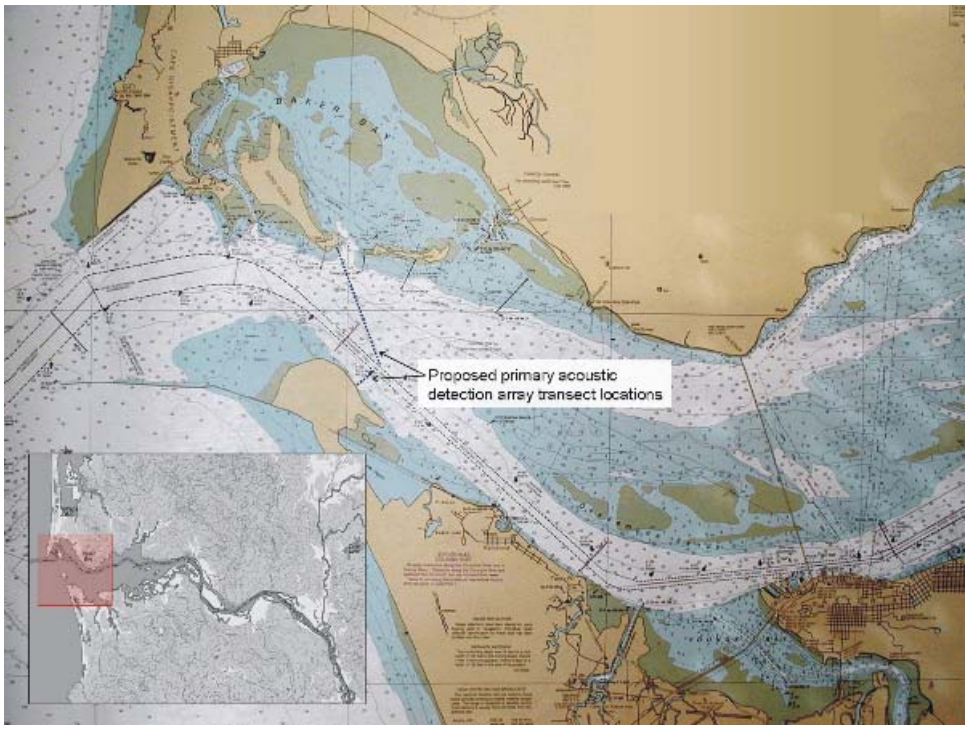


Figure 5. Proposed locations for a bottom mounted acoustic detection array near the mouth of the Columbia River.

OBJECTIVE 2: Develop a Small Microacoustic Transmitter Tag for Implant into Subyearling Chinook Salmon

The target fish size for acoustic transmitter (tag) development was 92 mm, which represented the upper 85% of the length-frequency distribution of subyearling chinook salmon passing Bonneville Dam (USGS, Unpublished data). Fish of this size presented the primary constraint on tag size, and nearly all tag-design parameters were affected by size and/or weight. The other overriding consideration was transmitter life.

Tag size components considered were volume, weight, and shape. For purposes of acoustic tag implantation, volume was defined as the region in the body cavity available for an implanted tag which can be used without seriously impairing physiological function. To make a reasonable volume estimate, molds of the body cavities of 10 subyearling chinook salmon were made using a biochemically inert and moderately fast-setting elastomer developed for injection molding (Table 3). The elastomer was injected into sacrificed fish approximately 3 mm to the right of the mid-ventral line, and approximately 10 mm forward of the pelvic girdle with the fish inverted, until a slight bulge was noticeable in the body wall. The injection needle was withdrawn, and elastomer liquid was allowed to exude back through the injection wound until pressure was equalized.

With the carcass refrigerated, elastomer remaining in the body cavity was left for 24 h to solidify. Once removed from the fish, volume of the solidified mold was determined by water displacement in a small graduated cylinder. Of the 10 fish used in the volume determination, one mold was suspect because of excessive deterioration of the internal organs prior to injection. Without that sample, resulting mold volume was 0.39 mL. However, lengths of subyearling chinook salmon used in the determination ranged from 81 to 97 mm, about a mean of 89 mm. This length was somewhat smaller than the 92-mm target. Therefore, using the mold method, 0.40 mL was used as the estimated volume available for a microacoustic tag in the relaxed body cavity of a 92-mm chinook salmon smolt.

The most commonly used estimate for assessing the effect of a transmitter on the subject has been the tag-to-fish weight ratio (Perry et al. 2001). The suggested ratio is for a dry tag weight of 2-5% of body weight (Winter 1983; Adams 1998). For a hypothetical 92-mm fish with a body weight of 8 g, this would suggest a tag with a

Table 3. Lengths, weights, and volume of molds removed from subyearling chinook salmon. Fish were injected with liquid polymer to determine body cavity volume available for surgical implant of a proposed microacoustic transmitter. Sample number 10 was omitted from calculations because internal organs appeared to have deteriorated prior to injection, creating excessive volume for the injected mold. Mean volume of remaining samples was 0.389 mL.

Sample number	Fish Length (mm)	Fish Weight (g)	Injected weight	Mold volume (mL)
1	91	8.9	9.1	0.4
2	88	8.2	8.4	0.4
3	84	7	6.9	0.2
4	92	9	9.2	0.3
5	87	7.2	7.2	0.25
6	87	6.8	7.1	0.35
7	95	8.9	9.6	0.7
8	97	9.5	9.9	0.55
9	81	6.9	7	0.35
10	85	7.5	8.3	0.6

maximum dry weight of 0.4 g. However, some researchers have indicated that the tag weight in water may be a more appropriate alternative (Brown et al. 1999; Perry et al. 2001). Tag weight in water represents the excess mass the fish must move and the volume (mL) to which it must fill the air bladder to compensate for the tag. Since excess mass can be calculated as tag weight minus tag volume, the suggested 0.4-g weight with a 0.4-mL volume would result in a tag with virtually neutral buoyancy.

In practice, nearly all tags have some excess mass. During recent tracking studies at North Fork Dam on the Clakamus River in Oregon, Timko et al. (2001) used acoustic transmitters with an excess mass of 0.8 g for wild fish with a mean weight of 34 g, or a 2.35% excess mass to body-weight ratio. For survival studies in 2001, Axel et al. (2003) used a 1.4-g radio tag for releases of chinook salmon with a mean weight of 31 g (range 18-109 g). Excess mass to body-weight ratio for these fish was 4.5%.

For purposes of the miniaturized acoustic tag design under discussion, we assumed that excess mass should lie between 2 and 5% of fish weight. As a starting point, we used 3.5% of body weight as a reasonable maximum estimator of excess mass. For an 8-g smolt, this resulted in a maximum design weight for the microacoustic tag of 0.75 g in air.

Tag shape represents a compromise between component limitations (mechanical as well as electronic) and surgical and biological acceptability. Most early tags for surgical implant approximated a cylinder, which reflected a simple and safe design for easy insertion through an incision. More recently, the smaller implantable tags available appear to be defined and limited by components (most notably batteries, but also the circuit board, processor packaging, transducer shape, etc.) rather than the molded encapsulating (potting) material. While this trend may not result in an optimal form for surgical insertion, safety, or biological function, there is a reduction in weight and volume.

In designing the microacoustic tag, we used the shape of the elastomer molds used for volume measurements as a general guide. The molds approximated an elongated and flattened teardrop, with the smaller end posterior and under the pelvic girdle. Based on measurement of the molds, our goal in tag design was a maximum dimension of 17 mm long, 6 mm at the wide end of the teardrop, and 3.5 mm thick at the wide end. Although the design was expected to be dependent on electronic and acoustic component architecture, rough, pointed or sharp edges were not acceptable.

Run-time constraints affect tag size since battery capacity is generally a function of size. For survival studies, tag life should be related to migration timing to reduce the number of undetectable expired tags passing the detection array. Also, assumptions for individual travel times should conservatively be worst-case estimates, since there is no way of accurately predicting how an individual tagged fish will migrate after release.

Ledgerwood et al. (2000) noted that travel speeds for chinook salmon downstream from Bonneville Dam were highly correlated to river flow. They found minimum travel speeds for PIT-tagged run-of-the-river yearling chinook salmon of about 32 km/d, with a mean of 99.1 km/d. Given a distance of approximately 233 km from Bonneville Dam to the river mouth, travel time to the mouth for slower-migrating yearling chinook salmon is approximately 7.3 d. In addition, there is evidence that tagged fish can be delayed from migrating past the river mouth the for at least one tidal cycle, bringing the total travel time to a conservative estimate of about 8 d.

For subyearling chinook salmon in the 90 mm range, travel times between Bonneville Dam and the ocean may be substantially greater than for yearling fish. Based on unpublished data, mean subyearling chinook salmon travel speeds are estimated to be approximately 40 km/d (Richard Ledgerwood, NOAA Fisheries, Personal communication), or less than half the speed estimated for yearling fish. Including a possible one-tidal-cycle delay and assuming that slower migrating individuals would migrate at half the speed of yearling fish, a conservative travel time for a subyearling chinook salmon was estimated at 15 d.

There is also evidence that subyearling chinook salmon spend some portion of their seaward migration residing in the estuary prior to entering the ocean environment. Levy and Northcote (1982) reported a maximum residency time of 30 d for chinook salmon during estuarine mark-recapture studies. Reimers (1973) also found that small subyearling chinook can rear in estuaries for extended periods. While fish in both of these studies were smaller than those intended for implant with the downsized acoustic tag, some residence time for these subyearling chinook salmon was anticipated in our preliminary tag design. Without better evidence, a 30-d tag life was considered prudent to allow for both travel and estuarine residence.

Several other interconnected factors affecting transmitter design involved selection of a suitable operational frequency. For example, one consideration directly influencing weight and size was the ceramic piezoelectric transducer element used to produce the acoustic signal. Since the transducer element size decreases linearly with increased frequency, low frequencies require a larger, heavier transducer, ultimately reflected in the tag weight. In addition, more power is required to drive the larger transducer element, resulting in larger batteries for a given tag life. Another frequency-related variable impacting power consumption is signal-to-noise ratio, since a transmitter must produce a signal strong enough to be detected above ambient (background) noise occurring in the same frequency range as the signal.

As the acoustic tag design evolved, three issues with the initial concept became apparent. First, transducer size and power requirements were too large to achieve tag downsizing goals within the frequency range selected during detection array design (105-150 kHz). Second, information was needed to identify higher frequency ranges with less intense background noise levels. Finally, initial design for the tag would require an interim prototype to field test concepts, components, and function prior to committing to a production version.

To select a more suitable frequency range for the tag, a survey was undertaken to document acoustic signatures of typical environmental noise sources (anthropogenic and natural) in the Columbia River estuary environment. Sources were sampled using a three-element hydrophone array mounted to an anchored vessel. Beam angle for all three hydrophones was 6 degrees, which allowed reasonably accurate focusing within a 200-m range of a target. Of the sources sampled, vessel noise values (engines, propellers, depth and fish sounders) were generally higher at frequencies ≤250 kHz, decreasing to a pronounced minimum from 300 to about 450 kHz (Figure 6). Naturally occurring ambient noise levels in the lower estuary were variable at lower frequencies, becoming more consistent above 250 kHz (Figure 7). Based on transducer size and noise frequency data obtained from specific targets in the estuary, the frequency selected for the prototype microacoustic tag was 416.7 kHz (nominal 420 kHz).

With frequency selected, design discussions centered on determining a signal encoding method suited to providing unique identifiers to a minimum of 500 individuals (2 comparison release groups comprised of at least 250 fish in each group). In addition to the number of available identifiers, encoding parameters considered size, number, and weights of components required for implementation, range comparisons for various encoding schemes, and power consumption required to transmit an identifiable code over a 30-d period.

Of the methods considered, differential phase shift keying (PSK) was chosen, in part because this strategy could be effected with the fewest components (resulting in tag size reduction) relative to other methods. In addition, since only a single pulse was needed for an encoded signal, power consumption was comparably reduced. As implemented, the 0.4 msec pulse encodes 32 bits of information, allowing over 64,000 simultaneous unique codes (24 bits) plus a cyclic redundancy check (CRC, 8 bits) to reduce false code discrimination. The most serious drawback to PSK encoding is susceptibility to multipath interference, the most serious consequence of which is decreased range. However, no other encoding method yielded the combination of power, weight, component number reduction, and code range necessary for downsizing.

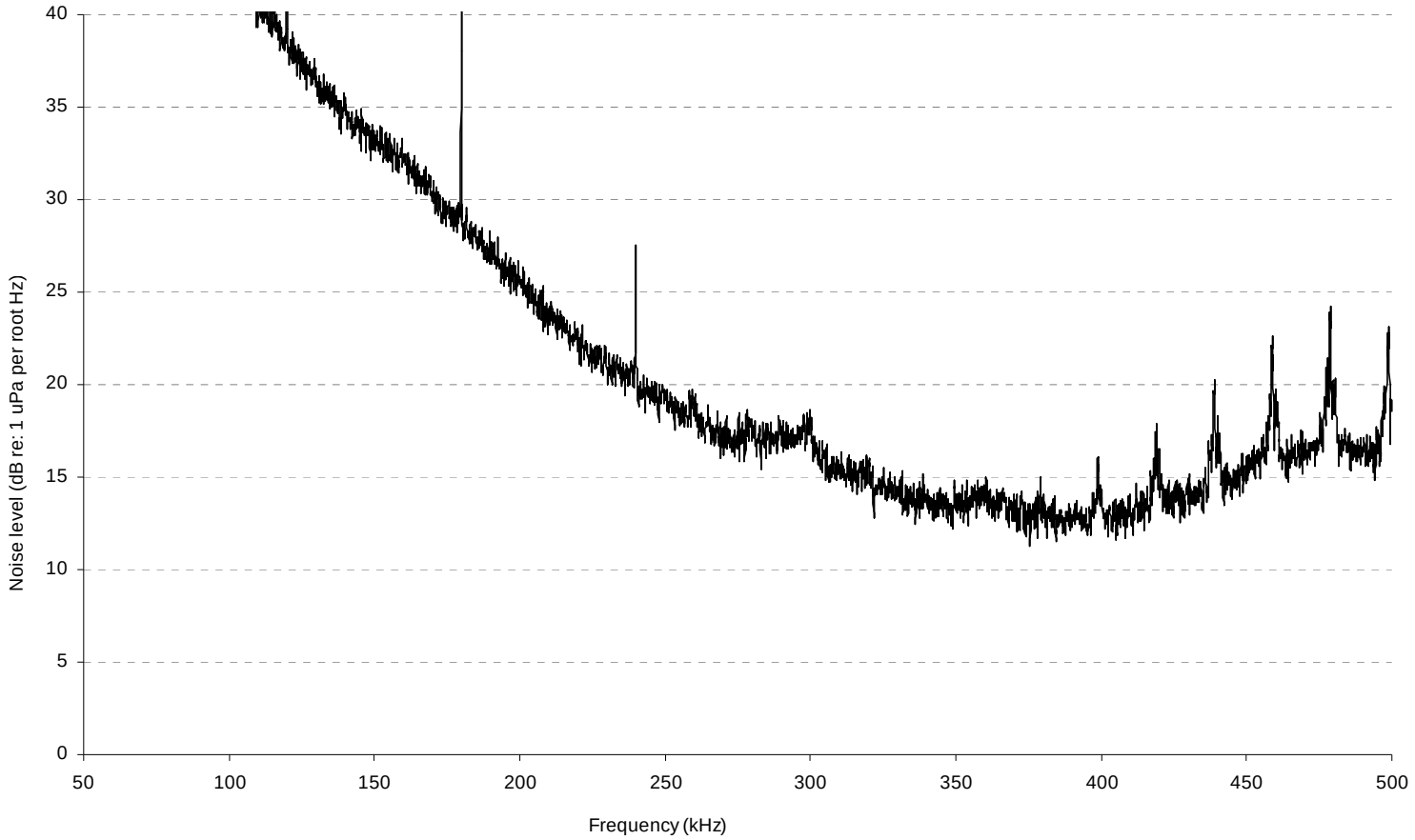


Figure 6. Background noise level by frequency for a tug vessel towing a wood chip barge past a stationary 420 kHz hydrophone in the Columbia River estuary.

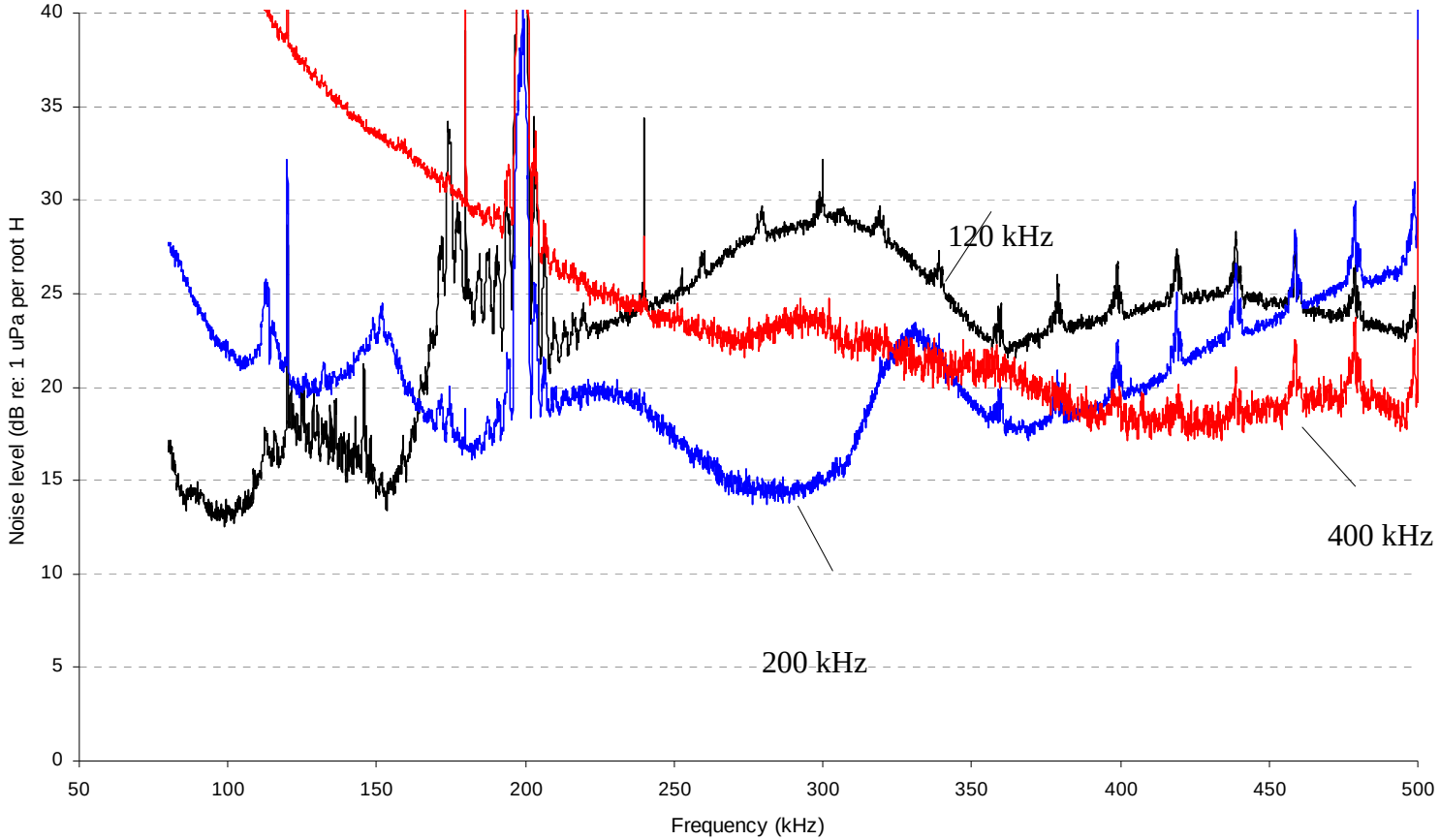


Figure 7. Background noise level recorded by frequency for wave action along Clatsop Spit, Oregon using 120-, 200-, and 420-kHz hydrophones mounted on a vessel anchored in the Columbia River estuary. Noise levels in the spectrum below 250 kHz are highly variable, becoming more consistent above 350 kHz.

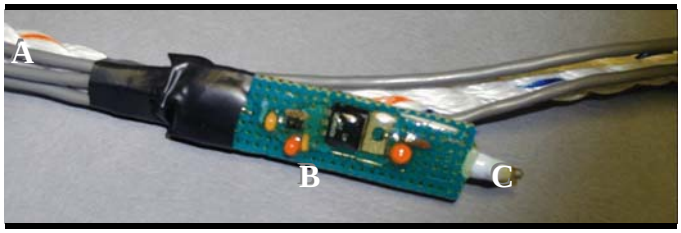
The final element in development was the potting material, or coating, used to form an impervious, bio-compatible barrier between tag and host fish, essentially protecting both from each other. Examination of various properties of non-conformal coatings generally used for the purpose, including a broad range of stable polymers (esters, vinyls, and epoxies), found two drawbacks which prevented their use for the microacoustic tag. Most of these products are relatively massive, increasing weight disproportionate to the encapsulation benefit. Also, nearly all polymers require a catalyzed process for curing, which can produce heat and may damage sensitive tag components.

A non-proprietary conformal coating, parylene C (para-para-xylylene), was selected for evaluation as a final coating material. Parylene-c is applied using chemical vapor deposition procedures to form an inert, hydrophobic barrier without pinholes (waterproof). The finished coating precisely matches substrate shape, forming an impervious layer as thin as several microns thick. Small amounts of non-conformal ultraviolet-cured epoxy, with and without micro-bubbles, were also used to blunt sharp edges or mask rough component surfaces prior to coating completely with parylene C.

Before using parylene C coated tags in free-roaming fish, an initial evaluation of the effects of the coating was required to ensure that the coating did not adversely impair physiological function. Two studies were carried out to evaluate coating effects on fish. The first of these examined growth and survival of subyearling chinook salmon over the 30-d design life of implanted tags, and the second was a clinical and pathological assay of histological response to the coated tag.

Complete reports of these studies are included as Appendix B and Appendix C, respectively. In general, growth and survival were similar among tagged and non-tagged fish groups. Histological results indicated differences in body cavity wall thickness between fish having undergone surgery and control fish, but healing was complete or nearly complete for the surgery treatments at the end of the 30-d test period, with sporadic incidence of dermal and peritoneal inflammation.

The first functional prototype acoustic transmitters were umbilical units developed to test functionality of mated components, transmission range, and code discrimination. These were similar to transmitter design specifications in electronic circuitry, source output level, and frequency, but umbilical transmitters were cabled to a surface-oriented 9-volt power source with appropriate power transformer electronics to provide extended transmission life during static testing (Figure 8, inset).



A: Umbilical cable; B: Voltage regulation board; C: Acoustic transmitter (tag)

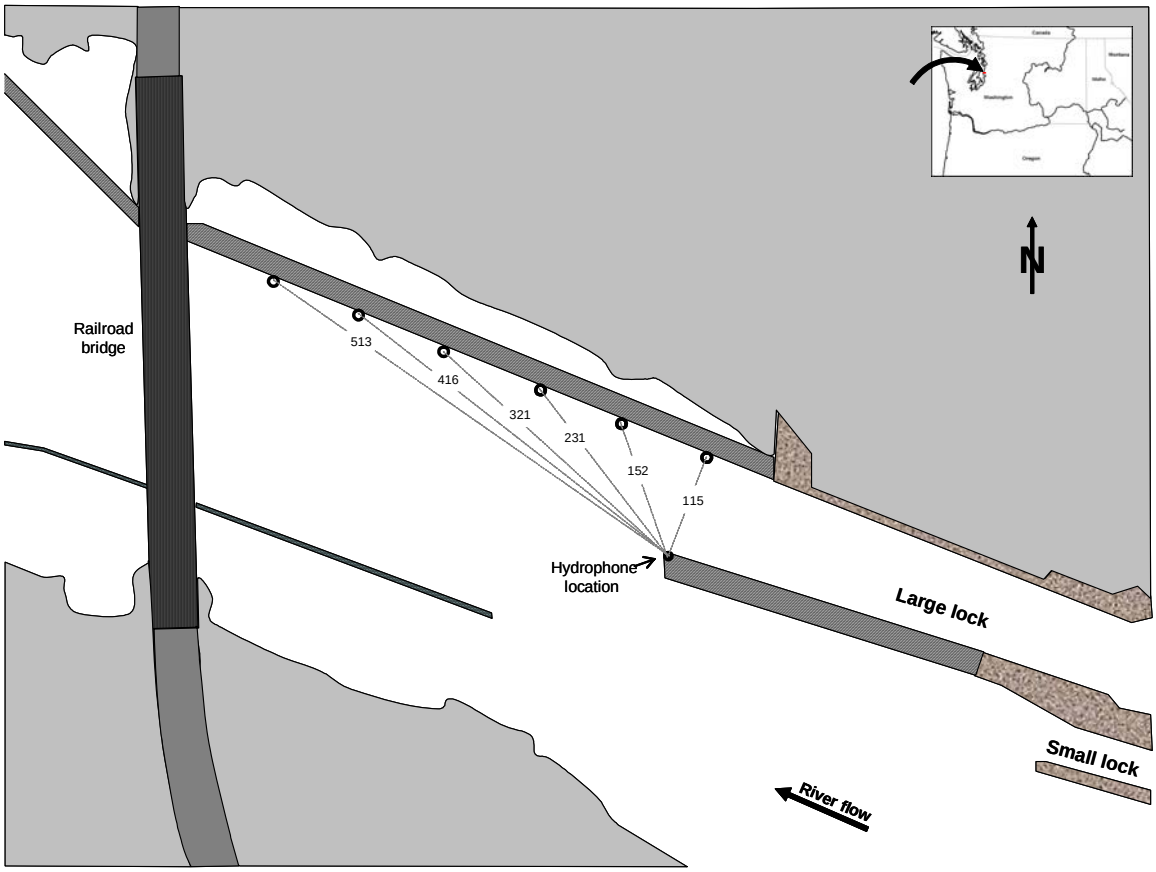


Figure 8. Hydrophone and acoustic transmitter locations during initial evaluation of a prototype micro-acoustic tag at Hiram Chittendon Locks in Seattle Washington, 18-20 July 2002. Evaluation ranges (m) and directions between the hydrophone and umbilical transmitter (inset) are indicated by dashed lines.

Initial range and code discrimination evaluations were carried out at the west end of Hiram Chittendon (Ballard) Locks in Seattle, Washington. This site was selected partially for its proximity to the tag design contractor and because acoustic properties and background noise sources were similar to the Columbia River estuary. A detection hydrophone with a 6° beam angle was used for all evaluations. The receiver hydrophone was attached to a mount which allowed rotation in azimuth and elevation, as well as changes in depth of the receiver unit. The hydrophone mount was positioned at the western end of the pier nose divider wall between the large and small locks along the northen side of the divider wall. Hydrophone depth was 4.6 m (15 ft) during tests.

Testing was accomplished using an umbilical transmitter attached to the end of an anechoic pole. The pole was lowered from the dock along the north side of the locks at predefined stations. The first station was perpendicular to the divider wall on which the hydrophone was located, and directly across from the hydrophone mount. Successive stations continued west along the dock at 30 m (100 ft) intervals to 152 m (500 ft; Figure 8). Four transmitter depths were sampled at each of the 6 stations for a total of 24 discrete sample points.

With the hydrophone rotated to point toward the transmitter, a minimum of 100 detections of transmissions from the umbilical transmitter were recorded for each sample point and stored in a computer cabled to the hydrophone. A log of simultaneous attempts to decode each signal was recorded for each detection.

Reception of the transmitted signal occurred at all ranges tested, indicating adequate signal-to-noise ratio over the ranges sampled. Ability to discriminate encrypted code generally decreased with range but increased with depth below the surface (Table 4), suggesting corruption of the primary path signal associated with multipath surface reflections. Code discrimination ranged from 46 to 100% (mean = 76%) at 100 m (322 ft) from the hydrophone, but from 0 to 79% (mean = 23%) at 127-156 m (409-500 ft).

Table 4. Percentage of correct code interpretations of differential phase shift encoded 416.7-kHz signals received by transmitter range from receiver and transmitter depth during initial prototype tag evaluations at Hiram Chittendon Locks, Seattle, Washington, 18-20 July 2002.

	Range (m)					
Tag depth (m)	35	46	70	98	127	156
surface	62	60	84	64	0	6
1.5	64	64	75	46	8	7
3	100	88	77	63	79	61
4.6	100	99	90	80	11	35

OBJECTIVE 3: Conduct Field Evaluations of Compatibility for the Prototype Microacoustic Tag and Detection Array

A prototype acoustic receiver node was assembled for field testing in late October 2002 (Figure 9), and installed at Jones Beach on the Columbia River (rkm 75; Figure 10). The NMFS Jones Beach research site was chosen for initial testing for security, to facilitate access to the system during anticipated software and hardware modifications, and to finalize prototype system development in a stable environment without the added complications of severe tidal and weather influences found near the river mouth.

The prototype deployment used for testing imitated design deployment specifications. The node was bottom-mounted 30.5 m (100 ft) south of the ship channel at a depth of approximately 11.5 m (38 ft) and cabled to a shore station for power and data communications. Components evaluated were the hydrophone array, pressure vessel housing, node electronics (signal conditioning, analog-to-digital conversion and signal detection, on-board computer, and data transmission), software, shore station (trailer housing, primary computer with data storage media, and power supply generators). These components were intended for reuse as part of the final estuary deployment following prototype evaluation.

However, though the test system was engineered to function similarly to the final design, some components were either substituted or eliminated during the compatibility test as a cost savings or to circumvent long-lead procurement issues. For example, the anchor used to secure the node was a substitute pending planning and evaluation of a suitable anchor design. Also, the power/communications cable was a relatively inexpensive, readily-obtainable remnant, and it was joined to the node and shore station with soft connections rather than with a costly, time-consuming connector assembly installation.

Initial compatibility and reception range evaluations between the prototype receiver node and the acoustic transmitter tag were conducted from 22 to 24 and from 29 to 31 October 2002. All transmitters used were umbilical transmitters. However, source level for two of the transmitters was set at 160 dB to determine whether increased signal-to-noise ratio would improve reception range or signal discrimination.

Figure 9. Prototype acoustic receiver node deployed at Jones Beach, Oregon, during receiver and acoustic tag compatibility and range evaluations 21-31 October 2002.

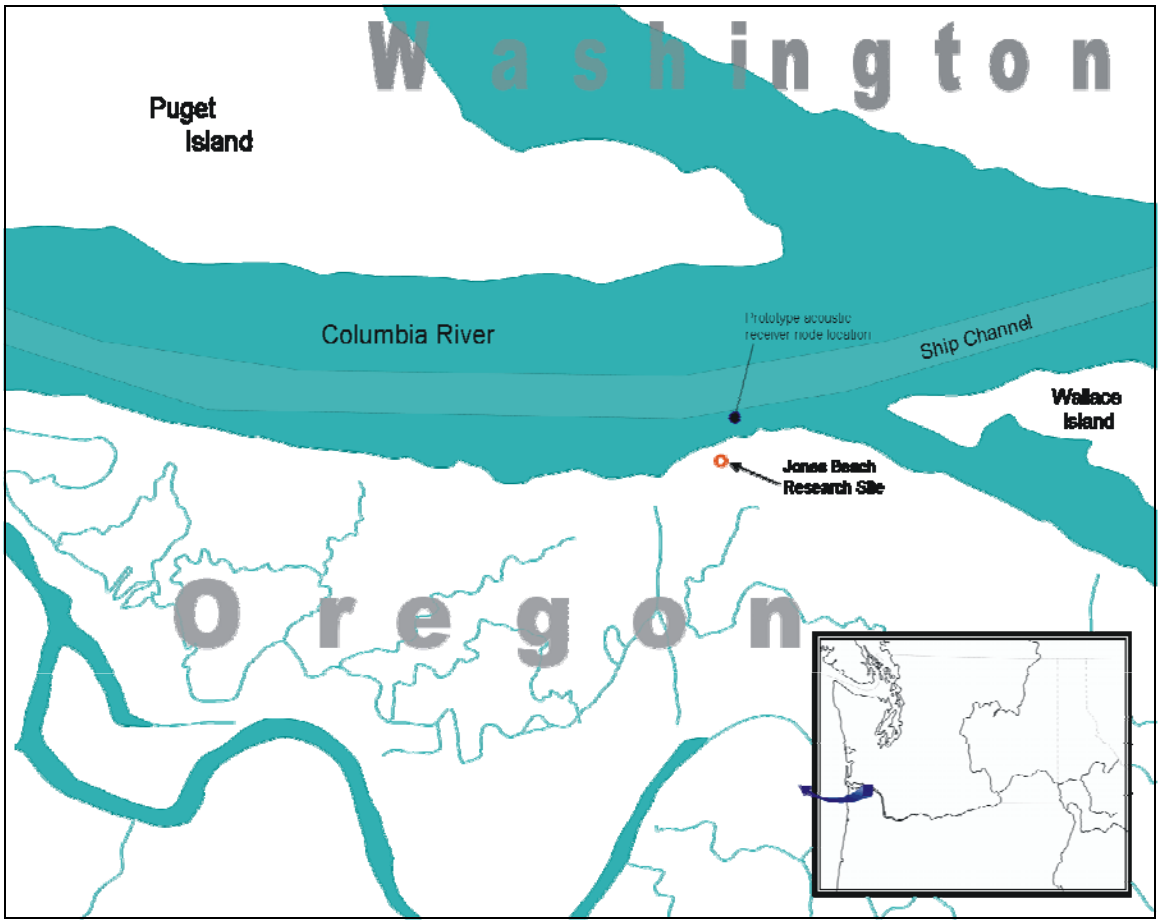


Figure 10. Location of Jones Beach research site on the Columbia River used for initial compatibility evaluations between the prototype acoustic receiver node and umbilical acoustic transmitters.

Four transmitters (2 with 160-dB source level and 2 with 150-dB source level) were attached to a 13 mm (0.5 in) braided nylon rope using electrical tape, spaced approximately 254 mm (12 in) apart beginning 457 mm (18 in) from the free end of the rope. This arrangement held the transmitter so that the maximum response axis of the transducer element was horizontal, or perpendicular to the suspended line. A 22.7-kg (50-lb) depressor weight attached to the free end of the rope maintained the line vertically in the water column.

To evaluate system range performance, the weighted line with attached transmitters was suspended from a buoy trailing approximately 6.1 m (20 ft) behind the smaller vessel. Starting from the GPS position for the receiver node, the boat was moved upstream away from the node. Distance of the boat from the node was estimated continuously using a hand-held GPS unit, and communicated to the shore station by radio at approximately 10-sec intervals until the tag signal was no longer detected. This procedure was repeated several times at various depths. It should be noted that these tests were not intended to be definitive, but rather to afford initial estimates of prototype receiver and transmitter function.

Results from these first tests were similar to results at the Ballard Locks. Reception range for the umbilical transmitters over which the code could normally be discriminated was approximately 48 m (168 ft), except when transmitters were near the surface. The maximum range recorded during these evaluations was approximately 128 m (425 ft) using one of the 160-dB transmitters. Reception between the 48 m constant range and the 128-m maximum was inconsistent.

Two problems requiring correction were identified during these tests. The first was a problem with the software on the shore-station computer, which did not associate a time stamp with each data record. This made association between field observations and specific data events difficult, and the problem was corrected for the 29-31 October test period.

The second problem was more serious and manifested in an apparent receiver-node malfunction. The malfunction was traced to a carrier board containing the analog-to-digital converter and digital signal processing modules, which process six channels of hydrophone data. The bus in this carrier board, which transfers data between modules, was found to have lost synchronism. This resulted in a non-recoverable error that was correctable only by cycling the node power. Therefore, we retrieved the detection node and returned it to the vendor for replacement.

CONCLUSIONS

1. Feasibility studies indicated that use of a microacoustic tag and dedicated detection array to estimate juvenile salmonid survival through the lower Columbia River and estuary is an achievable goal using current acoustic technology.

2. Based on acoustic environment assessment and modeling, a bottom-mounted detection array was recommended for installation between Clatsop Spit and West Sand Island. The proposed array will consist of several nodes (dependent on detection range) along two transects, cabled to separate shore stations for power and data communication.

3. A prototype microacoustic transmitter was constructed to evaluate weight and size constraints, imposed by fish size and gut-cavity volume available for surgical implant, in relation to a 30-d tag life, encoding scenario, and signal source level requirements. The prototype tag was used in 2002 to assess biocompatibility performance of a conformal encapsulation material to protect the tag while reducing weight and volume.

4. Assessment of acoustic tag performance at Ballard Locks in Seattle using umbilical transmitters cabled to an external power source indicated a range of about 100 m for signal code discrimination. Ability to decode the signal was related to depth, suggesting that range was limited by multipath signal corruption associated with surface reflection of the signal.

5. Similar range limitations were experienced using umbilical transmitters and a prototype detection array node during compatibility field trials at Jones Beach, Oregon. However, some signals were decoded as far away as 128 m. A carrier board failure in the prototype detection array node precluded definitive testing to explain factors limiting range.

RECOMMENDATIONS

Several objectives planned at project inception have been proposed for completion during the 2003 calendar year. These include completion of an autonomous microacoustic tag for longevity and full biocompatibility evaluations, and a survivability demonstration for a partial detection array prior to a working field deployment. Recommendations outside the scope of those objectives can be defined in light of experience gained with completion of testing in 2002.

1. Questions remain concerning the cause of the apparent range limitation observed during initial testing in 2002. A series of evaluations should be planned to examine the reason for observed range reduction compared to the modeled prediction. Tests should examine signal-to-noise ratio, multipath signal corruption, and environmental conditions as possible limiting factors.

2. Cost reduction analyses are necessary to review methods for decreasing the expense of production-run microacoustic tags and receiver nodes. Microacoustic tag assessments are of particular concern, since the price of tags will affect recurring costs over a number of years.

3. The most significant limitation to use of the microacoustic tag in smaller subyearling chinook salmon is physical dimensions of the prototype unit. Effort should be directed toward finalizing circuitry so that an application-specific integrated circuit (ASIC) can be designed and fabricated. Use of an ASIC will allow additional reductions to size, weight, and circuit board complexity.

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APPENDIX A

Data Tables and Figures

Appendix Table A1. Estimates of expected precision for assumed detection probabilities and discrete survival values from release point (Bonneville Dam) to a primary array (array 1, Columbia River kilometer 5), and from the primary array to a secondary array (array 2, Columbia River kilometer 3), by release group size.

Survival from Bonneville Dam to array 1 = 0.60, Survival from array 1 to array 2 = 0.80

Release group	Detection probability at array 1, Detection probability at array 2																										
	0.5, 0.5	**0.5, 0.6**	**0.5, 0.7**	**0.5, 0.8**	**0.5, 0.9**	**0.6, 0.5**	**0.6, 0.6**	**0.6, 0.7**	**0.6, 0.8**	**0.6, 0.9**	**0.7, 0.5**	**0.7, 0.6**	**0.7, 0.7**	**0.7, 0.8**	**0.7, 0.9**	**0.8, 0.5**	**0.8, 0.6**	**0.8, 0.7**	**0.8, 0.8**	**0.8, 0.9**	**0.9, 0.5**	**0.9, 0.6**	**0.9, 0.7**	**0.9, 0.8**	**0.9, 0.9**
100	0.209	0.185	0.165	0.149	0.135	0.180	0.161	0.146	0.134	0.123	0.155	0.141	0.130	0.122	0.114	0.134	0.124	0.117	0.112	0.107	0.114	0.110	0.106	0.103	0.101
150	0.171	0.151	0.135	0.122	0.110	0.147	0.131	0.119	0.109	0.101	0.127	0.115	0.106	0.099	0.093	0.109	0.102	0.096	0.091	0.087	0.093	0.089	0.087	0.084	0.083
200	0.148	0.131	0.117	0.105	0.095	0.127	0.114	0.103	0.095	0.087	0.110	0.100	0.092	0.086	0.081	0.095	0.088	0.083	0.079	0.076	0.081	0.077	0.075	0.073	0.071
250	0.132	0.117	0.105	0.094	0.085	0.114	0.102	0.092	0.085	0.078	0.098	0.089	0.082	0.077	0.072	0.085	0.079	0.074	0.071	0.068	0.072	0.069	0.067	0.065	0.064
300	0.121	0.107	0.095	0.086	0.078	0.104	0.093	0.084	0.077	0.071	0.090	0.081	0.075	0.070	0.066	0.077	0.072	0.068	0.064	0.062	0.066	0.063	0.061	0.060	0.058
350	0.112	0.099	0.088	0.080	0.072	0.096	0.086	0.078	0.071	0.066	0.083	0.075	0.070	0.065	0.061	0.071	0.066	0.063	0.060	0.057	0.061	0.059	0.057	0.055	0.054
400	0.105	0.092	0.083	0.074	0.067	0.090	0.080	0.073	0.067	0.062	0.078	0.071	0.065	0.061	0.057	0.067	0.062	0.059	0.056	0.054	0.057	0.055	0.053	0.052	0.051
450	0.099	0.087	0.078	0.070	0.064	0.085	0.076	0.069	0.063	0.058	0.073	0.067	0.061	0.057	0.054	0.063	0.059	0.055	0.053	0.050	0.054	0.052	0.050	0.049	0.048
500	0.094	0.083	0.074	0.067	0.060	0.080	0.072	0.065	0.060	0.055	0.069	0.063	0.058	0.054	0.051	0.060	0.056	0.052	0.050	0.048	0.051	0.049	0.047	0.046	0.045

Survival from Bonneville Dam to array 1 = 0.60, Survival from array 1 to array 2 = 0.85

Detection probability at array 1, Detection probability at array 2

	0.5, 0.5	**0.5, 0.6**	**0.5, 0.7**	**0.5, 0.8**	**0.5, 0.9**	**0.6, 0.5**	**0.6, 0.6**	**0.6, 0.7**	**0.6, 0.8**	**0.6, 0.9**	**0.7, 0.5**	**0.7, 0.6**	**0.7, 0.7**	**0.7, 0.8**	**0.7, 0.9**	**0.8, 0.5**	**0.8, 0.6**	**0.8, 0.7**	**0.8, 0.8**	**0.8, 0.9**	**0.9, 0.5**	**0.9, 0.6**	**0.9, 0.7**	**0.9, 0.8**	**0.9, 0.9**
100	0.201	0.177	0.158	0.142	0.128	0.173	0.155	0.140	0.128	0.118	0.150	0.137	0.126	0.118	0.111	0.130	0.121	0.115	0.109	0.105	0.113	0.108	0.105	0.102	0.100
150	0.164	0.145	0.129	0.116	0.104	0.141	0.126	0.115	0.105	0.096	0.123	0.112	0.103	0.096	0.090	0.107	0.099	0.094	0.089	0.086	0.092	0.088	0.085	0.083	0.082
200	0.142	0.125	0.112	0.100	0.090	0.122	0.110	0.099	0.091	0.083	0.106	0.097	0.089	0.083	0.078	0.092	0.086	0.081	0.077	0.074	0.080	0.076	0.074	0.072	0.071
250	0.127	0.112	0.100	0.090	0.081	0.110	0.098	0.089	0.081	0.075	0.095	0.087	0.080	0.074	0.070	0.083	0.077	0.073	0.069	0.066	0.071	0.068	0.066	0.065	0.063
300	0.116	0.102	0.091	0.082	0.074	0.100	0.089	0.081	0.074	0.068	0.087	0.079	0.073	0.068	0.064	0.075	0.070	0.066	0.063	0.061	0.065	0.062	0.060	0.059	0.058
350	0.107	0.095	0.084	0.076	0.068	0.093	0.083	0.075	0.069	0.063	0.080	0.073	0.067	0.063	0.059	0.070	0.065	0.061	0.058	0.056	0.060	0.058	0.056	0.055	0.053
400	0.101	0.089	0.079	0.071	0.064	0.087	0.077	0.070	0.064	0.059	0.075	0.068	0.063	0.059	0.055	0.065	0.061	0.057	0.055	0.052	0.056	0.054	0.052	0.051	0.050
450	0.095	0.083	0.074	0.067	0.060	0.082	0.073	0.066	0.060	0.056	0.071	0.064	0.060	0.056	0.052	0.061	0.057	0.054	0.051	0.049	0.053	0.051	0.049	0.048	0.047
500	0.090	0.079	0.071	0.063	0.057	0.077	0.069	0.063	0.057	0.053	0.067	0.061	0.056	0.053	0.050	0.058	0.054	0.051	0.049	0.047	0.050	0.048	0.047	0.046	0.045

Survival from Bonneville Dam to array 1 = 0.60, Survival from array 1 to array 2 = 0.90

Detection probability at array 1, Detection probability at array 2

	0.5, 0.5	**0.5, 0.6**	**0.5, 0.7**	**0.5, 0.8**	**0.5, 0.9**	**0.6, 0.5**	**0.6, 0.6**	**0.6, 0.7**	**0.6, 0.8**	**0.6, 0.9**	**0.7, 0.5**	**0.7, 0.6**	**0.7, 0.7**	**0.7, 0.8**	**0.7, 0.9**	**0.8, 0.5**	**0.8, 0.6**	**0.8, 0.7**	**0.8, 0.8**	**0.8, 0.9**	**0.9, 0.5**	**0.9, 0.6**	**0.9, 0.7**	**0.9, 0.8**	**0.9, 0.9**
100	0.193	0.170	0.151	0.135	0.121	0.167	0.149	0.135	0.123	0.113	0.146	0.133	0.123	0.114	0.107	0.128	0.119	0.112	0.107	0.103	0.111	0.107	0.104	0.101	0.099
150	0.158	0.139	0.123	0.11	0.099	0.137	0.122	0.11	0.101	0.092	0.119	0.108	0.1	0.093	0.088	0.104	0.097	0.092	0.087	0.084	0.091	0.087	0.085	0.083	0.081
200	0.137	0.120	0.107	0.095	0.086	0.118	0.106	0.096	0.087	0.080	0.103	0.094	0.087	0.081	0.076	0.09	0.084	0.079	0.076	0.073	0.079	0.076	0.073	0.071	0.070
250	0.122	0.107	0.095	0.085	0.076	0.106	0.094	0.085	0.078	0.072	0.092	0.084	0.078	0.072	0.068	0.081	0.075	0.071	0.068	0.065	0.07	0.068	0.065	0.064	0.063
300	0.112	0.098	0.087	0.078	0.070	0.097	0.086	0.078	0.071	0.065	0.084	0.077	0.071	0.066	0.062	0.074	0.069	0.065	0.062	0.059	0.064	0.062	0.060	0.058	0.057
350	0.103	0.091	0.081	0.072	0.065	0.089	0.080	0.072	0.066	0.061	0.078	0.071	0.066	0.061	0.057	0.068	0.064	0.060	0.057	0.055	0.059	0.057	0.055	0.054	0.053
400	0.097	0.085	0.075	0.067	0.060	0.084	0.075	0.068	0.062	0.057	0.073	0.066	0.061	0.057	0.054	0.064	0.059	0.056	0.054	0.051	0.056	0.053	0.052	0.051	0.050
450	0.091	0.080	0.071	0.064	0.057	0.079	0.070	0.064	0.058	0.053	0.069	0.063	0.058	0.054	0.051	0.060	0.056	0.053	0.050	0.048	0.052	0.050	0.049	0.048	0.047
500	0.086	0.076	0.067	0.060	0.054	0.075	0.067	0.060	0.055	0.051	0.065	0.059	0.055	0.051	0.048	0.057	0.053	0.050	0.048	0.046	0.050	0.048	0.046	0.045	0.044

Appendix Table A1. Continued.

Survival from Bonneville Dam to array 1 = 0.60, Survival from array 1 to array 2 = 0.95

Release group	Detection probability at array 1, Detection probability at array 2																										
	0.5, 0.5	**0.5, 0.6**	**0.5, 0.7**	**0.5, 0.8**	**0.5, 0.9**	**0.6, 0.5**	**0.6, 0.6**	**0.6, 0.7**	**0.6, 0.8**	**0.6, 0.9**	**0.7, 0.5**	**0.7, 0.6**	**0.7, 0.7**	**0.7, 0.8**	**0.7, 0.9**	**0.8, 0.5**	**0.8, 0.6**	**0.8, 0.7**	**0.8, 0.8**	**0.8, 0.9**	**0.9, 0.5**	**0.9, 0.6**	**0.9, 0.7**	**0.9, 0.8**	**0.9, 0.9**
100	0.186	0.163	0.144	0.128	0.115	0.162	0.144	0.130	0.119	0.109	0.142	0.129	0.119	0.111	0.104	0.125	0.116	0.110	0.105	0.101	0.110	0.106	0.103	0.100	0.098
150	0.152	0.133	0.118	0.105	0.094	0.132	0.118	0.106	0.097	0.089	0.116	0.105	0.097	0.091	0.085	0.102	0.095	0.090	0.086	0.082	0.090	0.086	0.084	0.082	0.080
200	0.132	0.115	0.102	0.091	0.081	0.114	0.102	0.092	0.084	0.077	0.100	0.091	0.084	0.079	0.074	0.088	0.082	0.078	0.074	0.071	0.078	0.075	0.072	0.071	0.069
250	0.118	0.103	0.091	0.081	0.072	0.102	0.091	0.082	0.075	0.069	0.090	0.082	0.075	0.070	0.066	0.079	0.074	0.070	0.066	0.064	0.069	0.067	0.065	0.063	0.062
300	0.108	0.094	0.083	0.074	0.066	0.093	0.083	0.075	0.068	0.063	0.082	0.075	0.069	0.064	0.060	0.072	0.067	0.064	0.061	0.058	0.063	0.061	0.059	0.058	0.057
350	0.100	0.087	0.077	0.069	0.061	0.087	0.077	0.070	0.063	0.058	0.076	0.069	0.064	0.059	0.056	0.067	0.062	0.059	0.056	0.054	0.059	0.056	0.055	0.054	0.053
400	0.093	0.082	0.072	0.064	0.057	0.081	0.072	0.065	0.059	0.054	0.071	0.065	0.060	0.056	0.052	0.062	0.058	0.055	0.053	0.050	0.055	0.053	0.051	0.050	0.049
450	0.088	0.077	0.068	0.061	0.054	0.076	0.068	0.061	0.056	0.051	0.067	0.061	0.056	0.052	0.049	0.059	0.055	0.052	0.050	0.048	0.052	0.050	0.048	0.047	0.046
500	0.083	0.073	0.065	0.057	0.051	0.072	0.065	0.058	0.053	0.049	0.063	0.058	0.053	0.050	0.047	0.056	0.052	0.049	0.047	0.045	0.049	0.047	0.046	0.045	0.044

Survival from Bonneville Dam to array 1 = 0.60, Survival from array 1 to array 2 = 1.00

Detection probability at array 1, Detection probability at array 2

	0.5, 0.5	**0.5, 0.6**	**0.5, 0.7**	**0.5, 0.8**	**0.5, 0.9**	**0.6, 0.5**	**0.6, 0.6**	**0.6, 0.7**	**0.6, 0.8**	**0.6, 0.9**	**0.7, 0.5**	**0.7, 0.6**	**0.7, 0.7**	**0.7, 0.8**	**0.7, 0.9**	**0.8, 0.5**	**0.8, 0.6**	**0.8, 0.7**	**0.8, 0.8**	**0.8, 0.9**	**0.9, 0.5**	**0.9, 0.6**	**0.9, 0.7**	**0.9, 0.8**	**0.9, 0.9**
100	0.180	0.157	0.138	0.122	0.109	0.157	0.140	0.126	0.114	0.105	0.138	0.126	0.116	0.108	0.102	0.122	0.114	0.108	0.103	0.099	0.109	0.105	0.102	0.099	0.097
150	0.147	0.128	0.113	0.100	0.089	0.128	0.114	0.103	0.093	0.085	0.113	0.103	0.095	0.088	0.083	0.100	0.093	0.088	0.084	0.081	0.089	0.085	0.083	0.081	0.080
200	0.127	0.111	0.098	0.087	0.077	0.111	0.099	0.089	0.081	0.074	0.098	0.089	0.082	0.076	0.072	0.087	0.081	0.076	0.073	0.070	0.077	0.074	0.072	0.070	0.069
250	0.114	0.099	0.087	0.077	0.069	0.099	0.088	0.080	0.072	0.066	0.087	0.080	0.073	0.068	0.064	0.077	0.072	0.068	0.065	0.063	0.069	0.066	0.064	0.063	0.062
300	0.104	0.091	0.080	0.071	0.063	0.091	0.081	0.073	0.066	0.060	0.080	0.073	0.067	0.062	0.059	0.071	0.066	0.062	0.060	0.057	0.063	0.060	0.059	0.057	0.056
350	0.096	0.084	0.074	0.065	0.058	0.084	0.075	0.067	0.061	0.056	0.074	0.067	0.062	0.058	0.054	0.065	0.061	0.058	0.055	0.053	0.058	0.056	0.054	0.053	0.052
400	0.090	0.078	0.069	0.061	0.054	0.078	0.070	0.063	0.057	0.052	0.069	0.063	0.058	0.054	0.051	0.061	0.057	0.054	0.052	0.050	0.054	0.052	0.051	0.050	0.049
450	0.085	0.074	0.065	0.058	0.051	0.074	0.066	0.059	0.054	0.049	0.065	0.059	0.055	0.051	0.048	0.058	0.054	0.051	0.049	0.047	0.051	0.049	0.048	0.047	0.046
500	0.080	0.070	0.062	0.055	0.049	0.070	0.062	0.056	0.051	0.047	0.062	0.056	0.052	0.048	0.045	0.055	0.051	0.048	0.046	0.044	0.049	0.047	0.045	0.044	0.044

Survival from Bonneville Dam to array 1 = 0.70, Survival from array 1 to array 2 = 0.80

Detection probability at array 1, Detection probability at array 2

	0.5, 0.5	**0.5, 0.6**	**0.5, 0.7**	**0.5, 0.8**	**0.5, 0.9**	**0.6, 0.5**	**0.6, 0.6**	**0.6, 0.7**	**0.6, 0.8**	**0.6, 0.9**	**0.7, 0.5**	**0.7, 0.6**	**0.7, 0.7**	**0.7, 0.8**	**0.7, 0.9**	**0.8, 0.5**	**0.8, 0.6**	**0.8, 0.7**	**0.8, 0.8**	**0.8, 0.9**	**0.9, 0.5**	**0.9, 0.6**	**0.9, 0.7**	**0.9, 0.8**	**0.9, 0.9**
100	0.220	0.193	0.171	0.152	0.136	0.187	0.166	0.149	0.135	0.123	0.159	0.143	0.131	0.121	0.112	0.135	0.124	0.116	0.109	0.103	0.112	0.106	0.102	0.099	0.096
150	0.180	0.157	0.140	0.124	0.111	0.153	0.135	0.122	0.110	0.100	0.130	0.117	0.107	0.098	0.091	0.110	0.101	0.094	0.089	0.084	0.091	0.087	0.083	0.081	0.078
200	0.156	0.136	0.121	0.108	0.096	0.132	0.117	0.105	0.095	0.087	0.113	0.101	0.093	0.085	0.079	0.095	0.088	0.082	0.077	0.073	0.079	0.075	0.072	0.070	0.068
250	0.139	0.122	0.108	0.096	0.086	0.118	0.105	0.094	0.085	0.078	0.101	0.091	0.083	0.076	0.071	0.085	0.078	0.073	0.069	0.065	0.071	0.067	0.065	0.062	0.061
300	0.127	0.111	0.099	0.088	0.079	0.108	0.096	0.086	0.078	0.071	0.092	0.083	0.076	0.070	0.065	0.078	0.072	0.067	0.063	0.060	0.065	0.061	0.059	0.057	0.055
350	0.118	0.103	0.091	0.081	0.073	0.100	0.089	0.080	0.072	0.066	0.085	0.077	0.070	0.064	0.060	0.072	0.066	0.062	0.058	0.055	0.060	0.057	0.055	0.053	0.051
400	0.110	0.096	0.085	0.076	0.068	0.093	0.083	0.074	0.067	0.061	0.080	0.072	0.065	0.060	0.056	0.067	0.062	0.058	0.054	0.052	0.056	0.053	0.051	0.049	0.048
450	0.104	0.091	0.081	0.072	0.064	0.088	0.078	0.070	0.064	0.058	0.075	0.068	0.062	0.057	0.053	0.064	0.058	0.054	0.051	0.049	0.053	0.050	0.048	0.047	0.045
500	0.098	0.086	0.076	0.068	0.061	0.084	0.074	0.067	0.060	0.055	0.071	0.064	0.059	0.054	0.050	0.060	0.055	0.052	0.049	0.046	0.050	0.048	0.046	0.044	0.043

Appendix Table A1. Continued.

Survival from Bonneville Dam to array 1 = 0.70, Survival from array 1 to array 2 = 0.85

Release group | Detection probability at array 1, Detection probability at array 2

Release group	0.5, 0.5	0.5, 0.6	0.5, 0.7	0.5, 0.8	0.5, 0.9	0.6, 0.5	0.6, 0.6	0.6, 0.7	0.6, 0.8	0.6, 0.9	0.7, 0.5	0.7, 0.6	0.7, 0.7	0.7, 0.8	0.7, 0.9	0.8, 0.5	0.8, 0.6	0.8, 0.7	0.8, 0.8	0.8, 0.9	0.9, 0.5	0.9, 0.6	0.9, 0.7	0.9, 0.8	0.9, 0.9
100	0.211	0.184	0.162	0.144	0.128	0.180	0.159	0.142	0.128	0.117	0.154	0.138	0.126	0.116	0.108	0.131	0.121	0.112	0.106	0.101	0.110	0.105	0.101	0.097	0.095
150	0.172	0.150	0.133	0.118	0.104	0.147	0.130	0.116	0.105	0.095	0.126	0.113	0.103	0.095	0.088	0.107	0.098	0.092	0.087	0.082	0.090	0.085	0.082	0.079	0.077
200	0.149	0.130	0.115	0.102	0.090	0.127	0.112	0.101	0.091	0.082	0.109	0.098	0.089	0.082	0.076	0.093	0.085	0.080	0.075	0.071	0.078	0.074	0.071	0.069	0.067
250	0.133	0.116	0.103	0.091	0.081	0.114	0.101	0.090	0.081	0.074	0.097	0.087	0.080	0.073	0.068	0.083	0.076	0.071	0.067	0.064	0.070	0.066	0.064	0.062	0.060
300	0.122	0.106	0.094	0.083	0.074	0.104	0.092	0.082	0.074	0.067	0.089	0.080	0.073	0.067	0.062	0.076	0.070	0.065	0.061	0.058	0.064	0.060	0.058	0.056	0.055
350	0.113	0.098	0.087	0.077	0.068	0.096	0.085	0.076	0.069	0.062	0.082	0.074	0.067	0.062	0.058	0.070	0.064	0.060	0.057	0.054	0.059	0.056	0.054	0.052	0.051
400	0.105	0.092	0.081	0.072	0.064	0.090	0.080	0.071	0.064	0.058	0.077	0.069	0.063	0.058	0.054	0.066	0.060	0.056	0.053	0.050	0.055	0.052	0.050	0.049	0.047
450	0.099	0.087	0.077	0.068	0.060	0.085	0.075	0.067	0.061	0.055	0.073	0.065	0.059	0.055	0.051	0.062	0.057	0.053	0.050	0.047	0.052	0.049	0.047	0.046	0.045
500	0.094	0.082	0.073	0.064	0.057	0.080	0.071	0.064	0.057	0.052	0.069	0.062	0.056	0.052	0.048	0.059	0.054	0.050	0.047	0.045	0.049	0.047	0.045	0.044	0.042

Survival from Bonneville Dam to array 1 = 0.70, Survival from array 1 to array 2 = 0.90

Detection probability at array 1, Detection probability at array 2

Release group	0.5, 0.5	0.5, 0.6	0.5, 0.7	0.5, 0.8	0.5, 0.9	0.6, 0.5	0.6, 0.6	0.6, 0.7	0.6, 0.8	0.6, 0.9	0.7, 0.5	0.7, 0.6	0.7, 0.7	0.7, 0.8	0.7, 0.9	0.8, 0.5	0.8, 0.6	0.8, 0.7	0.8, 0.8	0.8, 0.9	0.9, 0.5	0.9, 0.6	0.9, 0.7	0.9, 0.8	0.9, 0.9
100	0.202	0.176	0.154	0.136	0.120	0.173	0.153	0.136	0.123	0.111	0.149	0.134	0.122	0.112	0.104	0.128	0.117	0.110	0.103	0.098	0.108	0.103	0.099	0.096	0.094
150	0.165	0.144	0.126	0.111	0.098	0.141	0.125	0.111	0.1	0.09	0.122	0.109	0.099	0.091	0.085	0.104	0.096	0.090	0.084	0.080	0.088	0.084	0.081	0.078	0.076
200	0.143	0.124	0.109	0.096	0.085	0.122	0.108	0.096	0.087	0.078	0.105	0.095	0.086	0.079	0.073	0.090	0.083	0.078	0.073	0.069	0.077	0.073	0.070	0.068	0.066
250	0.128	0.111	0.098	0.086	0.076	0.110	0.097	0.086	0.078	0.070	0.094	0.085	0.077	0.071	0.066	0.081	0.074	0.069	0.065	0.062	0.068	0.065	0.063	0.061	0.059
300	0.117	0.102	0.089	0.079	0.069	0.100	0.088	0.079	0.071	0.064	0.086	0.077	0.070	0.065	0.060	0.074	0.068	0.063	0.060	0.057	0.063	0.059	0.057	0.055	0.054
350	0.108	0.094	0.083	0.073	0.064	0.093	0.082	0.073	0.066	0.059	0.080	0.071	0.065	0.060	0.055	0.068	0.063	0.059	0.055	0.052	0.058	0.055	0.053	0.051	0.050
400	0.101	0.088	0.077	0.068	0.060	0.087	0.076	0.068	0.061	0.055	0.074	0.067	0.061	0.056	0.052	0.064	0.059	0.055	0.052	0.049	0.054	0.052	0.050	0.048	0.047
450	0.095	0.083	0.073	0.064	0.057	0.082	0.072	0.064	0.058	0.052	0.070	0.063	0.057	0.053	0.049	0.060	0.055	0.052	0.049	0.046	0.051	0.049	0.047	0.045	0.044
500	0.090	0.079	0.069	0.061	0.054	0.077	0.068	0.061	0.055	0.050	0.067	0.060	0.054	0.050	0.046	0.057	0.053	0.049	0.046	0.044	0.048	0.046	0.044	0.043	0.042

Survival from Bonneville Dam to array 1 = 0.70, Survival from array 1 to array 2 = 0.95

Detection probability at array 1, Detection probability at array 2

Release group	0.5, 0.5	0.5, 0.6	0.5, 0.7	0.5, 0.8	0.5, 0.9	0.6, 0.5	0.6, 0.6	0.6, 0.7	0.6, 0.8	0.6, 0.9	0.7, 0.5	0.7, 0.6	0.7, 0.7	0.7, 0.8	0.7, 0.9	0.8, 0.5	0.8, 0.6	0.8, 0.7	0.8, 0.8	0.8, 0.9	0.9, 0.5	0.9, 0.6	0.9, 0.7	0.9, 0.8	0.9, 0.9
100	0.194	0.168	0.147	0.129	0.112	0.167	0.147	0.131	0.117	0.105	0.144	0.129	0.118	0.108	0.100	0.124	0.115	0.107	0.101	0.096	0.107	0.102	0.098	0.095	0.093
150	0.159	0.137	0.120	0.105	0.092	0.136	0.120	0.107	0.096	0.086	0.118	0.106	0.096	0.088	0.082	0.102	0.094	0.087	0.082	0.078	0.087	0.083	0.080	0.078	0.076
200	0.137	0.119	0.104	0.091	0.079	0.118	0.104	0.092	0.083	0.075	0.102	0.092	0.083	0.077	0.071	0.088	0.081	0.076	0.071	0.068	0.075	0.072	0.069	0.067	0.065
250	0.123	0.106	0.093	0.081	0.071	0.106	0.093	0.083	0.074	0.067	0.091	0.082	0.074	0.068	0.063	0.079	0.072	0.068	0.064	0.061	0.067	0.064	0.062	0.060	0.059
300	0.112	0.097	0.085	0.074	0.065	0.096	0.085	0.075	0.068	0.061	0.083	0.075	0.068	0.062	0.058	0.072	0.066	0.062	0.058	0.055	0.062	0.059	0.056	0.055	0.053
350	0.104	0.090	0.079	0.069	0.060	0.089	0.079	0.070	0.063	0.056	0.077	0.069	0.063	0.058	0.054	0.067	0.061	0.057	0.054	0.051	0.057	0.054	0.052	0.051	0.049
400	0.097	0.084	0.074	0.064	0.056	0.083	0.073	0.065	0.059	0.053	0.072	0.065	0.059	0.054	0.050	0.062	0.057	0.054	0.050	0.048	0.053	0.051	0.049	0.047	0.046
450	0.092	0.079	0.069	0.061	0.053	0.079	0.069	0.062	0.055	0.050	0.068	0.061	0.056	0.051	0.047	0.059	0.054	0.050	0.048	0.045	0.050	0.048	0.046	0.045	0.044
500	0.087	0.075	0.066	0.058	0.050	0.075	0.066	0.058	0.052	0.047	0.065	0.058	0.053	0.048	0.045	0.056	0.051	0.048	0.045	0.043	0.048	0.045	0.044	0.042	0.041

Appendix Table A1. Continued.

Survival from Bonneville Dam to array 1 = 0.70, Survival from array 1 to array 2 = 1.00

Release group — Detection probability at array 1, Detection probability at array 2

	0.5, 0.5	0.5, 0.6	0.5, 0.7	0.5, 0.8	0.5, 0.9	0.6, 0.5	0.6, 0.6	0.6, 0.7	0.6, 0.8	0.6, 0.9	0.7, 0.5	0.7, 0.6	0.7, 0.7	0.7, 0.8	0.7, 0.9	0.8, 0.5	0.8, 0.6	0.8, 0.7	0.8, 0.8	0.8, 0.9	0.9, 0.5	0.9, 0.6	0.9, 0.7	0.9, 0.8	0.9, 0.9
100	0.187	0.161	0.140	0.122	0.105	0.161	0.141	0.126	0.112	0.100	0.140	0.126	0.114	0.105	0.097	0.122	0.112	0.105	0.099	0.094	0.105	0.100	0.097	0.094	0.092
150	0.153	0.132	0.114	0.099	0.086	0.132	0.116	0.102	0.091	0.082	0.114	0.102	0.093	0.085	0.079	0.099	0.091	0.085	0.081	0.077	0.086	0.082	0.079	0.077	0.075
200	0.132	0.114	0.099	0.086	0.074	0.114	0.100	0.089	0.079	0.071	0.099	0.089	0.081	0.074	0.068	0.086	0.079	0.074	0.070	0.066	0.074	0.071	0.068	0.066	0.065
250	0.118	0.102	0.089	0.077	0.066	0.102	0.089	0.079	0.071	0.063	0.089	0.079	0.072	0.066	0.061	0.077	0.071	0.066	0.062	0.059	0.066	0.063	0.061	0.059	0.058
300	0.108	0.093	0.081	0.070	0.061	0.093	0.082	0.072	0.065	0.058	0.081	0.072	0.066	0.060	0.056	0.070	0.065	0.060	0.057	0.054	0.061	0.058	0.056	0.054	0.053
350	0.100	0.086	0.075	0.065	0.056	0.086	0.076	0.067	0.060	0.054	0.075	0.067	0.061	0.056	0.052	0.065	0.060	0.056	0.053	0.050	0.056	0.054	0.052	0.050	0.049
400	0.093	0.081	0.070	0.061	0.053	0.081	0.071	0.063	0.056	0.050	0.070	0.063	0.057	0.052	0.048	0.061	0.056	0.052	0.049	0.047	0.053	0.050	0.048	0.047	0.046
450	0.088	0.076	0.066	0.057	0.050	0.076	0.067	0.059	0.053	0.047	0.066	0.059	0.054	0.049	0.046	0.057	0.053	0.049	0.047	0.044	0.050	0.047	0.046	0.044	0.043
500	0.084	0.072	0.063	0.054	0.047	0.072	0.063	0.056	0.050	0.045	0.063	0.056	0.051	0.047	0.043	0.054	0.050	0.047	0.044	0.042	0.047	0.045	0.043	0.042	0.041

Survival from Bonneville Dam to array 1 = 0.80, Survival from array 1 to array 2 = 0.80

Detection probability at array 1, Detection probability at array 2

	0.5, 0.5	0.5, 0.6	0.5, 0.7	0.5, 0.8	0.5, 0.9	0.6, 0.5	0.6, 0.6	0.6, 0.7	0.6, 0.8	0.6, 0.9	0.7, 0.5	0.7, 0.6	0.7, 0.7	0.7, 0.8	0.7, 0.9	0.8, 0.5	0.8, 0.6	0.8, 0.7	0.8, 0.8	0.8, 0.9	0.9, 0.5	0.9, 0.6	0.9, 0.7	0.9, 0.8	0.9, 0.9
100	0.229	0.199	0.174	0.153	0.135	0.192	0.168	0.149	0.133	0.119	0.161	0.143	0.128	0.116	0.106	0.133	0.120	0.110	0.102	0.096	0.106	0.099	0.094	0.090	0.086
150	0.187	0.162	0.142	0.125	0.110	0.157	0.137	0.122	0.109	0.097	0.131	0.117	0.105	0.095	0.087	0.109	0.098	0.090	0.084	0.078	0.087	0.081	0.077	0.073	0.071
200	0.162	0.140	0.123	0.108	0.095	0.136	0.119	0.105	0.094	0.084	0.114	0.101	0.091	0.082	0.075	0.094	0.085	0.078	0.072	0.068	0.075	0.070	0.066	0.064	0.061
250	0.145	0.126	0.110	0.097	0.085	0.121	0.106	0.094	0.084	0.075	0.102	0.090	0.081	0.074	0.067	0.084	0.076	0.070	0.065	0.060	0.067	0.063	0.059	0.057	0.055
300	0.132	0.115	0.100	0.088	0.078	0.111	0.097	0.086	0.077	0.069	0.093	0.082	0.074	0.067	0.061	0.077	0.069	0.064	0.059	0.055	0.061	0.057	0.054	0.052	0.050
350	0.122	0.106	0.093	0.082	0.072	0.103	0.090	0.080	0.071	0.064	0.086	0.076	0.069	0.062	0.057	0.071	0.064	0.059	0.055	0.051	0.057	0.053	0.050	0.048	0.046
400	0.114	0.099	0.087	0.077	0.067	0.096	0.084	0.075	0.066	0.059	0.080	0.071	0.064	0.058	0.053	0.066	0.060	0.055	0.051	0.048	0.053	0.050	0.047	0.045	0.043
450	0.108	0.094	0.082	0.072	0.063	0.091	0.079	0.070	0.063	0.056	0.076	0.067	0.061	0.055	0.050	0.063	0.057	0.052	0.048	0.045	0.050	0.047	0.044	0.042	0.041
500	0.102	0.089	0.078	0.068	0.060	0.086	0.075	0.067	0.059	0.053	0.072	0.064	0.057	0.052	0.047	0.059	0.054	0.049	0.046	0.043	0.047	0.044	0.042	0.040	0.039

Survival from Bonneville Dam to array 1 = 0.80, Survival from array 1 to array 2 = 0.85

Detection probability at array 1, Detection probability at array 2

	0.5, 0.5	0.5, 0.6	0.5, 0.7	0.5, 0.8	0.5, 0.9	0.6, 0.5	0.6, 0.6	0.6, 0.7	0.6, 0.8	0.6, 0.9	0.7, 0.5	0.7, 0.6	0.7, 0.7	0.7, 0.8	0.7, 0.9	0.8, 0.5	0.8, 0.6	0.8, 0.7	0.8, 0.8	0.8, 0.9	0.9, 0.5	0.9, 0.6	0.9, 0.7	0.9, 0.8	0.9, 0.9
100	0.218	0.189	0.165	0.144	0.125	0.184	0.161	0.142	0.126	0.112	0.155	0.137	0.123	0.111	0.101	0.129	0.116	0.107	0.099	0.092	0.104	0.097	0.092	0.088	0.085
150	0.178	0.154	0.134	0.117	0.102	0.150	0.131	0.116	0.103	0.091	0.126	0.112	0.100	0.091	0.082	0.105	0.095	0.087	0.081	0.075	0.085	0.079	0.075	0.072	0.069
200	0.154	0.134	0.116	0.102	0.088	0.130	0.114	0.100	0.089	0.079	0.109	0.097	0.087	0.079	0.071	0.091	0.082	0.075	0.070	0.065	0.073	0.069	0.065	0.062	0.060
250	0.138	0.119	0.104	0.091	0.079	0.116	0.102	0.090	0.079	0.071	0.098	0.087	0.078	0.070	0.064	0.081	0.074	0.067	0.062	0.058	0.066	0.061	0.058	0.056	0.054
300	0.126	0.109	0.095	0.083	0.072	0.106	0.093	0.082	0.073	0.064	0.089	0.079	0.071	0.064	0.058	0.074	0.067	0.062	0.057	0.053	0.060	0.056	0.053	0.051	0.049
350	0.117	0.101	0.088	0.077	0.067	0.098	0.086	0.076	0.067	0.060	0.083	0.073	0.066	0.059	0.054	0.069	0.062	0.057	0.053	0.049	0.055	0.052	0.049	0.047	0.045
400	0.109	0.094	0.082	0.072	0.062	0.092	0.080	0.071	0.063	0.056	0.077	0.069	0.061	0.056	0.050	0.064	0.058	0.053	0.049	0.046	0.052	0.049	0.046	0.044	0.042
450	0.103	0.089	0.078	0.068	0.059	0.087	0.076	0.067	0.059	0.053	0.073	0.065	0.058	0.052	0.048	0.061	0.055	0.050	0.047	0.043	0.049	0.046	0.043	0.042	0.040
500	0.098	0.084	0.074	0.064	0.056	0.082	0.072	0.063	0.056	0.050	0.069	0.061	0.055	0.050	0.045	0.058	0.052	0.048	0.044	0.041	0.046	0.043	0.041	0.039	0.038

Appendix Table A1. Continued.

Survival from Bonneville Dam to array 1 = 0.80, Survival from array 1 to array 2 = 0.90

Release group	Detection probability at array 1, Detection probability at array 2																									
	0.5, 0.5	**0.5, 0.6**	**0.5, 0.7**	**0.5, 0.8**	**0.5, 0.9**	**0.6, 0.5**	**0.6, 0.6**	**0.6, 0.7**	**0.6, 0.8**	**0.6, 0.9**	**0.7, 0.5**	**0.7, 0.6**	**0.7, 0.7**	**0.7, 0.8**	**0.7, 0.9**	**0.8, 0.5**	**0.8, 0.6**	**0.8, 0.7**	**0.8, 0.8**	**0.8, 0.9**	**0.9, 0.5**	**0.9, 0.6**	**0.9, 0.7**	**0.9, 0.8**	**0.9, 0.9**
100	0.209	0.180	0.156	0.135	0.116	0.177	0.154	0.135	0.119	0.105	0.149	0.132	0.118	0.106	0.096	0.125	0.113	0.103	0.096	0.089	0.102	0.095	0.090	0.086	0.083
150	0.171	0.147	0.127	0.110	0.094	0.144	0.125	0.110	0.097	0.085	0.122	0.108	0.096	0.087	0.078	0.102	0.092	0.084	0.078	0.073	0.083	0.078	0.074	0.071	0.068
200	0.148	0.127	0.110	0.095	0.082	0.125	0.109	0.095	0.084	0.074	0.105	0.093	0.083	0.075	0.068	0.088	0.080	0.073	0.068	0.063	0.072	0.067	0.064	0.061	0.059
250	0.132	0.114	0.098	0.085	0.073	0.112	0.097	0.085	0.075	0.066	0.094	0.083	0.075	0.067	0.061	0.079	0.071	0.065	0.060	0.056	0.064	0.060	0.057	0.055	0.053
300	0.121	0.104	0.090	0.078	0.067	0.102	0.089	0.078	0.069	0.060	0.086	0.076	0.068	0.061	0.055	0.072	0.065	0.060	0.055	0.051	0.059	0.055	0.052	0.050	0.048
350	0.112	0.096	0.083	0.072	0.062	0.094	0.082	0.072	0.064	0.056	0.080	0.070	0.063	0.057	0.051	0.067	0.060	0.055	0.051	0.048	0.054	0.051	0.048	0.046	0.045
400	0.105	0.090	0.078	0.067	0.058	0.088	0.077	0.067	0.059	0.052	0.075	0.066	0.059	0.053	0.048	0.062	0.056	0.052	0.048	0.045	0.051	0.048	0.045	0.043	0.042
450	0.099	0.085	0.073	0.063	0.054	0.083	0.072	0.064	0.056	0.049	0.070	0.062	0.056	0.050	0.045	0.059	0.053	0.049	0.045	0.042	0.048	0.045	0.043	0.041	0.039
500	0.093	0.080	0.070	0.060	0.052	0.079	0.069	0.060	0.053	0.047	0.067	0.059	0.053	0.047	0.043	0.056	0.050	0.046	0.043	0.040	0.045	0.043	0.040	0.039	0.037

Survival from Bonneville Dam to array 1 = 0.80, Survival from array 1 to array 2 = 0.95

Release group	Detection probability at array 1, Detection probability at array 2																									
	0.5, 0.5	**0.5, 0.6**	**0.5, 0.7**	**0.5, 0.8**	**0.5, 0.9**	**0.6, 0.5**	**0.6, 0.6**	**0.6, 0.7**	**0.6, 0.8**	**0.6, 0.9**	**0.7, 0.5**	**0.7, 0.6**	**0.7, 0.7**	**0.7, 0.8**	**0.7, 0.9**	**0.8, 0.5**	**0.8, 0.6**	**0.8, 0.7**	**0.8, 0.8**	**0.8, 0.9**	**0.9, 0.5**	**0.9, 0.6**	**0.9, 0.7**	**0.9, 0.8**	**0.9, 0.9**
100	0.200	0.171	0.147	0.126	0.107	0.170	0.147	0.128	0.112	0.098	0.144	0.127	0.113	0.102	0.092	0.121	0.109	0.100	0.093	0.086	0.100	0.093	0.089	0.085	0.082
150	0.164	0.140	0.120	0.103	0.087	0.139	0.120	0.105	0.092	0.080	0.117	0.104	0.092	0.083	0.075	0.099	0.089	0.082	0.076	0.070	0.081	0.076	0.072	0.069	0.067
200	0.142	0.121	0.104	0.089	0.075	0.120	0.104	0.091	0.079	0.069	0.102	0.090	0.080	0.072	0.065	0.086	0.077	0.071	0.065	0.061	0.070	0.066	0.063	0.060	0.058
250	0.127	0.108	0.093	0.080	0.067	0.107	0.093	0.081	0.071	0.062	0.091	0.080	0.072	0.064	0.058	0.077	0.069	0.063	0.059	0.055	0.063	0.059	0.056	0.054	0.052
300	0.116	0.099	0.085	0.073	0.062	0.098	0.085	0.074	0.065	0.057	0.083	0.073	0.065	0.059	0.053	0.070	0.063	0.058	0.053	0.050	0.058	0.054	0.051	0.049	0.047
350	0.107	0.092	0.079	0.067	0.057	0.091	0.079	0.069	0.060	0.052	0.077	0.068	0.060	0.054	0.049	0.065	0.058	0.053	0.049	0.046	0.053	0.050	0.047	0.045	0.044
400	0.100	0.086	0.074	0.063	0.053	0.085	0.073	0.064	0.056	0.049	0.072	0.063	0.057	0.051	0.046	0.060	0.055	0.050	0.046	0.043	0.050	0.047	0.044	0.042	0.041
450	0.094	0.081	0.069	0.059	0.050	0.080	0.069	0.060	0.053	0.046	0.068	0.060	0.053	0.048	0.043	0.057	0.052	0.047	0.044	0.041	0.047	0.044	0.042	0.040	0.039
500	0.090	0.077	0.066	0.056	0.048	0.076	0.066	0.057	0.050	0.044	0.064	0.057	0.051	0.045	0.041	0.054	0.049	0.045	0.041	0.039	0.045	0.042	0.040	0.038	0.037

Survival from Bonneville Dam to array 1 = 0.80, Survival from array 1 to array 2 = 1.00

Release group	Detection probability at array 1, Detection probability at array 2																									
	0.5, 0.5	**0.5, 0.6**	**0.5, 0.7**	**0.5, 0.8**	**0.5, 0.9**	**0.6, 0.5**	**0.6, 0.6**	**0.6, 0.7**	**0.6, 0.8**	**0.6, 0.9**	**0.7, 0.5**	**0.7, 0.6**	**0.7, 0.7**	**0.7, 0.8**	**0.7, 0.9**	**0.8, 0.5**	**0.8, 0.6**	**0.8, 0.7**	**0.8, 0.8**	**0.8, 0.9**	**0.9, 0.5**	**0.9, 0.6**	**0.9, 0.7**	**0.9, 0.8**	**0.9, 0.9**
100	0.192	0.163	0.139	0.118	0.098	0.163	0.141	0.122	0.106	0.092	0.139	0.122	0.109	0.097	0.087	0.118	0.106	0.097	0.090	0.084	0.098	0.092	0.087	0.084	0.081
150	0.157	0.133	0.113	0.096	0.080	0.133	0.115	0.100	0.087	0.075	0.113	0.100	0.089	0.079	0.071	0.096	0.087	0.079	0.073	0.068	0.080	0.075	0.071	0.068	0.066
200	0.136	0.115	0.098	0.083	0.069	0.115	0.100	0.086	0.075	0.065	0.098	0.086	0.077	0.069	0.062	0.083	0.075	0.069	0.064	0.059	0.069	0.065	0.062	0.059	0.057
250	0.121	0.103	0.088	0.074	0.062	0.103	0.089	0.077	0.067	0.058	0.088	0.077	0.069	0.061	0.055	0.074	0.067	0.061	0.057	0.053	0.062	0.058	0.055	0.053	0.051
300	0.111	0.094	0.080	0.068	0.056	0.094	0.081	0.071	0.061	0.053	0.080	0.071	0.063	0.056	0.050	0.068	0.061	0.056	0.052	0.048	0.056	0.053	0.050	0.048	0.047
350	0.103	0.087	0.074	0.063	0.052	0.087	0.075	0.065	0.057	0.049	0.074	0.065	0.058	0.052	0.047	0.063	0.057	0.052	0.048	0.045	0.052	0.049	0.047	0.045	0.043
400	0.096	0.082	0.069	0.059	0.049	0.082	0.070	0.061	0.053	0.046	0.069	0.061	0.054	0.049	0.044	0.059	0.053	0.049	0.045	0.042	0.049	0.046	0.044	0.042	0.040
450	0.091	0.077	0.066	0.055	0.046	0.077	0.066	0.058	0.050	0.043	0.066	0.058	0.051	0.046	0.041	0.055	0.050	0.046	0.042	0.039	0.046	0.043	0.041	0.039	0.038
500	0.086	0.073	0.062	0.053	0.044	0.073	0.063	0.055	0.047	0.041	0.062	0.055	0.049	0.043	0.039	0.053	0.047	0.043	0.040	0.037	0.044	0.041	0.039	0.037	0.036

Appendix Table A1. Continued.

Survival from Bonneville Dam to array 1 = 0.90, Survival from array 1 to array 2 = 0.80

Release	Detection probability at array 1, Detection probability at array 2																										
group	**0.5, 0.5**	**0.5, 0.6**	**0.5, 0.7**	**0.5, 0.8**	**0.5, 0.9**	**0.6, 0.5**	**0.6, 0.6**	**0.6, 0.7**	**0.6, 0.8**	**0.6, 0.9**	**0.7, 0.5**	**0.7, 0.6**	**0.7, 0.7**	**0.7, 0.8**	**0.7, 0.9**	**0.8, 0.5**	**0.8, 0.6**	**0.8, 0.7**	**0.8, 0.8**	**0.8, 0.9**	**0.9, 0.5**	**0.9, 0.6**	**0.9, 0.7**	**0.9, 0.8**	**0.9, 0.9**
100	0.235	0.202	0.175	0.151	0.130	0.195	0.169	0.147	0.128	0.111	0.160	0.140	0.123	0.109	0.096	0.128	0.113	0.101	0.091	0.083	0.096	0.087	0.080	0.075	0.070
150	0.192	0.165	0.143	0.124	0.106	0.159	0.138	0.120	0.105	0.091	0.131	0.114	0.100	0.089	0.078	0.105	0.092	0.083	0.074	0.067	0.078	0.071	0.066	0.061	0.057
200	0.166	0.143	0.124	0.107	0.092	0.138	0.119	0.104	0.091	0.079	0.113	0.099	0.087	0.077	0.068	0.091	0.080	0.072	0.064	0.058	0.068	0.062	0.057	0.053	0.050
250	0.149	0.128	0.111	0.096	0.082	0.123	0.107	0.093	0.081	0.070	0.101	0.088	0.078	0.069	0.061	0.081	0.072	0.064	0.058	0.052	0.061	0.055	0.051	0.047	0.045
300	0.136	0.117	0.101	0.087	0.075	0.113	0.097	0.085	0.074	0.064	0.093	0.081	0.071	0.063	0.055	0.074	0.065	0.058	0.053	0.048	0.055	0.050	0.046	0.043	0.041
350	0.126	0.108	0.094	0.081	0.069	0.104	0.090	0.078	0.068	0.060	0.086	0.075	0.066	0.058	0.051	0.068	0.061	0.054	0.049	0.044	0.051	0.047	0.043	0.040	0.038
400	0.118	0.101	0.087	0.076	0.065	0.098	0.084	0.073	0.064	0.056	0.080	0.070	0.061	0.054	0.048	0.064	0.057	0.051	0.046	0.041	0.048	0.044	0.040	0.037	0.035
450	0.111	0.095	0.082	0.071	0.061	0.092	0.079	0.069	0.060	0.053	0.076	0.066	0.058	0.051	0.045	0.060	0.053	0.048	0.043	0.039	0.045	0.041	0.038	0.035	0.033
500	0.105	0.090	0.078	0.068	0.058	0.087	0.075	0.066	0.057	0.050	0.072	0.062	0.055	0.049	0.043	0.057	0.051	0.045	0.041	0.037	0.043	0.039	0.036	0.034	0.031

Survival from Bonneville Dam to array 1 = 0.90, Survival from array 1 to array 2 = 0.85

Release	Detection probability at array 1, Detection probability at array 2																										
group	**0.5, 0.5**	**0.5, 0.6**	**0.5, 0.7**	**0.5, 0.8**	**0.5, 0.9**	**0.6, 0.5**	**0.6, 0.6**	**0.6, 0.7**	**0.6, 0.8**	**0.6, 0.9**	**0.7, 0.5**	**0.7, 0.6**	**0.7, 0.7**	**0.7, 0.8**	**0.7, 0.9**	**0.8, 0.5**	**0.8, 0.6**	**0.8, 0.7**	**0.8, 0.8**	**0.8, 0.9**	**0.9, 0.5**	**0.9, 0.6**	**0.9, 0.7**	**0.9, 0.8**	**0.9, 0.9**
100	0.224	0.192	0.164	0.140	0.119	0.186	0.160	0.138	0.120	0.103	0.153	0.133	0.116	0.102	0.089	0.123	0.108	0.097	0.087	0.078	0.093	0.085	0.078	0.073	0.068
150	0.183	0.156	0.134	0.115	0.097	0.152	0.131	0.113	0.098	0.084	0.125	0.109	0.095	0.083	0.073	0.101	0.089	0.079	0.071	0.064	0.076	0.069	0.064	0.059	0.056
200	0.158	0.135	0.116	0.099	0.084	0.132	0.113	0.098	0.085	0.073	0.108	0.094	0.082	0.072	0.063	0.087	0.077	0.068	0.061	0.055	0.066	0.060	0.055	0.051	0.048
250	0.142	0.121	0.104	0.089	0.075	0.118	0.101	0.088	0.076	0.065	0.097	0.084	0.074	0.065	0.057	0.078	0.069	0.061	0.055	0.049	0.059	0.053	0.049	0.046	0.043
300	0.129	0.111	0.095	0.081	0.069	0.107	0.092	0.080	0.069	0.059	0.089	0.077	0.067	0.059	0.052	0.071	0.063	0.056	0.050	0.045	0.054	0.049	0.045	0.042	0.039
350	0.120	0.102	0.088	0.075	0.063	0.099	0.086	0.074	0.064	0.055	0.082	0.071	0.062	0.055	0.048	0.066	0.058	0.052	0.046	0.042	0.050	0.045	0.042	0.039	0.036
400	0.112	0.096	0.082	0.070	0.059	0.093	0.080	0.069	0.060	0.051	0.077	0.067	0.058	0.051	0.045	0.062	0.054	0.048	0.043	0.039	0.047	0.042	0.039	0.036	0.034
450	0.106	0.090	0.077	0.066	0.056	0.088	0.075	0.065	0.056	0.048	0.072	0.063	0.055	0.048	0.042	0.058	0.051	0.046	0.041	0.037	0.044	0.040	0.037	0.034	0.032
500	0.100	0.086	0.073	0.063	0.053	0.083	0.072	0.062	0.053	0.046	0.069	0.059	0.052	0.046	0.040	0.055	0.049	0.043	0.039	0.035	0.042	0.038	0.035	0.032	0.030

Survival from Bonneville Dam to array 1 = 0.90, Survival from array 1 to array 2 = 0.90

Release	Detection probability at array 1, Detection probability at array 2																										
group	**0.5, 0.5**	**0.5, 0.6**	**0.5, 0.7**	**0.5, 0.8**	**0.5, 0.9**	**0.6, 0.5**	**0.6, 0.6**	**0.6, 0.7**	**0.6, 0.8**	**0.6, 0.9**	**0.7, 0.5**	**0.7, 0.6**	**0.7, 0.7**	**0.7, 0.8**	**0.7, 0.9**	**0.8, 0.5**	**0.8, 0.6**	**0.8, 0.7**	**0.8, 0.8**	**0.8, 0.9**	**0.9, 0.5**	**0.9, 0.6**	**0.9, 0.7**	**0.9, 0.8**	**0.9, 0.9**
100	0.214	0.181	0.154	0.130	0.108	0.178	0.152	0.130	0.111	0.094	0.147	0.127	0.110	0.096	0.083	0.118	0.104	0.092	0.083	0.074	0.090	0.082	0.076	0.070	0.066
150	0.175	0.148	0.126	0.106	0.088	0.145	0.124	0.106	0.091	0.077	0.120	0.104	0.090	0.078	0.068	0.097	0.085	0.075	0.067	0.060	0.074	0.067	0.062	0.057	0.054
200	0.151	0.128	0.109	0.092	0.076	0.126	0.107	0.092	0.079	0.067	0.104	0.090	0.078	0.068	0.059	0.084	0.074	0.065	0.058	0.052	0.064	0.058	0.053	0.050	0.047
250	0.135	0.115	0.097	0.082	0.068	0.112	0.096	0.082	0.070	0.060	0.093	0.080	0.070	0.061	0.053	0.075	0.066	0.058	0.052	0.047	0.057	0.052	0.048	0.045	0.042
300	0.123	0.105	0.089	0.075	0.062	0.103	0.088	0.075	0.064	0.054	0.085	0.073	0.064	0.055	0.048	0.068	0.060	0.053	0.048	0.043	0.052	0.047	0.044	0.041	0.038
350	0.114	0.097	0.082	0.069	0.057	0.095	0.081	0.070	0.060	0.050	0.078	0.068	0.059	0.051	0.045	0.063	0.056	0.049	0.044	0.040	0.048	0.044	0.040	0.038	0.035
400	0.107	0.091	0.077	0.065	0.054	0.089	0.076	0.065	0.056	0.047	0.073	0.063	0.055	0.048	0.042	0.059	0.052	0.046	0.041	0.037	0.045	0.041	0.038	0.035	0.033
450	0.101	0.086	0.073	0.061	0.051	0.084	0.072	0.061	0.053	0.044	0.069	0.060	0.052	0.045	0.039	0.056	0.049	0.044	0.039	0.035	0.043	0.039	0.036	0.033	0.031
500	0.096	0.081	0.069	0.058	0.048	0.080	0.068	0.058	0.050	0.042	0.066	0.057	0.049	0.043	0.037	0.053	0.047	0.041	0.037	0.033	0.040	0.037	0.034	0.031	0.030

Appendix Table A1. Continued.

Survival from Bonneville Dam to array 1 = 0.90, Survival from array 1 to array 2 = 0.95

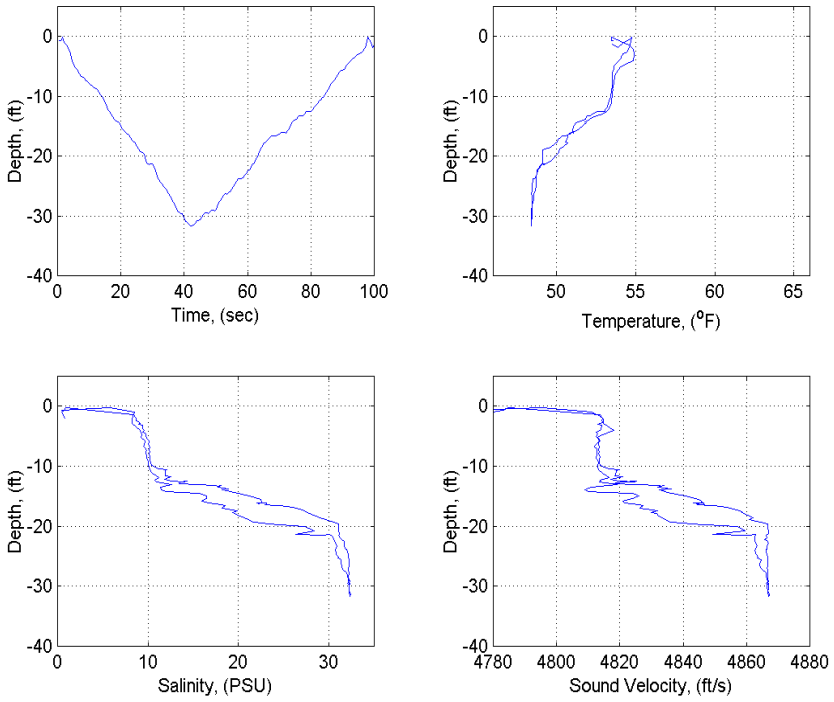
Release	Detection probability at array 1, Detection probability at array 2																										
group	**0.5, 0.5**	**0.5, 0.6**	**0.5, 0.7**	**0.5, 0.8**	**0.5, 0.9**	**0.6, 0.5**	**0.6, 0.6**	**0.6, 0.7**	**0.6, 0.8**	**0.6, 0.9**	**0.7, 0.5**	**0.7, 0.6**	**0.7, 0.7**	**0.7, 0.8**	**0.7, 0.9**	**0.8, 0.5**	**0.8, 0.6**	**0.8, 0.7**	**0.8, 0.8**	**0.8, 0.9**	**0.9, 0.5**	**0.9, 0.6**	**0.9, 0.7**	**0.9, 0.8**	**0.9, 0.9**
100	0.204	0.172	0.144	0.120	0.097	0.170	0.144	0.123	0.104	0.086	0.141	0.121	0.105	0.090	0.077	0.114	0.100	0.088	0.079	0.070	0.088	0.080	0.073	0.068	0.064
150	0.167	0.140	0.118	0.098	0.079	0.139	0.118	0.100	0.085	0.070	0.115	0.099	0.085	0.074	0.063	0.093	0.082	0.072	0.064	0.057	0.072	0.065	0.060	0.056	0.052
200	0.144	0.122	0.102	0.085	0.068	0.120	0.102	0.087	0.073	0.061	0.100	0.086	0.074	0.064	0.055	0.081	0.071	0.062	0.056	0.050	0.062	0.056	0.052	0.048	0.045
250	0.129	0.109	0.091	0.076	0.061	0.108	0.091	0.078	0.066	0.054	0.089	0.077	0.066	0.057	0.049	0.072	0.063	0.056	0.050	0.044	0.056	0.050	0.046	0.043	0.041
300	0.118	0.099	0.083	0.069	0.056	0.098	0.083	0.071	0.060	0.050	0.081	0.070	0.060	0.052	0.045	0.066	0.058	0.051	0.045	0.041	0.051	0.046	0.042	0.039	0.037
350	0.109	0.092	0.077	0.064	0.052	0.091	0.077	0.066	0.055	0.046	0.075	0.065	0.056	0.048	0.041	0.061	0.053	0.047	0.042	0.038	0.047	0.043	0.039	0.037	0.034
400	0.102	0.086	0.072	0.060	0.048	0.085	0.072	0.061	0.052	0.043	0.070	0.060	0.052	0.045	0.039	0.057	0.050	0.044	0.039	0.035	0.044	0.040	0.037	0.034	0.032
450	0.096	0.081	0.068	0.057	0.046	0.080	0.068	0.058	0.049	0.040	0.066	0.057	0.049	0.043	0.036	0.054	0.047	0.042	0.037	0.033	0.041	0.038	0.035	0.032	0.030
500	0.091	0.077	0.065	0.054	0.043	0.076	0.065	0.055	0.046	0.038	0.063	0.054	0.047	0.040	0.035	0.051	0.045	0.040	0.035	0.031	0.039	0.036	0.033	0.031	0.029

Survival from Bonneville Dam to array 1 = 0.90, Survival from array 1 to array 2 = 1.00

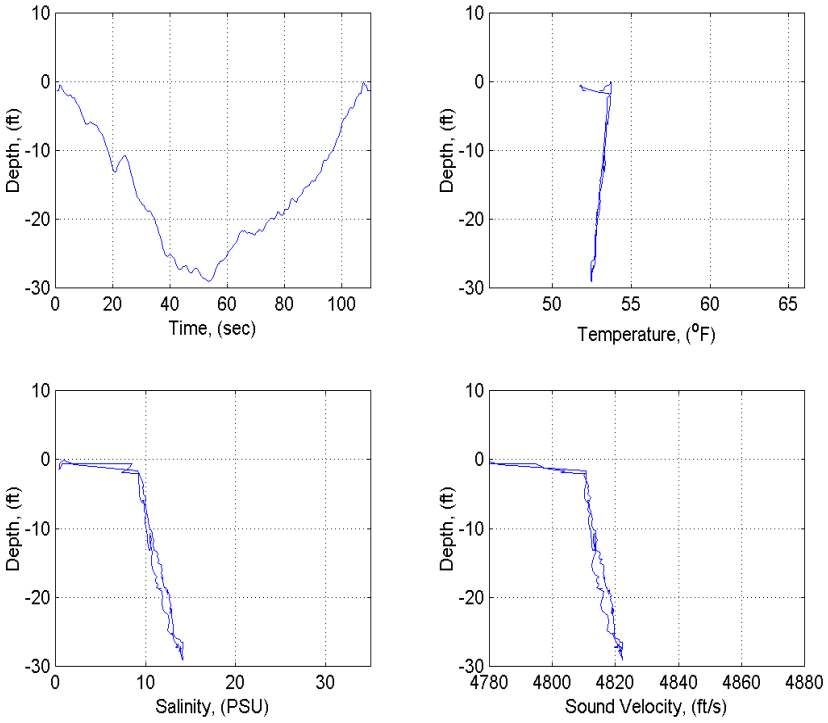
Release	Detection probability at array 1, Detection probability at array 2																										
group	**0.5, 0.5**	**0.5, 0.6**	**0.5, 0.7**	**0.5, 0.8**	**0.5, 0.9**	**0.6, 0.5**	**0.6, 0.6**	**0.6, 0.7**	**0.6, 0.8**	**0.6, 0.9**	**0.7, 0.5**	**0.7, 0.6**	**0.7, 0.7**	**0.7, 0.8**	**0.7, 0.9**	**0.8, 0.5**	**0.8, 0.6**	**0.8, 0.7**	**0.8, 0.8**	**0.8, 0.9**	**0.9, 0.5**	**0.9, 0.6**	**0.9, 0.7**	**0.9, 0.8**	**0.9, 0.9**
100	0.195	0.163	0.135	0.110	0.085	0.163	0.137	0.115	0.096	0.078	0.135	0.115	0.099	0.085	0.071	0.110	0.096	0.085	0.075	0.066	0.085	0.078	0.071	0.066	0.062
150	0.159	0.133	0.110	0.090	0.070	0.133	0.112	0.094	0.078	0.063	0.110	0.094	0.081	0.069	0.058	0.090	0.078	0.069	0.061	0.054	0.070	0.063	0.058	0.054	0.051
200	0.138	0.115	0.096	0.078	0.060	0.115	0.097	0.082	0.068	0.055	0.096	0.082	0.070	0.060	0.051	0.078	0.068	0.060	0.053	0.047	0.060	0.055	0.051	0.047	0.044
250	0.123	0.103	0.085	0.070	0.054	0.103	0.087	0.073	0.061	0.049	0.085	0.073	0.063	0.054	0.045	0.070	0.061	0.054	0.047	0.042	0.054	0.049	0.045	0.042	0.039
300	0.113	0.094	0.078	0.064	0.049	0.094	0.079	0.067	0.055	0.045	0.078	0.067	0.057	0.049	0.041	0.064	0.055	0.049	0.043	0.038	0.049	0.045	0.041	0.038	0.036
350	0.104	0.087	0.072	0.059	0.046	0.087	0.073	0.062	0.051	0.041	0.072	0.062	0.053	0.045	0.038	0.059	0.051	0.045	0.040	0.036	0.046	0.041	0.038	0.036	0.033
400	0.098	0.081	0.068	0.055	0.043	0.081	0.069	0.058	0.048	0.039	0.068	0.058	0.050	0.042	0.036	0.055	0.048	0.042	0.037	0.033	0.043	0.039	0.036	0.033	0.031
450	0.092	0.077	0.064	0.052	0.040	0.077	0.065	0.054	0.045	0.037	0.064	0.054	0.047	0.040	0.034	0.052	0.045	0.040	0.035	0.031	0.040	0.037	0.034	0.031	0.029
500	0.087	0.073	0.060	0.049	0.038	0.073	0.061	0.052	0.043	0.035	0.060	0.052	0.044	0.038	0.032	0.049	0.043	0.038	0.034	0.030	0.038	0.035	0.032	0.030	0.028

Appendix Figure A1. Temperature, salinity and sound velocity characteristics by depth and CTD cast for waypoints sampled during acoustic characterization tests near the mouth of the Columbia River, 2001. Time indicates initial instrument deployment.

Waypoint 1
CTD cast 1
1010, 22 May 2001

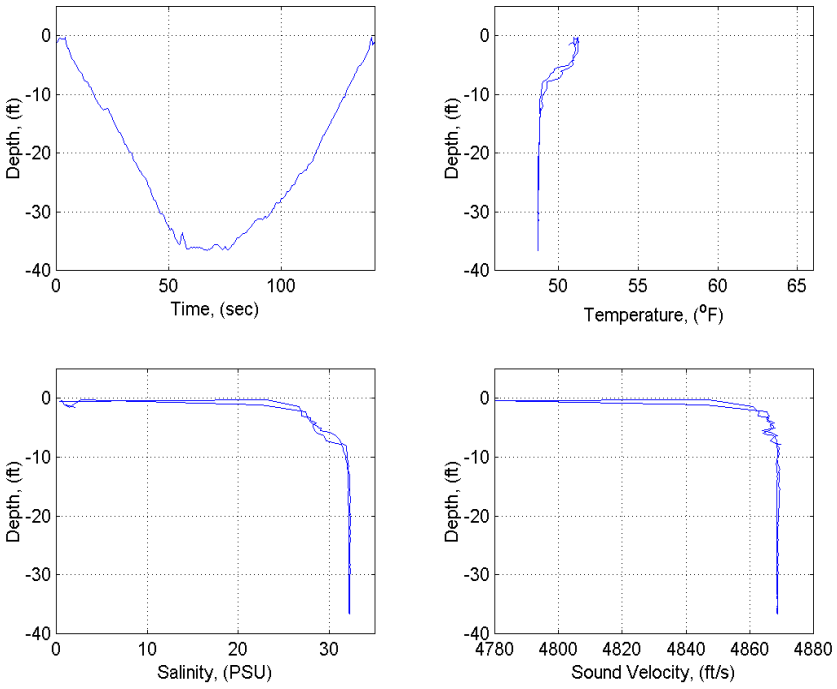


Waypoint 1
CTD cast 2
1227, 5 May 2001

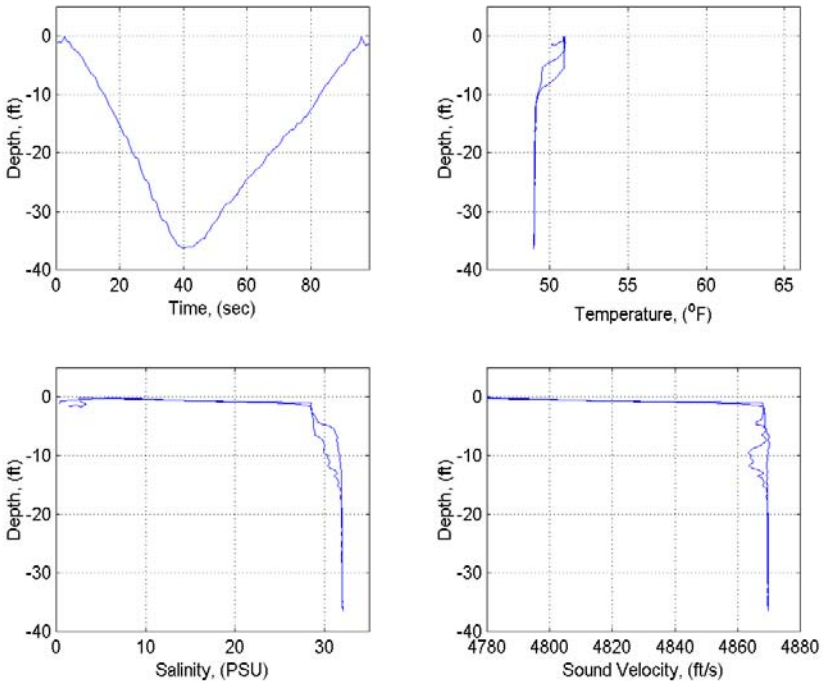


Appendix Figure A1. Continued.

Waypoint 1
CTD cast 3
1537, 5 May 2001

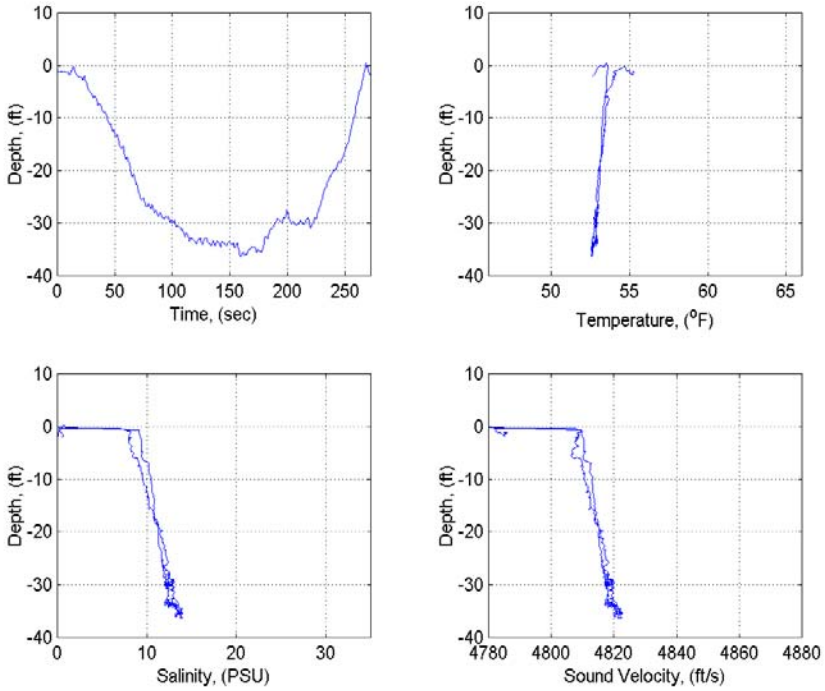


Waypoint 1
CTD cast 4
1649, 5 May 2001

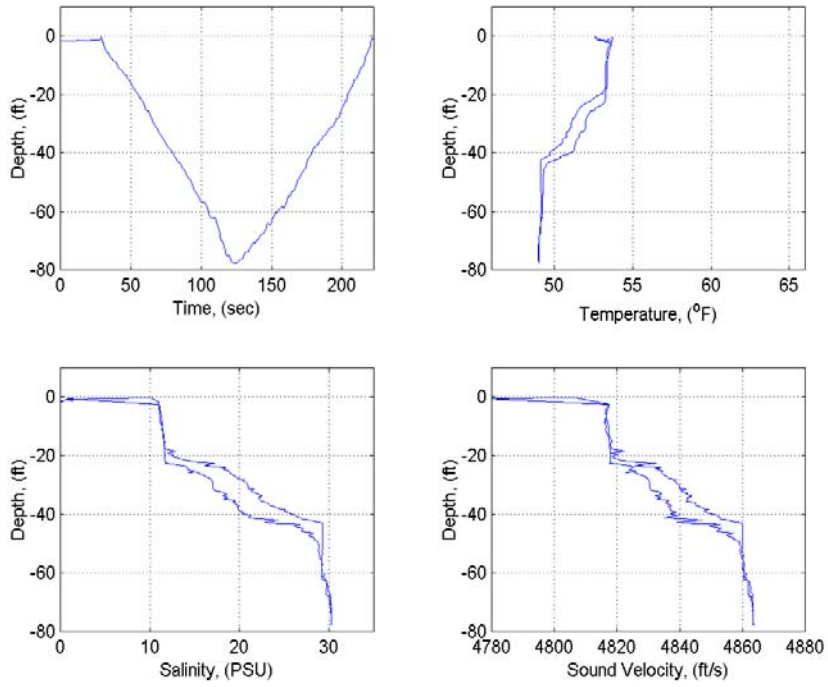


Appendix Figure A1. Continued.

Waypoint 2
CTD cast 1
0959, 5 May 2001

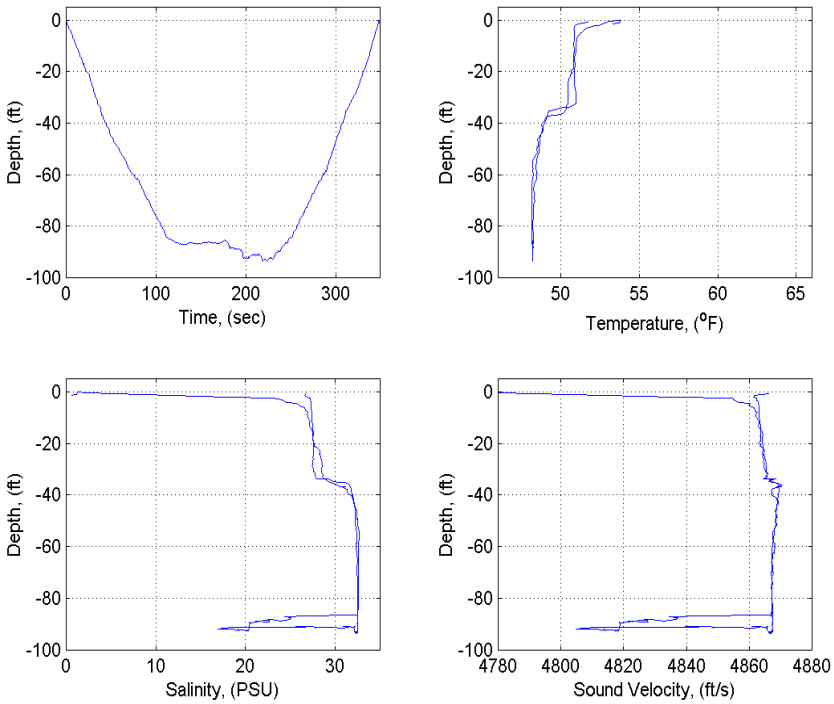


Waypoint 2
CTD cast 2
1214, 5 May 2001

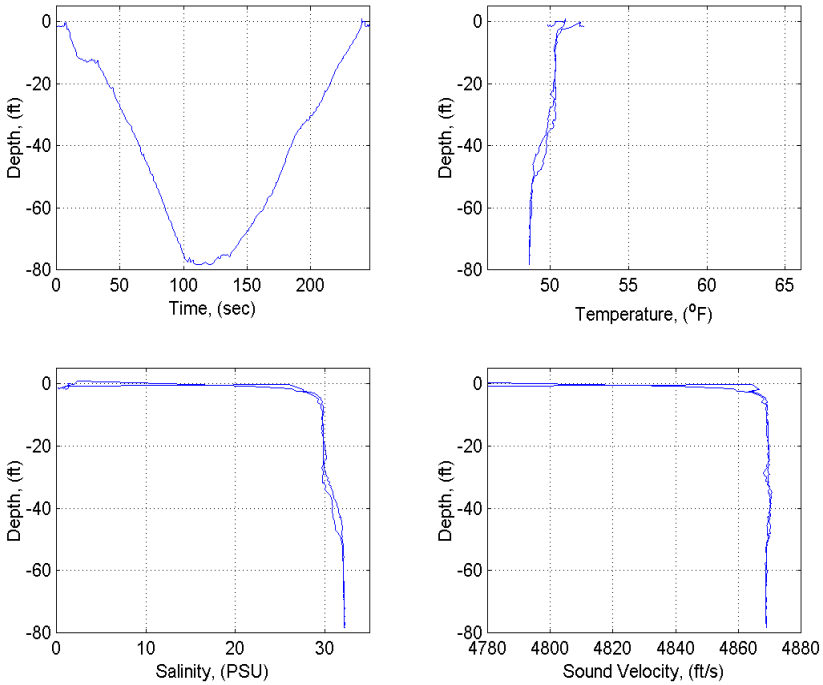


Appendix Figure A1. Continued.

Waypoint 2
CTD cast 3
1524, 5 May 2001



Waypoint 2
CTD cast 4
1644, 5 May 2001



Appendix Figure A1. Continued.

Waypoint 3
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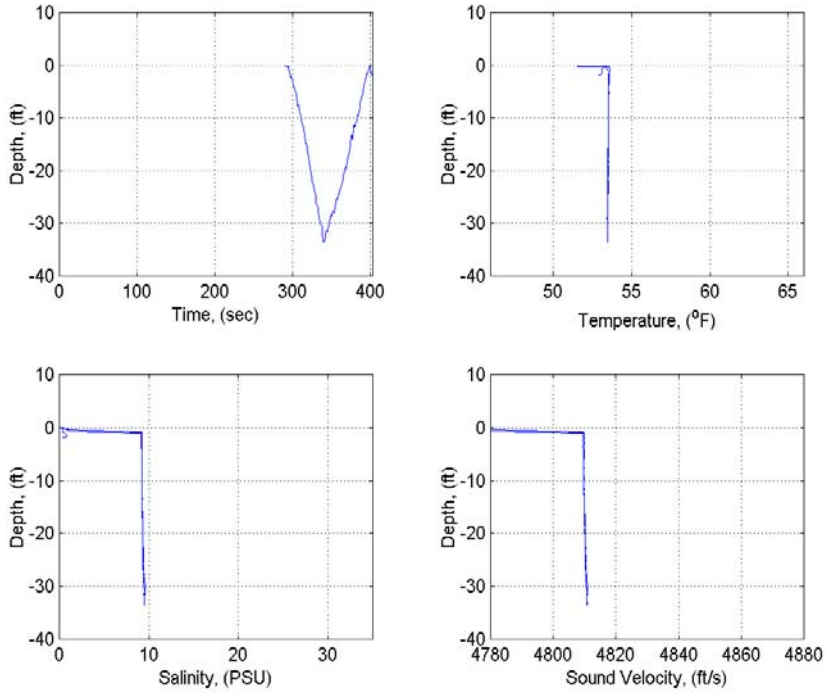
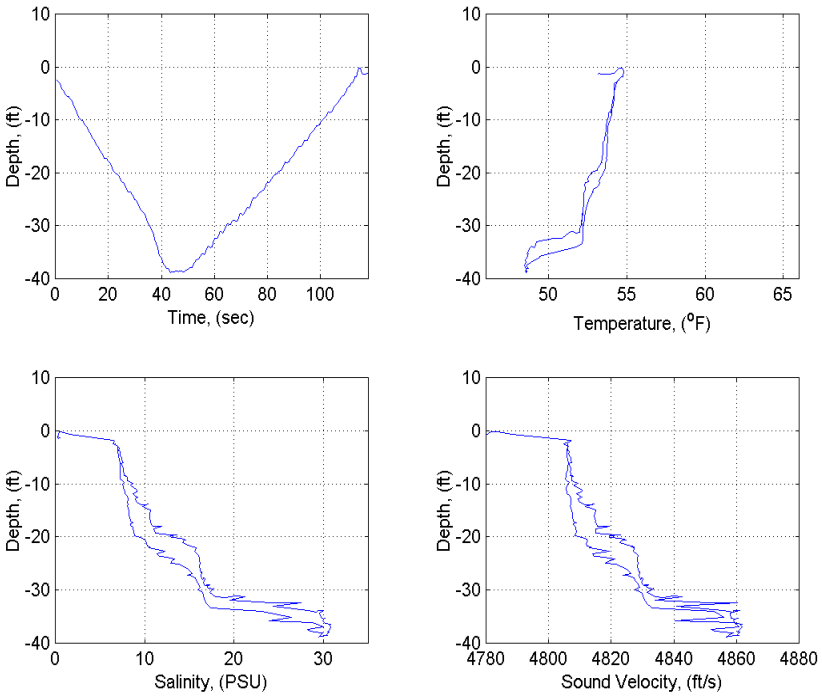
0937, 5 May 2001

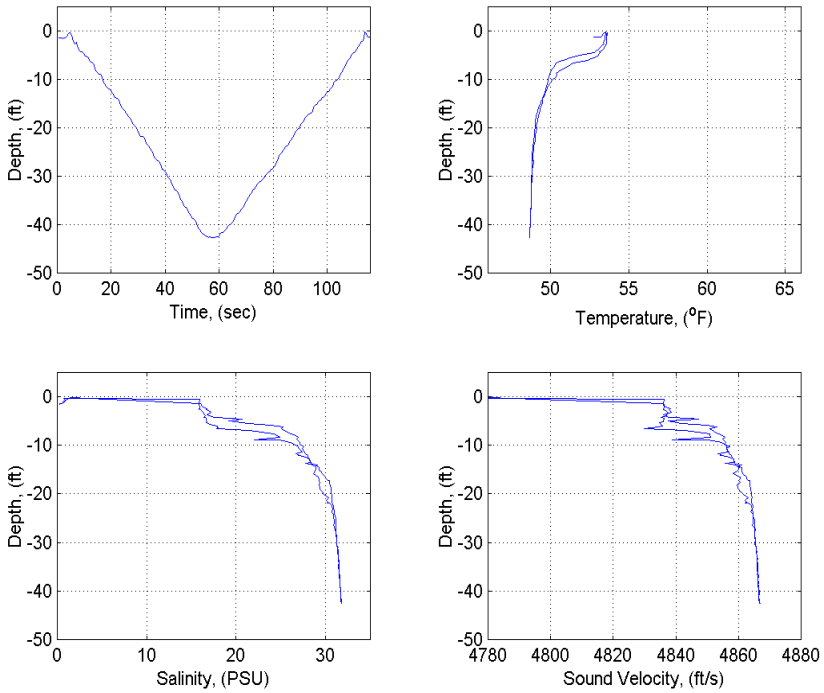


Waypoint 3
CTD cast 2
1205, 5 May 2001



Appendix Figure A1. Continued.

Waypoint 3
CTD cast 3
1517, 5 May 2001



Waypoint 3
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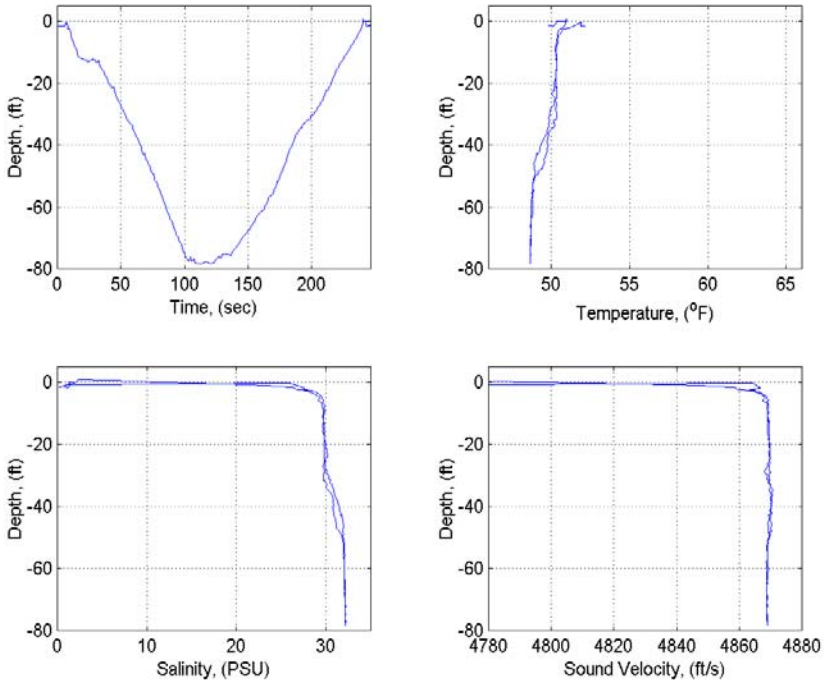
1632, 5 May 2001



Appendix Figure A1. Continued.

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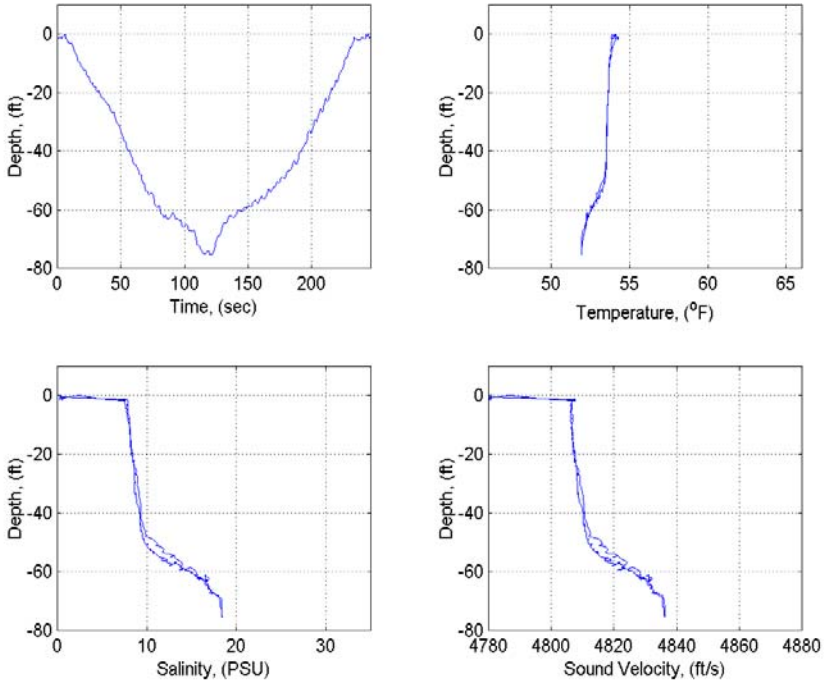
1024, 5 May 2001



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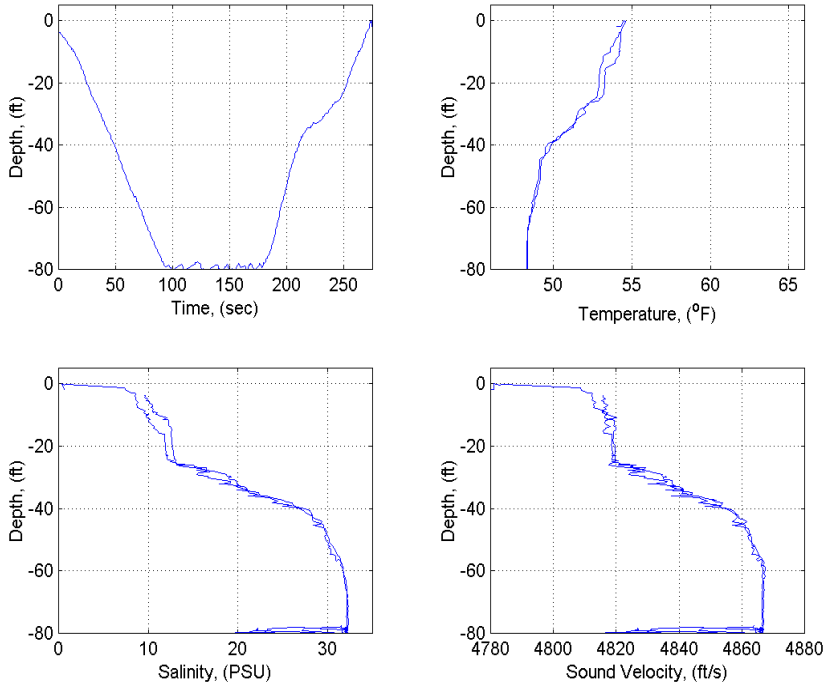
1238, 5 May 2001



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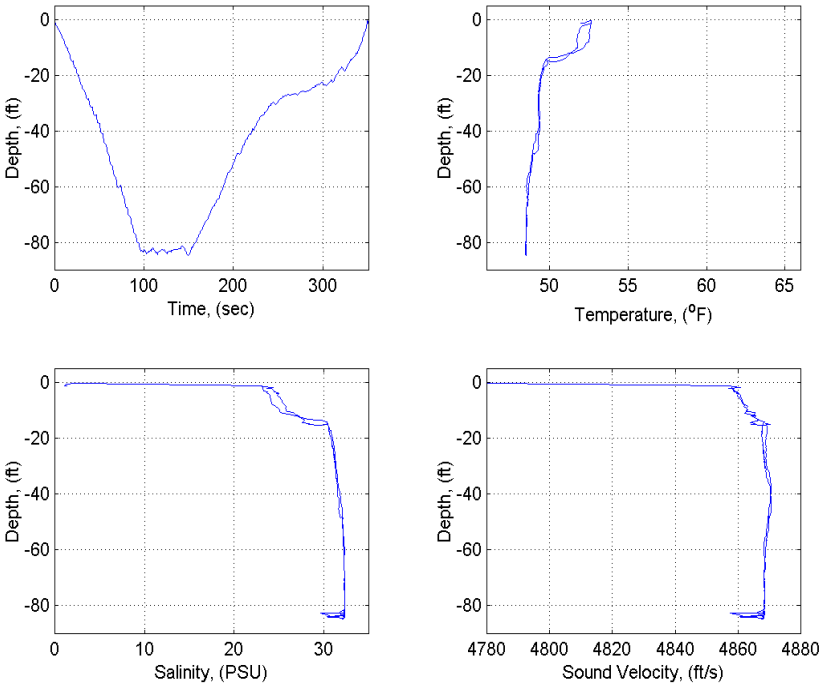

Waypoint 4
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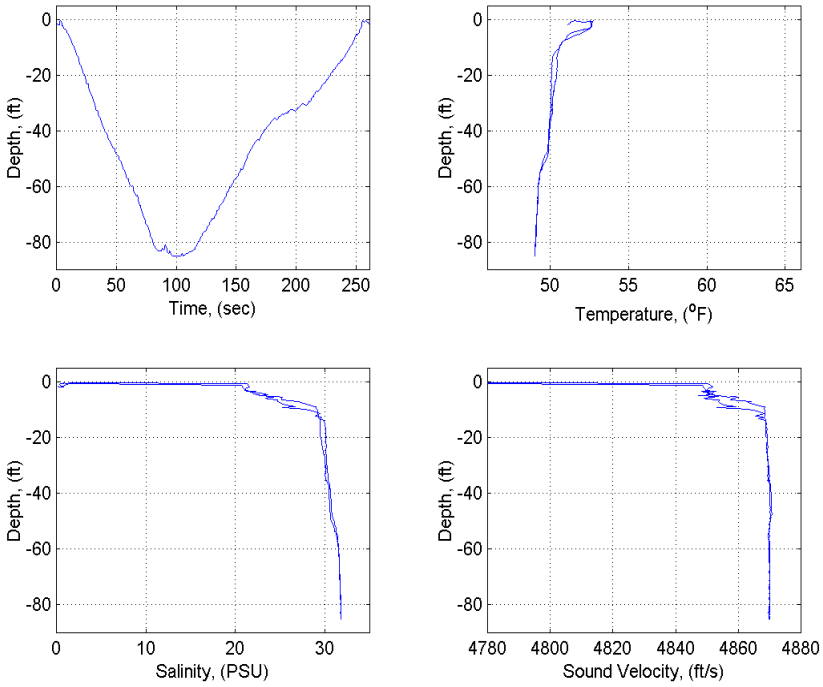
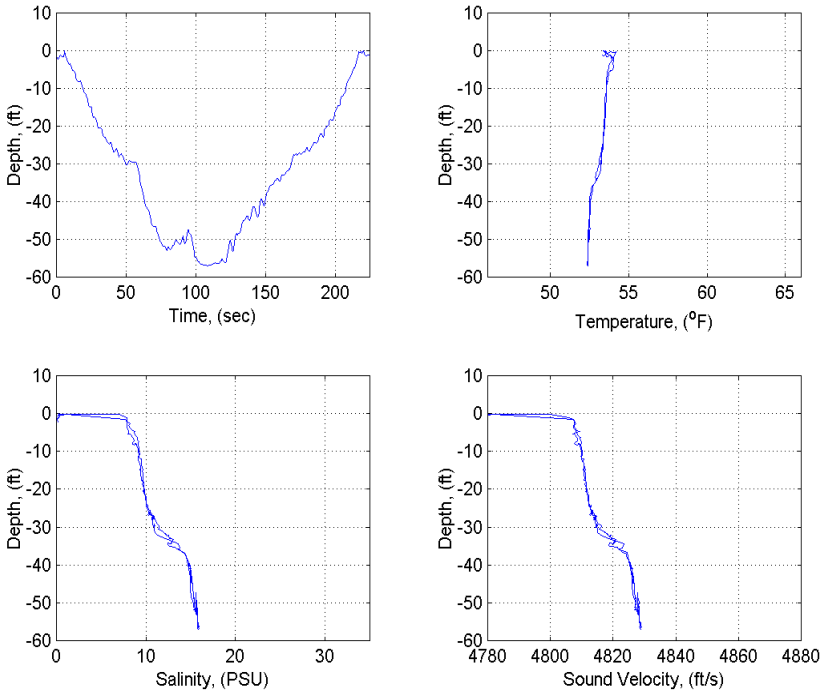
1658, 5 May 2001



Appendix Figure A1. Continued.

Waypoint 5
CTD cast 1
1032, 5 May 2001



Waypoint 5
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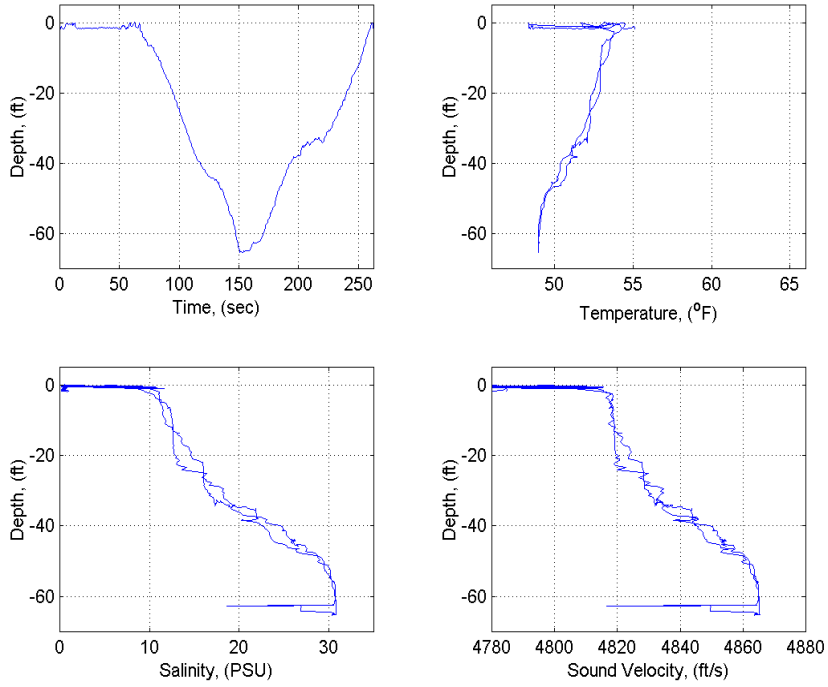
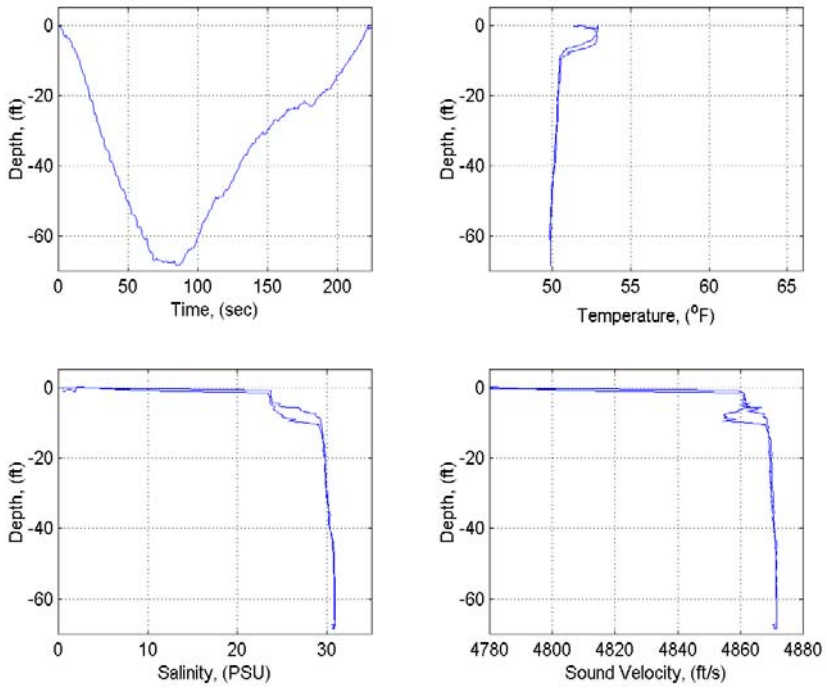
1252, 5 May 2001



Appendix Figure A1. Continued.

Waypoint 5
CTD cast 3
1601, 5 May 2001



Waypoint 5
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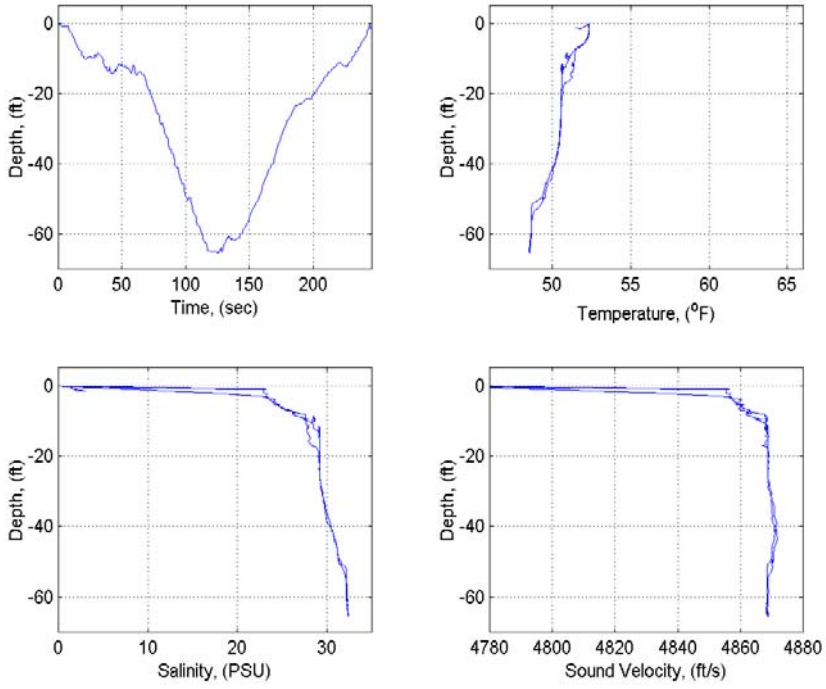
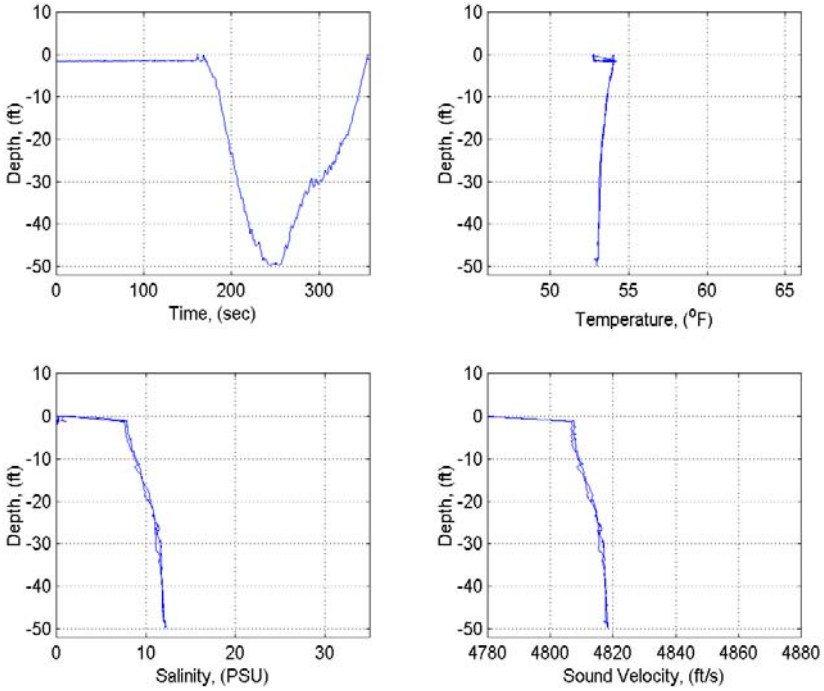
1709, 5 May 2001



Appendix Figure A1. Continued.

Waypoint 6
CTD cast 1
1043, 5 May 2001



Waypoint 6
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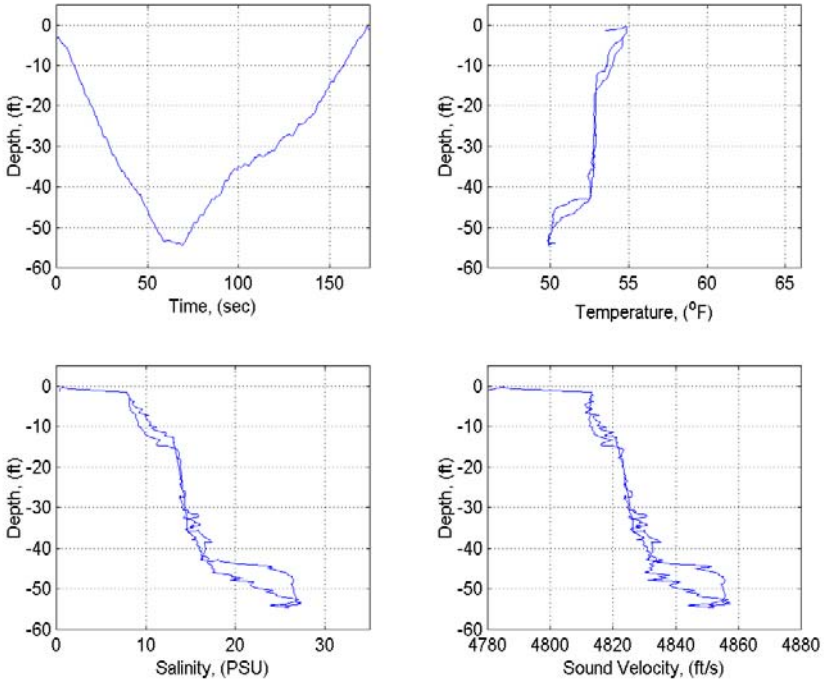
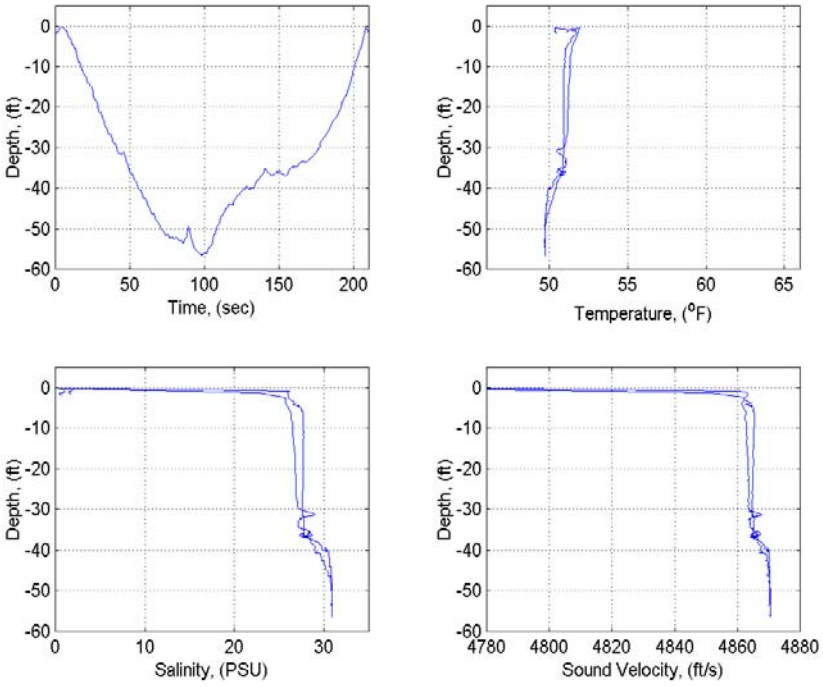
1301, 5 May 2001

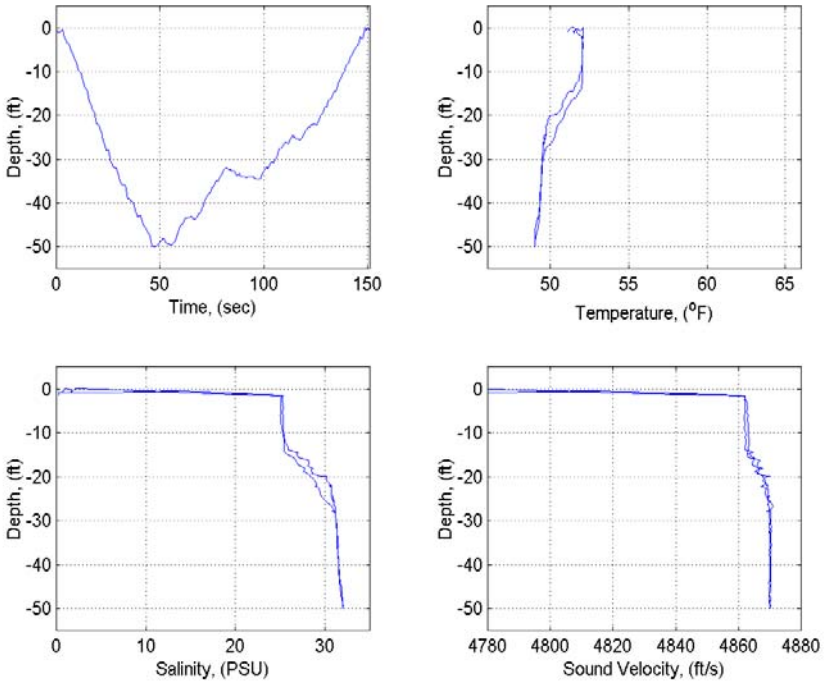


Appendix Figure A1. Continued.

Waypoint 6
CTD cast 3
1612, 5 May 2001

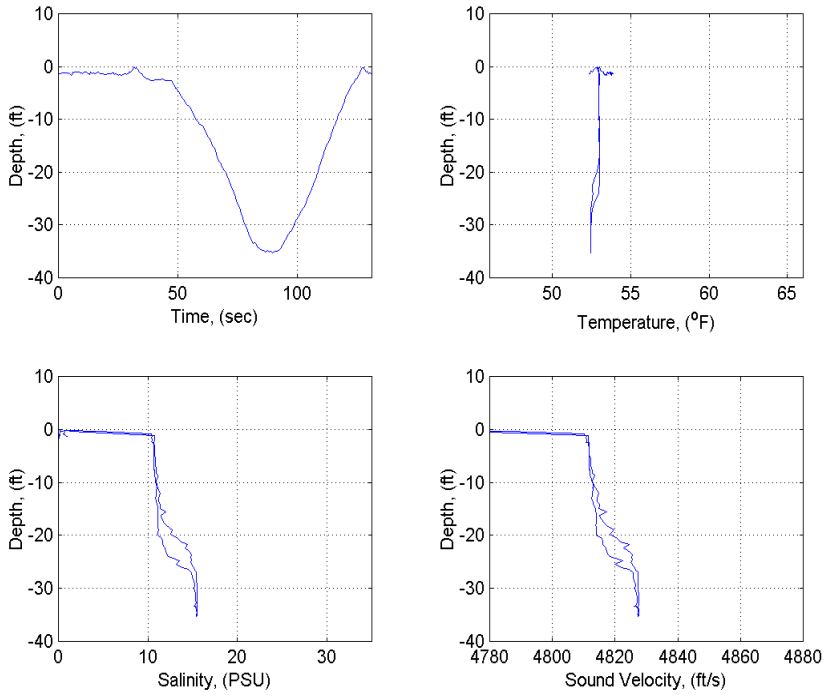


Waypoint 6
CTD cast 4
1719, 5 May 2001

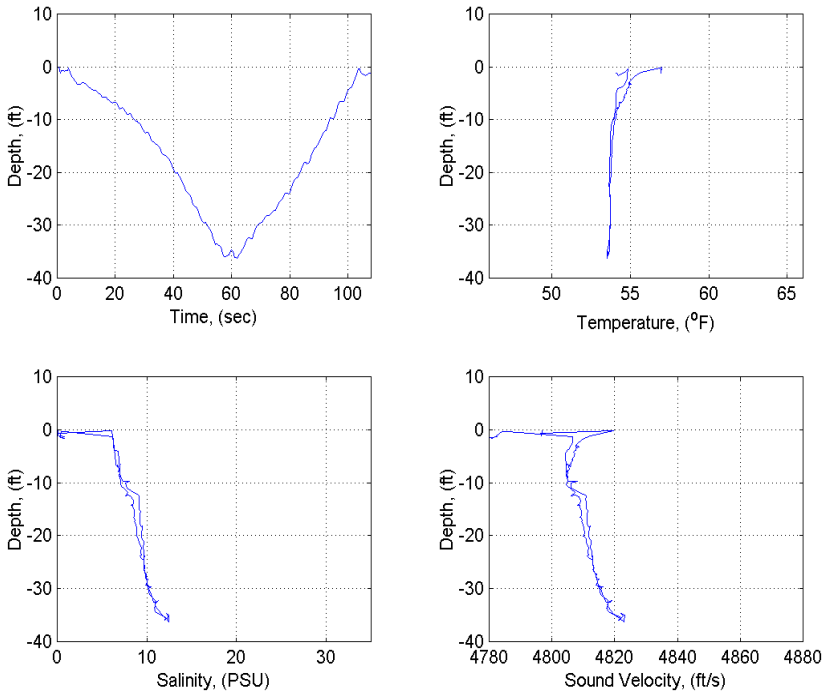


Appendix Figure A1. Continued.

Waypoint 7
CTD cast 1
0909, 5 May 2001

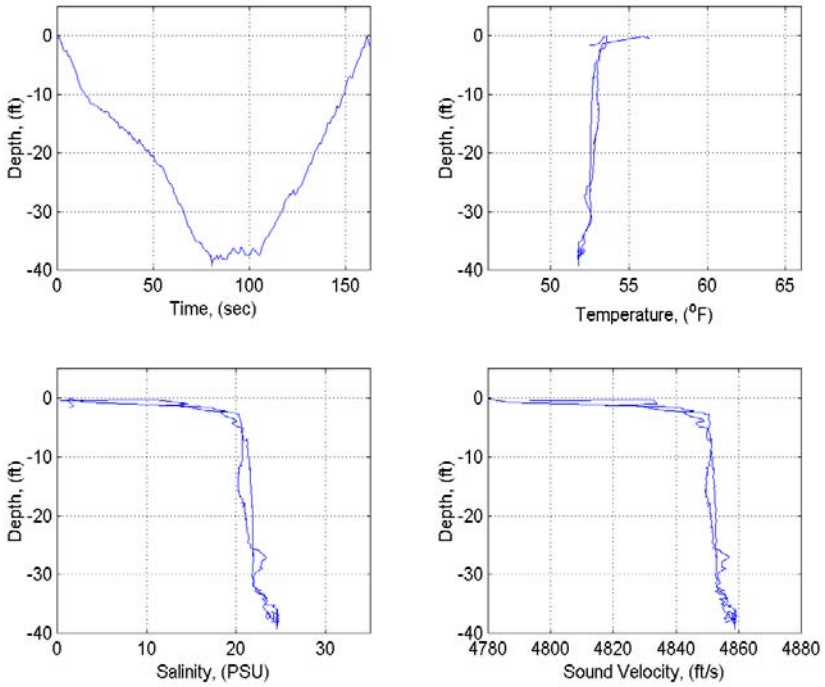


Waypoint 7
CTD cast 2
1153, 5 May 2001



Appendix Figure A1. Continued.

Waypoint 7
CTD cast 3
1507, 5 May 2001



Waypoint 7
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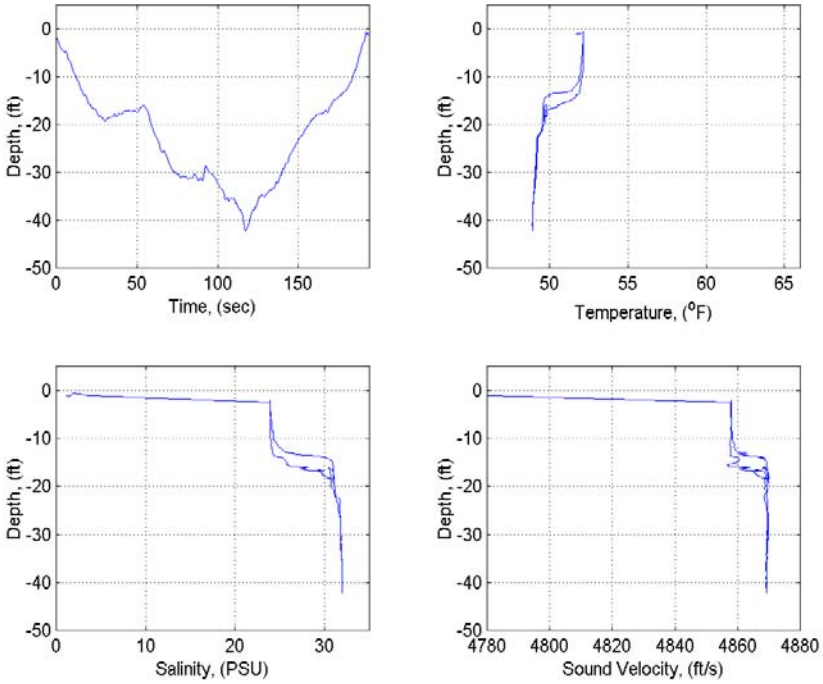
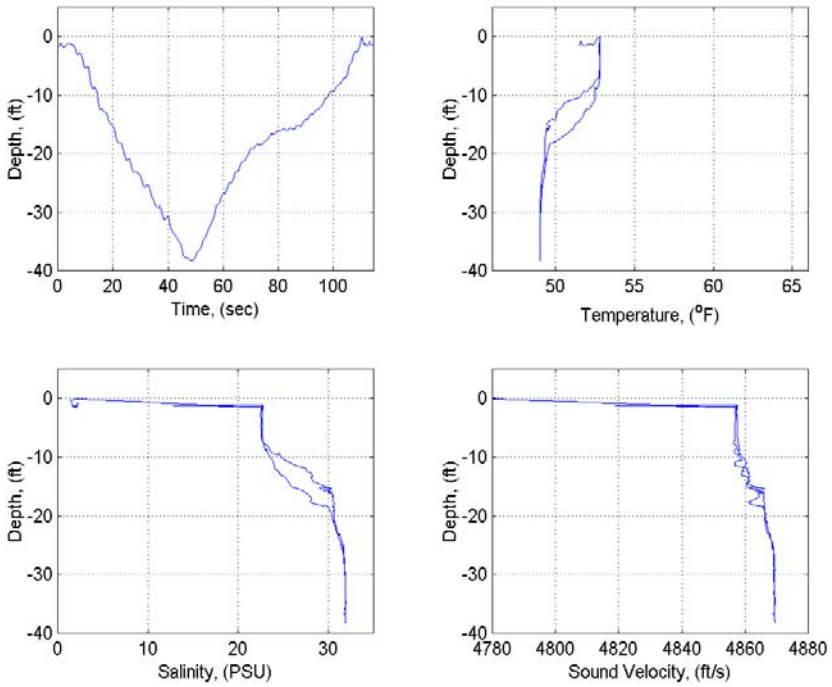
1619, 5 May 2001



Appendix Figure A1. Continued.

Waypoint 7
CTD cast 5
1728, 5 May 2001



Appendix Table A2. Parameters and parameter values used for receiver array configuration and range estimation during alternative trade study comparisons.

Parameter abbreviation	Parameter description	Values	Value units
AG	Hydrophone array gain	0.0	dB (omni directional hydrophone)
		11.4	dB (2 beam formed + omni hydrophone)
		11.4	dB (12 beam formed omni hydrophones)
DIs	Source directivity	0.0	dB
DT	Detection threshold	7.3	dB
FL	Signal loss in fish	10.0	dB
NL	Noise level	42.0	dB
P_D	Detection probabilty	0.6	dB
P_{fa}	False detection probability	0.1	dB
PG	Processing gain	12.7	dB
SL	Source level	150.0	dB
TL	Direct path propagation loss	30	dB/1000 yd @ 110 kHz
		35	dB/1000 yd @ 130 kHz
		38	dB/1000 yd @ 150 kHz
		47	dB/1000 yd @ 200 kHz
*	Heavy rain	7.5	dB
*	Receiver bandwidth	50.0	kHz

* No abbreviation

APPENDIX B

Effects of Parylene C Conformal Encapsulation Coating on Subyearling Chinook Salmon Growth and Survival over the Thirty-day Transmission Life of Surgically Implanted Microacoustic Tags

INTRODUCTION

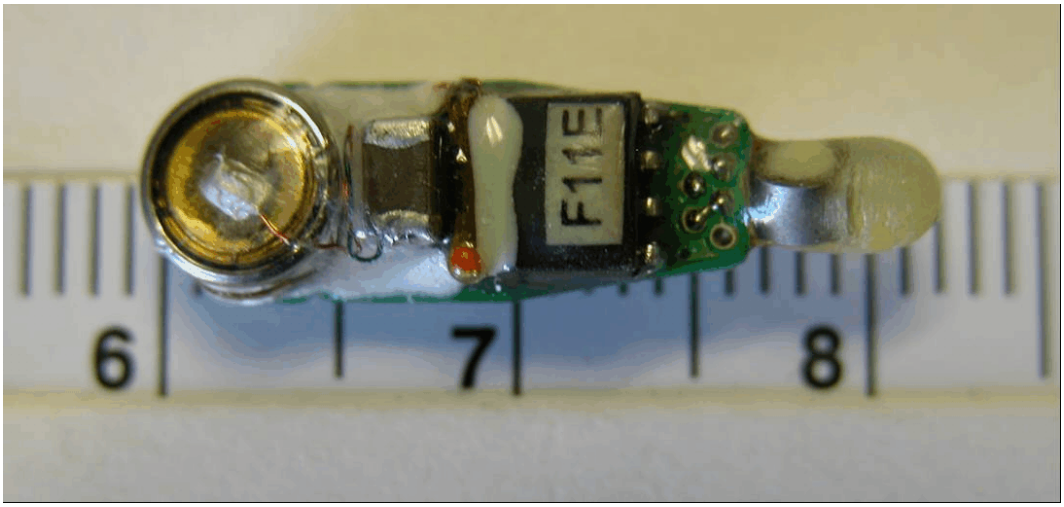
Parylene-c (para-para-xylylene) is a true conformal gas vapor deposition coating used to surface medical devices since 1967. It is pinhole free (waterproof) down to at least 0.4 micrometers, and the resulting film has excellent biocompatibility and biostability, very low thrombogenic properties, and low immune response trigger potential. Parylene has been shown to be highly resistant to the potentially damaging effects of corrosive body fluids, electrolytes, proteins, enzymes, and lipids. The film also forms an effective barrier against the passage of contaminants from a coated substrate to the body or surrounding environment.

Based on the long use in medical applications, relative ease of application and low cost of coating, and its thin film, parylene-c was selected as a potential material for encapsulating microacoustic transmitters (tags) being developed for surgical implant into juvenile salmonid smolts. Unfortunately, little information exists in professional literature concerning the use of parylene for coating fish specific implants. Prentice et al. (1998) found that some encapsulation of passive integrated transponder (PIT) tags coated with parylene occurred over a 15 d period. However, effects of longer term exposure could not be determined due to experimental complications.

NOAA Fisheries personnel proposed a series of studies to determine effects of the microacoustic tag on juvenile chinook salmon over the 30-d design life the tag, including growth and survival, susceptibility of tagged fish to predation, and post tagging behavior (buoyancy compensation, swimming behavior). In view of the size and weight reduction potential of coating an acoustic tag with parylene, this study was initiated as a first step in that process to determine whether parylene C provided a suitable barrier between the fish and tag electronics, while not triggering an adverse physiological response in the fish.

METHODS

Twenty prototype microacoustic tags measuring 5 mm thick, 6 mm wide and 22 mm long (Figure B1) were coated with parylene C for use in the external coating evaluation. The tags were complete with respect to numbers and location of components, and size of the prototype design. Due to an unanticipated capacitance problem, the tags used in this study were non-functional; however, since the goal of the test was to evaluate effects of the encapsulation material, operational tags were not required.



Appendix Figure B1. Prototype microacoustic tag used for evaluation of biological effects of the parylene C conformal encapsulation material on subyearling chinook salmon, 8 August-9 September 2002.

Hatchery reared subyearling chinook salmon were used as test fish. Test fish were assigned to one of three treatments (control, sham tagged, and tagged), with 20 fish per treatment, during handling. Test fish were anesthetized using tricaine methanesulfonate (MS-222) and subsequently weighed to the nearest gram, measured to fork length, and placed dorsal surface down on a moist foam operating pad. A continuous supply of anesthetic water was supplied while the fish were on the operating pad through a rubberized tube inserted into the mouth.

Treatments were defined by handling after the rubberized tube was inserted. For individuals in the tagged treatment, a 10 mm incision was made to the left of the-mid ventral line just anterior to the pelvic girdle.

A prototype microacoustic tag was inserted into the abdominal cavity through the incision, and the incision was closed with two interrupted sutures using 0.1 mm Polyglactin 910 absorbable suture material. Sham tagged fish received the same surgical procedure as fish in the tagged group, but no acoustic tag was inserted. Control fish remained on the operating pad for approximately 30 sec with no surgical procedure and no further handling after the tube was inserted.

Following the handling procedure period on the operating pad fish from each treatment were uniquely marked using fin clips to facilitate external identification. The tagged fish group had adipose fins clipped, a small portion of the upper caudal lobe of sham tagged fish was clipped, and controls received a small lower caudal clip. All fish were then placed into individual containers of oxygenated fresh water for observation during recovery from the anesthetic.

After recovery, fish were randomly assigned to one of four holding tanks so that each holding tank was populated by 5 animals from each treatment. Fish were held for 30 d and fed a daily ration of 2.5 mm Bio Oregon Biodiet pellets.

At the end of the 30 d evaluation period, all test fish were individually sacrificed by placing them in a 200 mg/L solution of MS-222. Immediately following extinction, each fish was weighed, measured to fork length, and data was recorded by holding tank for each treatment. A total of 49 test fish (16 tagged, 17 sham, and 16 control) were preserved in individual labeled containers containing 10 % neutral buffered formalin with tags in place and submitted for histological examination. To ensure preservation of growth structures in the abdominal cavity, heads and opercula were removed anterior to the body cavity of all fish, and the caudal portion was removed posterior to the vent. This exposed the body cavity to preservative solution influx from both ends.

RESULTS AND DISCUSSION

Individual length and weight data recorded at the start and end of the evaluation period are presented in Table B1. Recorded weights at the end of the period necessarily included tag weights for the tagged fish group. However, the mean weight of microacoustic tags used in the study (0.807 g, SE = 0.002) was subtracted from weights of tagged fish prior to statistical analysis. Mean weights and lengths of fish at the beginning and end of the evaluation period are presented by treatment in Table B2 and by holding tank in Table B3.

The evaluation period began 8 August and concluded 9 September 2002. A total of 54 fish survived the 30-d evaluation period. One tagged fish mortality was recorded during the evaluation, compared to 3 control and two sham tagged mortalities. All control fish and one of the sham tagged mortalities were from the same holding tank (Tank 4). The tagged fish mortality and remaining sham tagged fish mortality were from Tanks 2 and 3 , respectively.

Appendix Table B1. Length and weight of subyearling chinook salmon by treatment before and after a 30-d growth and survival evaluation of parylene C coating material for encapsulating microacoustic tags.

Pre-evaluation		Post-evaluation		Pre-evaluation		Post-evaluation	
Weight (g)	Length (mm)	Weight (g)	Length (mm)	Weight (g)	Length (mm)	Weight (g)	Length (mm)
Control				Sham tag			
28.0	136	45.0	159	33.5	137	44.5	153
27.7	133	44.9	155	29.3	135	41.0	154
30.9	141	39.1	148	26.4	134	39.6	152
24.7	131	41.0	150	26.4	134	40.1	151
26.1	137	31.2	137	23.0	133	35.3	154
26.2	132	47.6	161	27.7	135	46.4	157
36.3	144	45.9	162	24.1	131	48.2	159
34.2	143	44.9	158	30.8	139	48.3	159
30.2	141	59.1	168	27.9	138	37.6	149
22.1	136	27.2	136	28.8	143	41.2	148
31.5	140	62.2	164	31.2	141	36.6	155
28.3	138	33.1	145	34.2	143	56.6	164
26.3	133	35.0	146	29.2	133	31.1	144
65.4	147	39.9	150	20.9	132	52.5	167
27.4	135	43.6	158	28.6	137	38.9	157
33.9	139	43.4	159	36.8	147	47.9	162
27.8	137	53.4	155	30.6	138	39.1	150
26.2	129			31.4	144	45.7	157
25.7	134			28.0	134		
30.4	140			28.2	141		
Acoustic tag							
26.7	135	44.2	158				
35.4	145	43.3	155				
30.3	137	42.5	154				
27.9	139	46.2	148				
22.4	128	32.9	139				
28.1	137	38.9	147				
20.7	128	43.5	156				
32.5	149	34.4	144				
28.6	137	49.0	159				
23.7	131	43.5	153				
30.5	138	34.2	146				
36.5	132	48.3	161				
27.3	131	39.3	146				
25.7	139	32.5	140				
28.7	137	46.5	162				
29.9	140	44.5	156				
29.5	138	43.1	157				
25.2	130	47.9	159				
23.5	129	45.5	157				
24.3	129						

Appendix Table B2. Mean weight and length with standard errors (SE) of hatchery subyearling chinook salmon by treatment prior to tagging with acoustic tags (Initial) and at the end of a 30-d evaluation period after tagging (Final).

	Weight (g)						Length (mm)					
	Initial		Final		Difference		Initial		Final		Difference	
Treatment	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Control	29	0.8	43.2	1.7	15	1	137.3	1	153.3	1.8	16.4	0.6
Sham	28.9	0.8	42.8	1.7	14	1	137.5	1	154.5	1.7	17.1	0.6
Tagged	27.4	0.8	42	1.6	14.8	1	135.5	1	152.4	1.7	17.1	0.6

Appendix Table B3. Mean weights (g), lengths (mm), and standard errors (SE) for hatchery reared subyearling chinook salmon, by holding tank, prior to tagging with acoustic tags (Initial) and at the end of an evaluation period 30 d after tagging (Final).

	Weight (g)						Length (mm)					
	Initial		Final		Difference		Initial		Final		Difference	
Treatment	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
2	27.9	0.9	41.2	1.9	13.6	1	135.3	1	151.3	2	16.2	0.7
3	27.5	0.9	43.1	1.9	15.8	1	136.2	1	153.9	2	17.8	0.7
4	28	0.9	41.8	2.2	14.9	1	136.1	1	151.5	2.2	16	0.7
5	30.2	0.9	44.5	1.9	14.3	1	139.3	1	156.8	1.9	17.5	0.7

There was no significant difference in mean weights or lengths of test fish by treatment or by holding tank at the beginning of the evaluation period, and no significant difference in weight or length at the end of the evaluation period. Mean weight gain for all treatment groups combined was 14.6 g, (SE = 1.0), and length increase averaged 16.9 mm (SE = 0.6).

Wound healing was similar between surgery treatments. In general, the surgical incision had healed externally in most cases, though portions of the incision were not completely healed on 3 sham tagged and 2 microacoustic tagged fish. Sutures had dissolved in 50% (9) sham tagged and 58% (11) tagged individuals, and suture (needle) wound healing was complete or advanced. Suture material remained in the wounds of remaining fish, which probably contributed to incomplete healing in these individuals.

Five fish were retained for gross internal examination during the post evaluation data collection. Of these, one fish was from the control treatment, one was from the sham tagged group, and three were from the microacoustic tagged treatment. There were no abnormal internal macro structures visible in the control treatment fish. External and internal wound healing along the incision of the sham tagged fish appeared to be complete. However, the anterior suture was intact and the suture wound had not healed completely. All three tagged fish had one suture still intact, though all surgical incisions were healed. Tags in the three tagged fish were completely to partially encapsulated, with the tag free within the encapsulating tissue. Adhesions were noted in one individual between the encapsulation membrane and the air bladder and from the encapsulation membrane and body cavity wall.

Results of the histological analysis are presented elsewhere in this report.

The presence of encapsulating membrane indicates that the foreign body was recognized by the host. However, since overall growth and survival were not impaired by comparison to the control and sham tagged groups, the tag and formation of the associated encapsulating membrane did not appear to hinder development over the 30-d evaluation period. This, and the absence of gross adhesions to the tag itself, would suggest that the parylene C coating on the tag formed an inert barrier encapsulating the microacoustic tag. The conclusion from this portion of the study is that parylene C is a biologically safe material for use in coating microacoustic transmitters for use in salmonid fish, at least over the 30-d design life of the transmitter.

One area of concern arising from this work involves the persistence of sutures over the study period. In addition to delayed healing through mechanical aggravation, we observed that the trailing suture material furnished substrate for growth of what appeared to be a filamentous fungus, particularly on longer tails. This may contribute to a study-induced survival reduction by presenting a disease entry point in free-roaming fish. One method of overcoming this potential would be to clip the suture ends as closely as possible on closing. Also, since suture types have different persistence properties (Aderrioitis and Sandor 1999, Fihlo et al. 2002), another suture material or filament diameter may have more appropriate deterioration characteristics.

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APPENDIX C

Parylene-Coated Acoustic Tag Treatment Study

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Report of research for

Fish Ecology Division
Northwest Fisheries Science Center
National Marine Fisheries Service
National Oceanic and Atmospheric Administration
2725 Montlake Boulevard East
Seattle WA 98112-2097

November 2002

INTRODUCTION

The aim of this parylene coated acoustic tagging study was to evaluate fish response to a new tagging system, clinically and pathologically, 30-31 days post-exposure. Gross changes and histologic response were recorded to evaluate the healing process and internal effects of intra-abdominal tagging on the visceral organs (adhesions, inflammation, bleeding, etc.).

METHODS

Fish

A total of 49 juvenile Chinook fish were included in this study and were divided into three groups: first, 16 fish that were intra-abdominally tagged (tag group); second, 17 fish were surgically manipulated in a similar manner to the previous group without tagging (sham group); third, 16 fish were kept as control fish (control group). All fish were clinically examined before, during and after the surgical manipulation. At the end of the study all fish were humanely euthanised and submitted in 10 % neutral buffered formalin for pathologic examination where gross and histologic lesions were recorded and photographed. The fish were trimmed and processed in the standard procedure for histological.

Gross Examination

A thorough macroscopic examination was carried out of every fish to evaluate the surgical site for the healing process, thickness of body wall through and surrounding the surgical site, and visual inspection of the abdomen to detect any internal lesions e.g. adhesions between the viscera grossly. Less than 0.5 cm thick slice through the whole fish at the level of the surgical wound was obtained with the corresponding internal organs, if adhered to the body wall, from every fish including the control fish.

RESULTS

Gross Findings

No remarkable adhesions were found around any of the tags in the tag group with the tag being easily extracted. Minimal to moderate adhesions were found between the viscera and the body wall or between different viscera in both the tag and a very few fish in the sham groups. The location of the surgical wound varied moderately between the fish in both the tag and sham groups. In many fish, the wound was 0.4-0.7 mm cranial to the base of the pelvic fins. In several fish, the site was either more proximal or more distal to the average location. In three fish, the location of the surgical site was just at the base of the pelvic fins. The thickness of the body wall ranged from 2-5 mm in both the control and sham groups with the average being decreased in the sham group. The thickness in the tag group was the most variable with fish no. 9 having the thinnest and fish no. 16, 23, and 40 having body wall thickness ranging from 1-2 mm. Tag placement within the peritoneal cavity was consistent for all fish with the tag being in the caudal abdomen near the spleen.

Histopathology

The body wall and the abdominal organs corresponding to the surgical incision in all fish were histologically examined. The healing process was evaluated by comparing the following structures between the different fish groups: Epidermis was evaluated for the thickness of epidermis overlying the surgical wound, content of mucous cells, integrity of basement membrane underlying the healed epidermis; hypodermis (dermis) was evaluated for the amount of fibrosis and presence of inflammation; musculature was evaluated for the amount of fibrosis (myofibrosis), inflammation and size changes of muscle fibers (atrophy or hypertrophy); and finally the peritoneum was evaluated for the thickness, inflammation and/or adhesions between the abdominal wall and visceral organs on one side and between the visceral organs to one another on the other side.

Appendix Table C1. Gross findings in all fish groups including the tag codes.

Fish No.	Group	Thickness of body wall (mm)	Incision	Sutures	Remarkable gross findings	Tag No.
			Control group			
5	Control	4	No	No	Overall small fish	
6	Control	4	No	No	No	
11	Control	4	No	No	No	
12	Control	4	No	No	No	
15	Control	4	No	No	No	
17	Control	4	No	No	No	
19	Control	3-4	No	No	No	
26	Control	4	No	No	Large fish	
28	Control	3-4	No	No	Smaller than average	
31	Control	4-5	No	No	Large testicle in a very large fish	
38	Control	3-4	No	No	Smaller than average	
42	Control	4	No	No	No	
45	Control	4	No	No	No	
47	Control	2-3	No	No	No	
52	Control	4	No	No	No	
54	Control	4	No	No	Large testicle and the fish was overall larger than average	
			Sham group			
1	Sham	3	healed	Yes	No	
4	Sham	4	healed	No	No	
8	Sham	4	healed	No	No	
10	Sham	2-3	healed	Yes	No	
18	Sham	4-5	healed	No	No	
20	Sham	2-3	healed	Yes	No	

Appendix Table C1. Continued.

Fish No.	Group	Thickness of body wall (mm)	Incision	Sutures	Remarkable gross findings	Tag No.
			Sham group (continued)			
25	Sham	3-4	healed	Yes	No	
27	Sham	4	healed	No	No	
29	Sham	2	healed	No	No	
32	Sham	2	healed	Yes	No	
34	Sham	4	healed	Yes	No	
39	Sham	3	healed	No	No	
41	Sham	4	healed	No	No	
43	Sham	3	healed	Yes	No	
44	Sham	2	healed	No	No	
49	Sham	2	Healed	Yes	No	
50	Sham	3	healed	No	No	
			Tag group			
2	Tag	2-3	healed	No	No	F0FF
3	Tag	3	healed	No	No	F115
7	Tag	2	healed	No	Small fish	F122
9	Tag	1	healed	No	*	F119
16	Tag	1-2	Healed	Yes	No	F12D
21	Tag	3-4	healed	Yes	No	F0FB
22	Tag	2-3	healed	Yes	No	F0F4
23	Tag	1-2	healed	Yes	No	F102
30	Tag	5	healed	Yes	No	F112
33	Tag	3	healed	Yes	No	F0F6
35	Tag	3	healed	Yes	No	F10F
36	Tag	3	healed	No	No	F111
40	Tag	1-2	healed	No	No	F10A
46	Tag	2	healed	No	No	F123
48	Tag	2	Healed	No	No	F11E
51	Tag	3-4	healed	Yes	No	F0F5

* A white mass occupy most of the abdomen and displace the viscera cranially

Epidermis

The average epidermal thickness in normal (control) fish and in the epidermis of other sites than the surgical site ranged from 5-10 cell thick. The thickness was graded as (+) if it increased to 15-20 cell thick and (++) if it exceeds 20 cell thick. Duplication of mucous cells was roughly estimated by counting how many mucous cells are present per 400 × microscopic field in both normal epidermis and healed epidermis. The basement membrane integrity was evaluated after special staining by periodic acid Schiff (PAS).

Dermis

The amount of fibrosis in the hypodermis was roughly calibrated in the surgically manipulated fish in comparison with the normal control fish, and special staining (Masson's trichrome) was applied to several fish to highlight the connective tissue fibers. Inflammation if present is indicated by (+) or (-) when absent.

Musculature

If less than 25% of certain muscle groups were infiltrated and/or replaced by fibrous connective tissue, it was graded as (+). Twenty-five to 50% involvement was graded as (++). If more than 50 % of the muscle group was replaced by fibrous connective tissue, it was graded as (+++).

Peritoneum

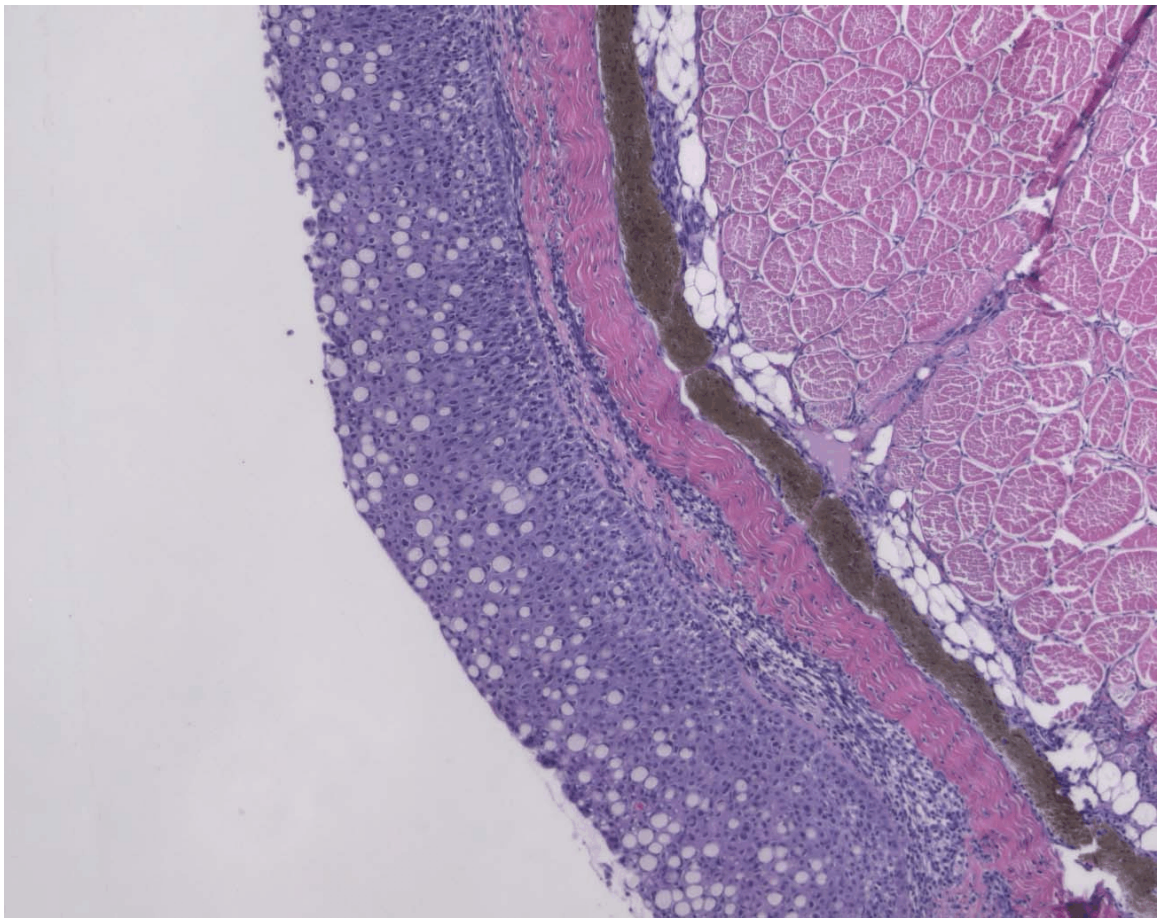
The thickness of the peritoneum lining the abdominal wall was measured and compared between different fish groups. If the peritoneum lining the surgical site was doubled in thickness, a grade of (+) was given to the fibrous change. If more than double the thickness, a grade of (++) was given to the redundant collagenous fibrous tissue, and if the thickness involved both the wall and resulted in adhesion between the wall and the viscera or between a viscous and one another, a grade (+++) was given. Special staining (acid fast) was applied if there was granulomatous inflammation and PAS if there was foreign body suspected in the lesion. A summary of histologic findings of different fish groups is given in Appendix Table C2.

Appendix Table C2. Summary of histologic findings for different fish groups. Abbreviations: N--Normal, ±--Inconclusive to slightly increased, A--Atrophy, H--Hypertrophy.

	EPIDERMIS			DERMIS			PERITONEUM	
Fish No.	Epidermal thickness	Duplication of mucous cells	Integrity of basement membrane	Thickness of the dermis	Inflammation	MUSCLE	Thickness	Inflammation
				Control group				
5	N	NO	Intact	NO	NO	N	N	NO
6	N	NO	"	NO	NO	N	N	NO
11	N	NO	"	NO	NO	N	N	NO
12	N	NO	"	NO	NO	N	N	NO
15	N	NO	"	NO	NO	N	N	NO
17	N	NO	"	NO	NO	N	N	NO
19	N	NO	"	NO	NO	N	N	NO
26	N	NO	"	NO	NO	N	N	NO
28	N	NO	"	NO	NO	N	N	NO
31	N	NO	"	NO	NO	N	N	NO
38	N	NO	"	NO	NO	N	N	NO
42	N	NO	"	NO	NO	N	N	NO
45	N	NO	"	NO	NO	N	N	NO
47	N	NO	"	NO	NO	N	N	NO
52	N	NO	"	NO	NO	N	N	NO
54	N	NO	"	NO	NO	N	N	NO
				Tag group				
2	(+)	(++)	±	(++)	(+)	(+)	(+)	(+)
3	(+)	(++)	Intact	N	(-)	(+)	(+)	(-)
7	±	(+)	"	N	(-)	A	N	(-)
9	±	(-)	"	±	(-)	(++)	(+)	(-)
16	±	(+)	±	N	(-)	(+)	(+)	(-)
21	N	(+)	(-)	(+)	(+)	(+)	(+++)	(+)
22	(+)	(+)	(-)	(+)	(+)	(+)A	(+++)	(+)
23	(+)	(+)	Intact	N	(-)	(+)A	(+)	(-)
30	(+)	(+)	(-)	(+)	(+)	(+)H	(+++)	(+)
33	(+)	(+)	(-)	(++)	(+)	(++)	(+)	(-)
35	±	(+)	Intact	N	(-)	(++)	(+++)	(+++)
36	±	(+)	(-)	(++)	(++)	(+)	(+++)	(+++)
40	(+)	(+)	Intact	N	(-)	(+)A	(+)	(-)
46	±	(+)	Intact	N	(-)	(+)	(+)	(-)
48	(++)	(++)	±	(++)	(+)	(++)	(++)	(-)
51	(+)	(+)	(-)	(++)	(+)	(++)	(+)	(-)

Appendix Table C2. Continued.

	EPIDERMIS			DERMIS			PERITONEUM	
Fish No.	Epidermal thickness	Duplication of mucous cells	Integrity of basement membrane	Thickness of the dermis	Inflammation	MUSCLE	Thickness	Inflammation
				Sham group				
1	(++)	(++)	Intact	(+++)	(+)	(+)A	(+)	(-)
4	±	(+)	"	N	(-)	N	(+)	(-)
8	?	?	?	?	?	N	N	(-)
10	(+)	(+)	Intact	(+)	(-)	±	N	(-)
18	(+)	±	"	(+)	(+)	±	N	(-)
20	(+)	(+)	(-)	(++)	(++)	(+++)	(+)	(-)
25	(++)	(++)	(-)	(+++)	(+++)	(+++)A	(+)	(-)
27	(+)	(+)	Intact	(+)	(+)	(+)	N	(-)
29	(+)	(++)	"	N	(-)	(+)	N	(-)
32	(+)	(+)	(-)	(+)	±	(+)A	N	(-)
34	(+)	(+)	(-)	(+)	(+)	(+)	(++)	(-)
39	(+)	(+)	Intact	N	(-)	N	N	(-)
41	(+)	(+)	(-)	(+)	(+)	(+)	N	(-)
43	(+)	(+)	±	(+++)	(++)	(+)H	(+)	(-)
44	(+)	(+)	(-)	(+)	(+)	(+)A	(+++)	(+)
49	(+)	(+)	Intact	(+)	(+)	(+)	N	(-)
50	(+)	(+)	Intact	±	(-)	A	N	(-)



Appendix Figure C. Photograph showing the normal thickness of the epidermis and the normal mucous cell content.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

1. Both tag and sham groups were associated with epidermal and dermal changes with negligible differences between the two groups.

2. Tag placement within the body cavity tends to elicit more inflammation (of the foreign body type) with the resulting peritoneal adhesions. However, one fish in the sham group had somewhat similar adhesions.

3. The histologic changes seemed ***not to be enough to cause clinical derangements to the fish*** except for slower growth or thinner body wall.

4. Most of the tissue reactions found in tag and sham groups were interpreted to be a result of microtrauma to the skin and peritoneum.

5. Surgical wounds of some fish were infected, which resulted in more inflammation in the dermis and peritoneal cavity.

Recommendations for Future Work

1. Standardize the location of the surgical slit, best being ventral and close to the base of the pelvic fins as it was observed to elicit less inflammatory reaction and better healing.

2. Avoid slitting the fish from the side.

3. Revise the efficiency of aseptic surgical technique and sterilization of the tags.