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Evaluation of a flat-plate PIT tag interrogation system at Bonneville Dam

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Abstract

In the spring of 1996 and 1997, a prototype 400 kHz flat-plate (pass-by) passive integrated transponder tag interrogation (PIT tag) system was installed at the terminus of the downstream migrant (DSM) channel of the Bonneville Dam First Powerhouse, located on the Columbia River. The system was designed to interrogate previously PIT tagged juvenile salmonids migrating down the Columbia River without interfering with the traditional subsampling of fish passing through the facility. In addition, the design enables fish of virtually any size, and debris, to pass over the system's antennas without the port restrictions imposed by traditional pass-through PIT tag interrogation systems. We describe the fish facility in addition to the flat-plate system and its operation. The system tag reading efficiency was evaluated during 1996 and 1997 using a direct method based on the release of known numbers of tagged test fish and an indirect statistical procedure based on tagged run-at-large fish. The results showed that PIT tag reading efficiency during both years using the direct method averaged 97%, while that using the statistical procedure averaged 99% for the dual multiplexed antenna array. During the 1996 and 1997 field seasons 4371 and 14733 fish, respectively, were recorded. Daily system functionality was monitored using stick tests (i.e., the passing of PIT tagged sticks across the antenna array). © 1998 Elsevier Science B.V. All rights reserved.

Keywords: Flat-plate; PIT tag; Passive integrated transponder; Interrogation; Columbia River; Salmon; Radio frequency identification; RFID

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1. Introduction

Plans for the construction and implementation of improved juvenile fish collection and sampling facilities at the Bonneville Dam First and Second Powerhouses located on the Columbia River are being prepared by the US Army Corps of Engineers (COE). These new facilities, scheduled for completion in 1999–2000, include provisions for improved fish passage and the interrogation of all fish passing through the facility for passive integrated transponder (PIT) tags. In the interim, however, there is an immediate need for information on the fish passing the existing facility to, in part, address the issues expressed in both the Biological Opinion for the operation of the Federal Columbia River Power System and the proposed Snake River Recovery Plan.

PIT tags are a 12 mm long \times 2.1 mm diameter, glass encapsulated electronic transponder that can be coded with one of nearly 34 billion unique codes. The tags are injected into the body cavity of the fish and can remain with the fish through its life cycle. The tags are electronically detected and decoded in situ, eliminating the need to anesthetize, handle, restrain or sacrifice the fish during data retrieval. PIT tag interrogation facilities using special fish bypass structures have been installed at four of the eight Federal dams in the Columbia River Basin (CRB), but have not been built at the Bonneville Dam. The need to collect PIT tag data at the Bonneville Dam was partially addressed in the spring of 1996 by the installation of a prototype 400 kHz flat-plate (pass-by) PIT tag interrogation system at the terminus of the downstream migrant (DSM) channel of the dam's first powerhouse. This system differs in a number of ways from the traditional pass-through PIT tag interrogation system traditionally used in the CRB. This paper describes the system and its performance.

2. Materials and methods

To protect juvenile fish from the turbines at the Bonneville Dam First Powerhouse, traveling screens are deployed within the turbine intakes to divert the fish into safe passage areas that lead to a DSM collection channel within the powerhouse (Farr, 1974; Gessel et al., 1991; Monk et al., 1993). At the terminus of the DSM channel, fish enter a downwell and pipe system that directs them to the river below the powerhouse. In 1984, provisions were made to sample the fish entering the downwell for body condition and species composition. Samples were collected using a retractable sample box suspended within the downwell. The sampling mechanism and procedures used prior to the installation of the flat-plate PIT tag interrogation system are described by Gessel et al. (1985) and Martinson et al. (1996).

In early spring 1996, the existing sample box was removed and replaced with a unit that could accommodate a flat-plate PIT tag interrogation antenna array without affecting the traditional subsample quality or collection methods (Fig. 1). The new sampling box was constructed mostly of polyvinyl chloride (PVC) and

fiberglass structural members to reduce the potential of metal interfering with the magnetic field used for detection of PIT tags.

The flat-plate PIT tag interrogation system has two major component groups. The interrogation array consists of one upstream and one downstream antenna. Electronic equipment energizes the interrogation antennas and processes the tag codes. The antenna array was located in a movable carriage attached to the top of the juvenile fish sampling box (Fig. 1). The system electronics were located in an instrument rack near the DSM channel, about 18 m upstream from the antenna housings. Electrical power was supplied via an isolation transformer. Cabling between the electronic components and the antenna array was tensioned and passed through pulley blocks that allowed unrestricted positioning (4.7 m vertical movement) of the sampling box and the antenna array within the downwell.

A dewatering screen with an attached screen cleaner was installed to bridge the gap between the DSM channel and the flat-plate antenna array/sample box assembly (Fig. 1). The dewatering screen was positioned for use with pneumatic pistons. Under normal operating conditions, the dewatering screen was positioned

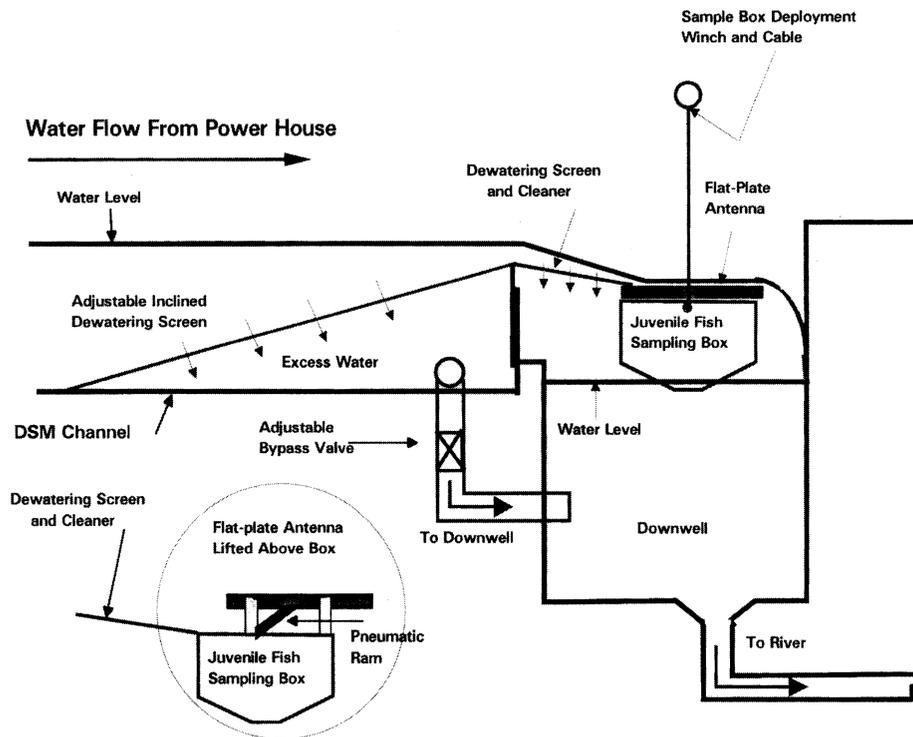


Fig. 1. Diagram of the juvenile fish sampling facility and flat-plate antenna array, shown in a side view, within the DSM of the Bonneville Dam First Powerhouse. The main diagram shows the flat-plate antenna array lowered for PIT tag detection. The insert shows the antenna array raised for juvenile fish sampling.

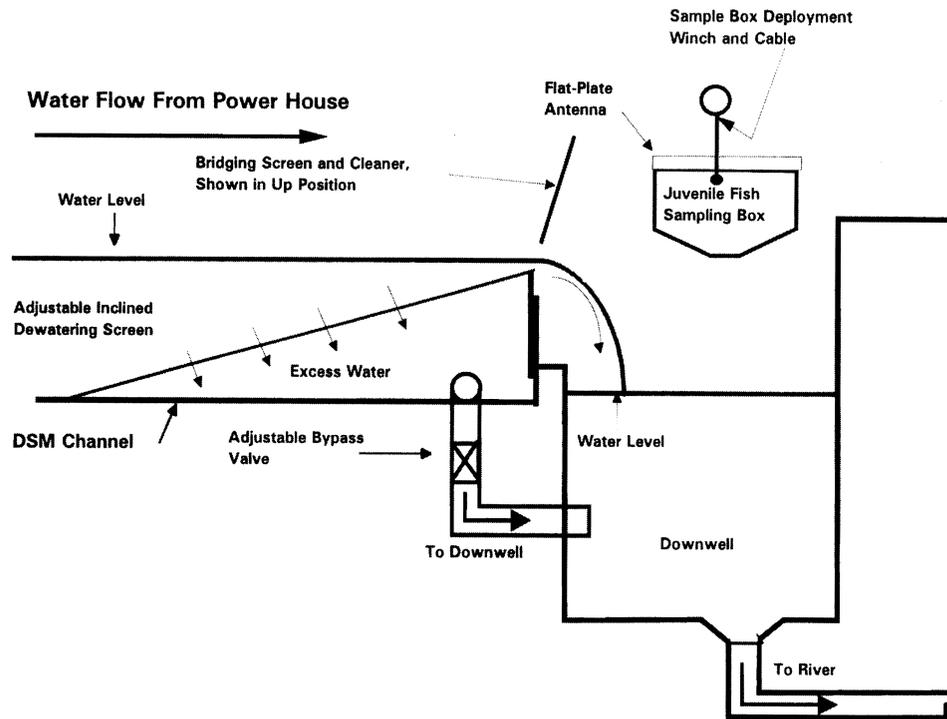


Fig. 2. Diagram of the juvenile fish sampling facility and flat-plate antenna array, shown in a side view, within the DSM channel of Bonneville Dam First Powerhouse. The juvenile fish sampling box is shown in the raised (sample retrieval) position, and the small bridging screen is in the retracted position. Fish passing through the DSM channel will pass from the crest of the inclined screen directly into the downwell.

so that fish exiting the DSM channel either passed over the PIT tag antennas or entered the sample box when the antenna carriage was lifted. When the sample box was lifted for sample retrieval, the dewatering screen was lifted, allowing the fish to pass directly into the downwell and to the river (Fig. 2). During this period the PIT tag interrogation was disabled. All subsampled fish collected were physically examined and interrogated for PIT tags using a portable PIT tag interrogation system.

Each antenna assembly, consisting of an independent tag-excitation loop and a signal-receiving loop, was housed in a watertight enclosure measuring 2.2 m wide \times 0.51 m long \times 0.1 m deep. The antennas were positioned in an array, one upstream of the other, at a side-to-side spacing of 25 cm, and were placed within the antenna carriage such that the water flow was perpendicular to the antenna's long dimension (Figs. 3 and 4).

The 400 kHz flat-plate system consisted of a number of electronic components in addition to the two antennas (Fig. 5). The major components included a single controller which managed the operation of the entire system, and an exciter and

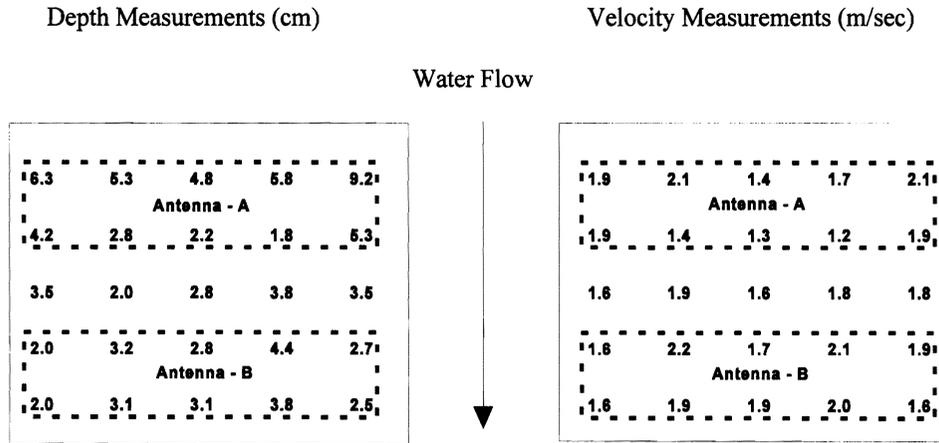


Fig. 3. Water depth and velocity measurements on the flat-plate antenna array under normal flow conditions. Values are shown at the measurement locations.

receiver for each antenna. The controller performed three key functions. First, to eliminate electrical interference it multiplexed (simultaneously activated and deactivated) the electronics associated with the two antennas. This was accomplished by alternately enabling and disabling the two antenna exciters, the corresponding receivers, and the antenna excitation switches. Second, it interpreted the PIT tag code signals coming from the receivers. Finally, it reported the codes to an external computer for data storage. Each exciter included a circuit (timed by the controller) that applied a gated burst of the 400 kHz signal to a power amplifier. The high power output from the amplifier was passed to an antenna's tag excitation loop via

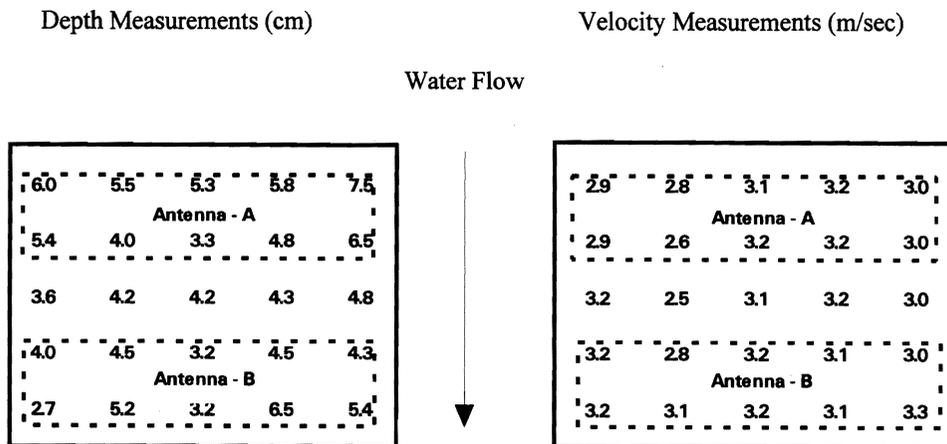


Fig. 4. Water depth and velocity measurements on the flat-plate antenna array under high flow conditions. Values are shown at the measurement locations.

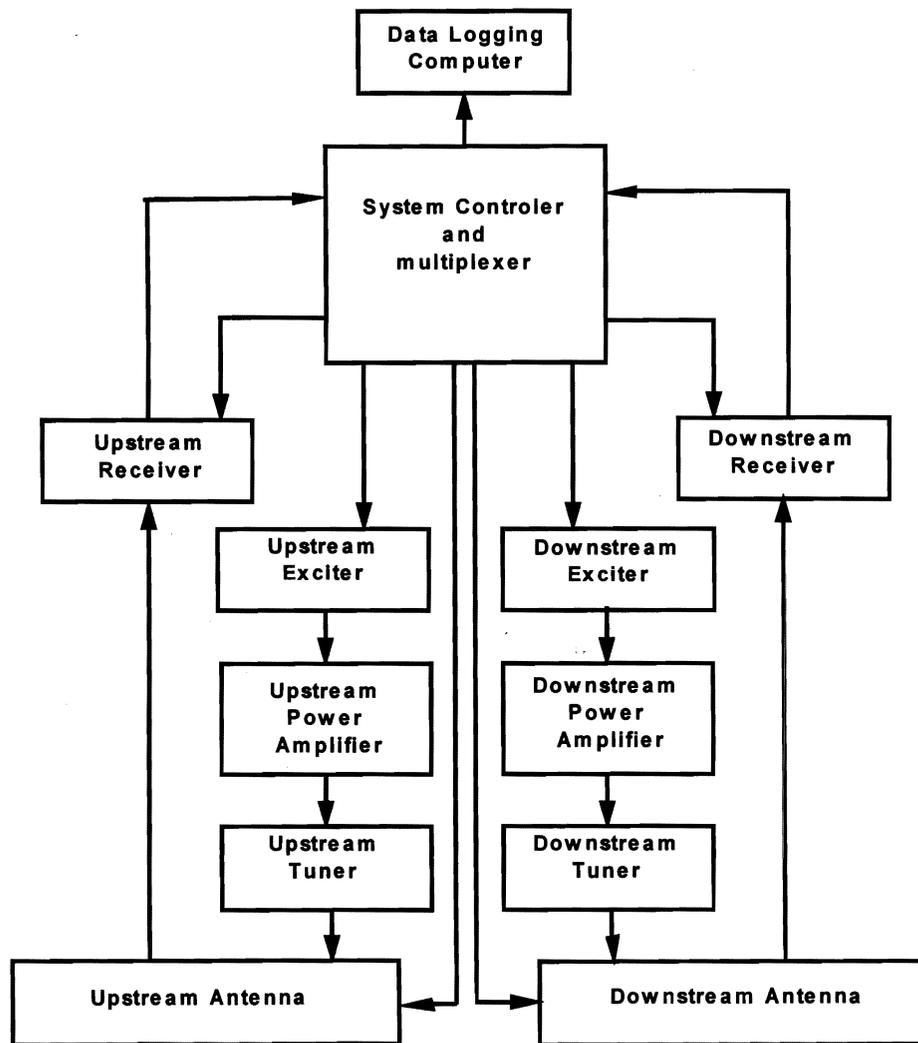


Fig. 5. A simplified block diagram of the flat-plate PIT tag detection system installed in the DSM of the Bonneville Dam First Powerhouse.

a tuning circuit. Simultaneously, the active receiving loop of the same antenna sent the PIT tag code signals to the receiver for demodulation and amplification prior to their being transferred to the controller.

The timing of the antenna multiplexing cycle was determined by the controller and consisted of four steps. First, the upstream antenna was energized for 5 ms while the downstream antenna remained inactive. Second, both antennas were deactivated for 2 ms whilst the tag detection operations were switched to the downstream antenna. During the third step, the downstream antenna was energized

for 5 ms while the upstream antenna remained inactive. In the final step, the tag detection operations switched back (2 ms) to the upstream antenna while both antennas were inactive. Overall, the full multiplexing cycle required about 14 ms when no tags were present, and thus was repeated at a maximum rate of about 71 times s^{-1} . The antenna activation time was automatically extended by the system controller until a tag passing over an antenna could be read, or passed out of the field of detection.

The flat-plate PIT tag interrogation system was operated from March to October 1996 to determine the suitability of the electronic and mechanical design, the effectiveness in detecting PIT tagged fish under field conditions, and system reliability over an extended period of operation. System operation (16:30–00:00) was initiated on 4 May. Full time operation (24 h day^{-1}) occurred from 10 May to 14 June. After 14 June, the system was again operated from 16:30–00:00 daily until the DSM channel monitoring and fish sampling were terminated for the season on 30 October 1996. During 1997, the flat plate system was re-installed in its original configuration, and 24 h daily operation commenced on 8 April.

The reading efficiency of the flat-plate system was determined using direct and indirect methods. The direct method used the number of tag codes correctly read divided by the number of tags released times 100. The reading efficiency using this method was conducted just prior to the start of the regular operation of the flat-plate system (19–20 April, 1996). Fish were tagged with Destron/Fearing 400 kHz, 12 mm long tags using the method of Prentice et al. (1990). The tests were made by releasing known numbers of PIT tagged 1-year-old juvenile chinook salmon (*Oncorhynchus tshawytscha*), averaging 134 mm fork-length, directly into the DSM channel 20 m upstream from the antenna array. The water flow within the DSM channel fluctuates with changes in turbine operation; thus tests were conducted under two water flow conditions (i.e. normal 19 April and maximum 20 April). Mean water depth and velocity over the flat-plate at normal flow was 3.7 cm and 1.8 $m s^{-1}$ (ranges = 1.8–6.3 cm and 1.2–2.2 $m s^{-1}$), and at maximum water flow was 4.8 cm and 3.0 $m s^{-1}$ (ranges = 2.7–7.5 cm and 2.6–3.3 $m s^{-1}$). The locations and values of the depth measurements and the water velocity for normal and maximum flow are depicted in Figs. 3 and 4. In total, 226 and 162 fish were released during normal and maximum flow tests, respectively. During 17 April 1997 the reading efficiency of the system was tested with PIT-tagged fish, using procedures similar to those employed in 1996. A total of 148 PIT tagged fish were released into the DSM channel during normal water flow conditions. Each test required from 2 to 3 h to conduct.

The indirect method employed to determine tag-reading efficiency used a statistical procedure based upon the total number of individual PIT tags detected in run-at-large fish, without knowing the actual number of tags that passed over the antenna array. Point estimates were calculated for the probability of missing tags by either antenna and by the total array. The calculation was used as an estimate of the reading efficiency of the system. We used the estimation method described by Prentice et al. (1993).

The functionality of the flat-plate system was monitored on a daily bases using PIT tagged wooden test sticks (2 cm × 2 cm × 14 cm), which were passed over the flat-plate antenna array. Two types of test sticks were used: one with PIT tags inserted parallel (0°), the other at a 45° orientation with respect to the long axis of the stick. The 0° test sticks were used to represent fish at near-ideal tag reading orientation as they crossed the flat-plate, whilst the 45° test sticks represented fish at a poor orientation and provided a test of system tag-reading sensitivity. All stick tests were performed under the normal water-flow condition. Each test consisted of 100 trials of a single test stick passing over the antenna array. The stick tests were conducted daily at the beginning of each work shift throughout the 1996 and 1997 field season. The presence or absence of tag detections indicated the system operational status.

3. Results and discussion

The direct measurement of the system reading efficiency, using PIT tagged juvenile chinook salmon during normal water flow conditions, was high for both 1996 and 1997. Individual reading efficiencies for the upstream and downstream antennas were 89.4 and 86.7% during 1996, and 89.9 and 93.2% during 1997. The combined reading efficiency for the antenna array was 97.3% for each year. Individual upstream and downstream antenna efficiencies measured during maximum water flow in 1996 were 68.5 and 81.5%, with a combined array efficiency of 92.0% (Table 1). The reading efficiency for maximum water flow was not measured in 1997. The reading accuracy for both years was 100%; no erroneous tag codes were recorded.

We postulate that the differences in the reading efficiencies observed between normal and maximum water-flow test conditions resulted from water turbulence and depth affecting the fish orientation. It was observed that water turbulence

Table 1
PIT tag reading efficiencies for the flat-plate system using juvenile chinook salmon at the Bonneville Dam First Power house, under normal and maximum water flow conditions

| | 1996 | | 1996 | | 1997 | |
|-----------------------------------|-------------------|-------|--------------------|-------|-------------------|-------|
| | Normal water flow | | Maximum water flow | | Normal water flow | |
| | Counts | % | Counts | % | Counts | % |
| Total test fish | 226 | 100.0 | 162 | 100.0 | 148 | 100.0 |
| Upstream antenna detections | 202 | 89.4 | 111 | 68.5 | 133 | 89.9 |
| Downstream antenna detections | 196 | 86.7 | 132 | 81.5 | 138 | 93.2 |
| Total missed tags (both antennas) | 6 | 2.7 | 13 | 8.0 | 4 | 2.7 |
| Total reading errors | 0 | 0.0 | 0 | 0.0 | 0 | 0.0 |
| Combined efficiency | — | 97.3 | — | 92.0 | — | 97.3 |

increased as water flow increased. The water turbulence was created by an irregular approach geometry and the presence of a screen cleaning mechanism upstream of the sample box and PIT tag interrogation system. The turbulence caused fish to be forced in various directions whilst being interrogated. Deviation of the fish orientation from the ideal (i.e. aligned with the direction of water flow across the antenna) can result in reduced tag detectability since the tag is no longer in an orientation for optimal energizing. Furthermore, increases in water depth can result in a greater distance between the antenna and a PIT tag, thus reducing detectability. These factors could at times cause a PIT tag to be unreadable. The difference in the reading efficiencies observed between the upstream and downstream antenna was thought to also be related to these factors. In future the tag read range will be increased through improvements to the receiver and energizing electronics and by changing the system's operating frequency to one other than 400 kHz. These improvements will reduce the effect of small variations in water depth.

The indirect estimates of the system reading efficiency, using PIT tagged run-at-large fish, were similar to the results using the direct method for both 1996 and 1997. The statistical method showed 86.8 and 84.8% efficiency for the upstream and downstream antennas, and 98.0% for the overall array efficiency for 1996 (4271 fish). Upstream and downstream efficiencies were estimated at 91.2 and 90.7%, and the overall array efficiency was 99.2% for 1997 (14371 fish). In comparison, the direct method (using PIT tagged fish) yielded values of 89.4 and 86.7% for the upstream and downstream antennas, respectively, for 1996 and 89.9 and 93.2%, respectively, for 1997. The overall array efficiencies for each year was 97.3%.

During 1996 and 1997, the operational status of the flat-plate system was monitored using data obtained from daily testing of the system using tagged sticks and data obtained from the passage of PIT tagged run-at-large fish. The daily stick tests proved to be invaluable in the rapid identification of loss of system detection sensitivity or equipment failure, whereas periodic checks of the estimated array reading efficiency provided a long-term measure of the system stability. The prototype flat-plate system required maintenance and repair on six occasions during the 1996 field season (4 May–30 October), and required a total time for system repair of 23 h over six months of continuous operation. At no time was the system totally inoperable, as only one antenna ceased to operate on each occasion. Most failures were traced to the antenna multiplexer switching circuits, located within the antenna housings, where condensation created electrical shorts on the circuit boards. In addition, on two occasions water damage was found in the external antenna connectors. Prior to the start of the 1997 field season, underwater electrical connectors were installed on the antenna housings to facilitate connection to the antennas and to eliminate water damage to the connectors. In addition, all circuit boards inside the antenna housings were coated with a protective conformal spray for moisture protection, and desiccators were placed in the antenna housings. Finally, cable connectors were installed on all of the electronic component boxes to allow rapid exchange and testing of the individual units. Improper operation of the sampling box resulted in the only system failure in 1997. The antenna cabling was over stretched causing a breakage at the onset of the field season.

This prototype flat-plate interrogation system incorporates several advances over other known flat-plate (pass-by) or tunnel type (pass-through) systems for fisheries applications. First, the antennas were nearly twice the size of those reported by Armstrong et al. (1996). This feature enables a single antenna to cover a large channel width. However, there are potential disadvantages of having large antennas with this type of system. With each antenna covering a large area, a single tagged fish located at any point over the array can interrupt the simultaneous reading of all other tagged fish present on the array. Also, if a single antenna fails, a large proportion of the interrogation capability is lost. The probability of either occurrence would be reduced by using smaller, multiple antennas, but the complexity and cost of such a system would be greater than for a more simple antenna system.

A second major difference between the system described by Armstrong et al. (1996) and ours is that the antennas in our system were multiplexed to allow for operation in close proximity to one another without undue electromagnetic field (EMF) interference. The antennas in the Bonneville Dam system were positioned at a side-to-side spacing of 25 cm, compared to the 1.5 m reported by Armstrong et al. (1996). Tests showed that the antenna spacing in the Bonneville Dam system could have been reduced to 10 cm without significant loss of reading efficiency. The multiplexing feature enables multiple antennas to be operated in close proximity to increase area coverage and/or increase system redundancy for higher overall reading efficiencies and system reliability. The disadvantage of a multiplexing system is that a fish might pass without being interrogated during the switching from one antenna to another or during the antenna deactivation portion of the switching cycle. This problem increases as the number of antennas increases. However, the distribution of antennas in an array, and the rate at which they are multiplexed can reduce these risks.

Third, the design of the flat-plate antenna array allows fish to be interrogated without physically restricting their passage, and is resistant to clogging by debris that could endanger the fish or damage the equipment. This is in contrast to the pass-through system described by Prentice et al. (1993), where fish are forced to pass through an orifice (round or rectangular) of a relatively small dimension, which is subject to clogging by debris.

Finally, the antenna array of the pass-by system has the potential to be oriented in either a horizontal plane, as described in this paper, or in a vertical plane for other applications. One application may be the vertical water-control slots of some types of adult fish ladders or passageways. Two or more antennas placed end-to-end could be deployed to extend the vertical interrogation area. In addition, the placement of two or more antennas on either side of an opening may result in increased PIT tag reading distance through synergism. However, this latter approach has yet to be investigated.

The flat-plate PIT tag interrogation system installed in the Bonneville Dam First Powerhouse DSM channel has been shown to be reliable and efficient in the detection of PIT tags in migrating fish. Compared to the direct sampling used in the past at the facility, the system has greatly expanded the ability to collect PIT tag data while reducing the need to physically handle the fish. The system will aid

resource stakeholders in assessing the effectiveness of various actions taken to enhance the survival of juvenile and adult salmonids. Specifically, this system or a variation of the system, will: (1) provide an approach to the interrogation of PIT tagged fish in locations previously not feasible; (2) expand fishery researchers ability to obtain accurate and reliable data in near real time thus enabling effective decisions to be made regarding actions taken or to be taken; (3) provide accurate and timely information on the survival and migration timing of stocks of interest, for evaluating water management strategies and fish passage/collection facilities, and for the management of multiple species in a variety of locations and habitats; and (4) provide previously unobtainable information which can be used in genetic, physiology, behavior, and broodstock research efforts related to endangered species as listed under the Endangered Species Act. While the pass-by interrogation system design is still in its developmental infancy, its potential for future applications is considerable.

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