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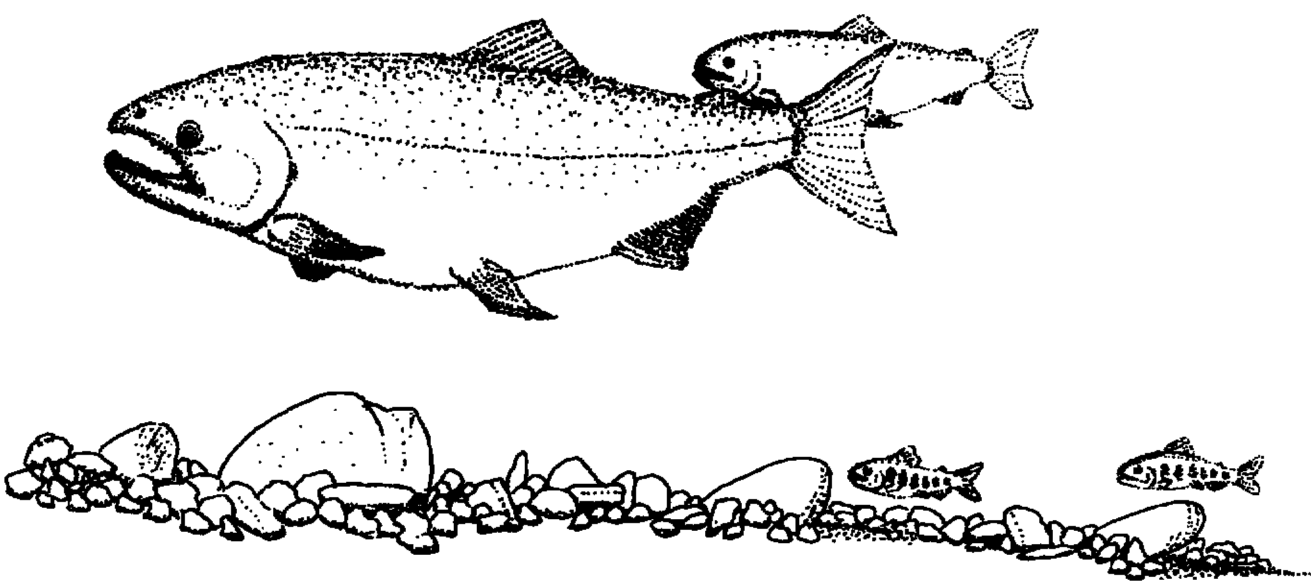

WESTERN WASHINGTON FISHERY RESOURCE OFFICE

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SONIC TAGGING AND TRACKING OF WILD WINTER STEELHEAD AT THE BALLARD LOCKS, SEATTLE, WASHINGTON

SPRING, 1994

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ABSTRACT

Adult steelhead (*Oncorhynchus mykiss*) migrating past Ballard Locks are vulnerable to predation by California sea lions (*Zalophus californianus*). To better understand movements of steelhead as they approach the fish ladder and/or locks, we attempted to track steelhead with acoustic tagging equipment. Steelhead were captured with gill nets and an acoustic tag was inserted into their stomach. Steelhead were tracked by a fixed hydrophone system below the spillgates, three hydrophones in the fish ladder, and mobile tracking equipment. Due to the small run size, we were able to capture only nine fish. All fish except one moved downstream and left Salmon Bay within 21 h of release. The one tag that remained in Salmon Bay was in the same location for nine days and was presumed to be a regurgitated tag or dead fish. Of the remaining eight fish, only two returned to Salmon Bay and passed upstream through the Ballard Locks area. One fish came through during no-spill conditions and was accurately tracked by the fixed hydrophone array system. The fish spent 8 h in the array, and was usually located near one of the three sources of freshwater (large lock, small lock, or fish ladder), until it passed through the fish ladder. The other fish passed through Ballard Locks during spill conditions and was detected but not by enough hydrophones to determine the fish's position. This fish was in the array for 4.7 h before entering the fish ladder. Both fish took a little over an hour to pass through the fish ladder. Due to the small sample size in 1994, further tagging is recommended to 1) further refine tracking techniques, 2) test fish passage under a variety of conditions and 3) make more definitive conclusions. Due to the small run size of wild steelhead, we recommend using hatchery steelhead or another species such as coho salmon (*O. kisutch*) to refine techniques prior to further studies of wild steelhead.

INTRODUCTION

Predation on returning winter steelhead (*Oncorhynchus mykiss*) by California sea lions (*Zalophus californianus*) has been an acute problem at the Ballard Locks in Seattle, Washington for the past 10 years. Between 1984 and 1991, the proportion of the total wild run taken by sea lions has ranged from 15 to 65%. During the last three years in which detailed predation monitoring was conducted (1989-91), the proportion taken averaged 61% (Scordino and Pfeifer 1993).

Winter steelhead run sizes to the Lake Washington basin have declined dramatically in recent years (Table 1). The total run size, after accounting for predation, harvests (if any), and escapement, has been less than the basin escapement goal since 1990. Therefore, all steelhead returning to the basin in future years should be fully protected from all controllable forms of mortality. Sport and tribal fisheries have been closed for a number of years. The remaining source of significant adult mortality is marine mammal predation which should be minimized if possible.

Steelhead are killed by sea lions throughout much of the lower Lake Washington Ship Canal (LWSC, includes lower Salmon Bay and inner Shilshole Bay) downstream of Ballard Locks (Figure 1), although predation is not uniformly distributed throughout this area. The proportion of the seasonal total number of steelhead predated varies widely between areas of LWSC. There is also variation in the percentage of fish taken in any area from one year to the next. This variability is affected by the experience level of sea lions present (many animals return from one year to the next), the amount of water being spilled at the spillway dam, and other factors (Pfeifer 1989, 1991a, 1991b).

It has long been recognized that most of the steelhead kills occur in a few areas near the spillway dam and fishway entrance, but significant numbers of fish are also taken in lower areas of the LWSC. There have been numerous suggestions by various interest groups that placement of an underwater structural refuge would effectively reduce steelhead losses by separating the steelhead from sea lions. An interagency committee of biologists and engineers recommended in 1990 that detailed information be obtained on the behavior of returning fish to support recommendations regarding costly experiments with prototype refugia (Ad Hoc Technical Committee 1990).

The purpose of this steelhead tagging and tracking study was to develop methods of tracking steelhead in the unique environment at the Ballard Locks, and to learn as much as possible about the entry timing and behavior of the fish as they pass the locks/dam complex.

Table 1. Lake Washington wild steelhead escapement and predation by California sea lions. Estimated values appear in parentheses. Steelhead escapement goal throughout 1982-94 was 1600 fish.

Run Year	Run Size Estimate PreSeason	Run Size Estimate PostSeason	Steelhead Escapements	Percent of Goal	Monitored Steelhead Predation	% of Post Season Reconstructed Run Predated
82/83	---	----	2575	160.9	---	----
83/84	---	2166	1250	78.1	---	----
84/85	---	2527	474	29.6	(1500)	(59%)[1]
85/86	---	2261	1816	113.5	329	15%
86/87	2965	2997	1172	73.3	1254	42%
87/88	2635	2274	858	53.6	1178	52%
88/89	1655	1973	686	42.9	1287	65%
89/90	2093	1806	714	44.6	1065	59%
90/91	2355	1520	621	38.8	899	59%
91/92	1442	(1498)[3]	599	37.4	---[2]	----
92/93	1611	(460)[3]	184	11.5	---[2]	----
93/94	1159	(in prep.)	70	4.4	(in prep.)	(in prep.)

[1] Predation not monitored; based on estimate.
[2] Predation not monitored.
[3] Estimated, assuming 60% exploitation by sea lions.

Data source: WDW Winter Steelhead Inventory Tables

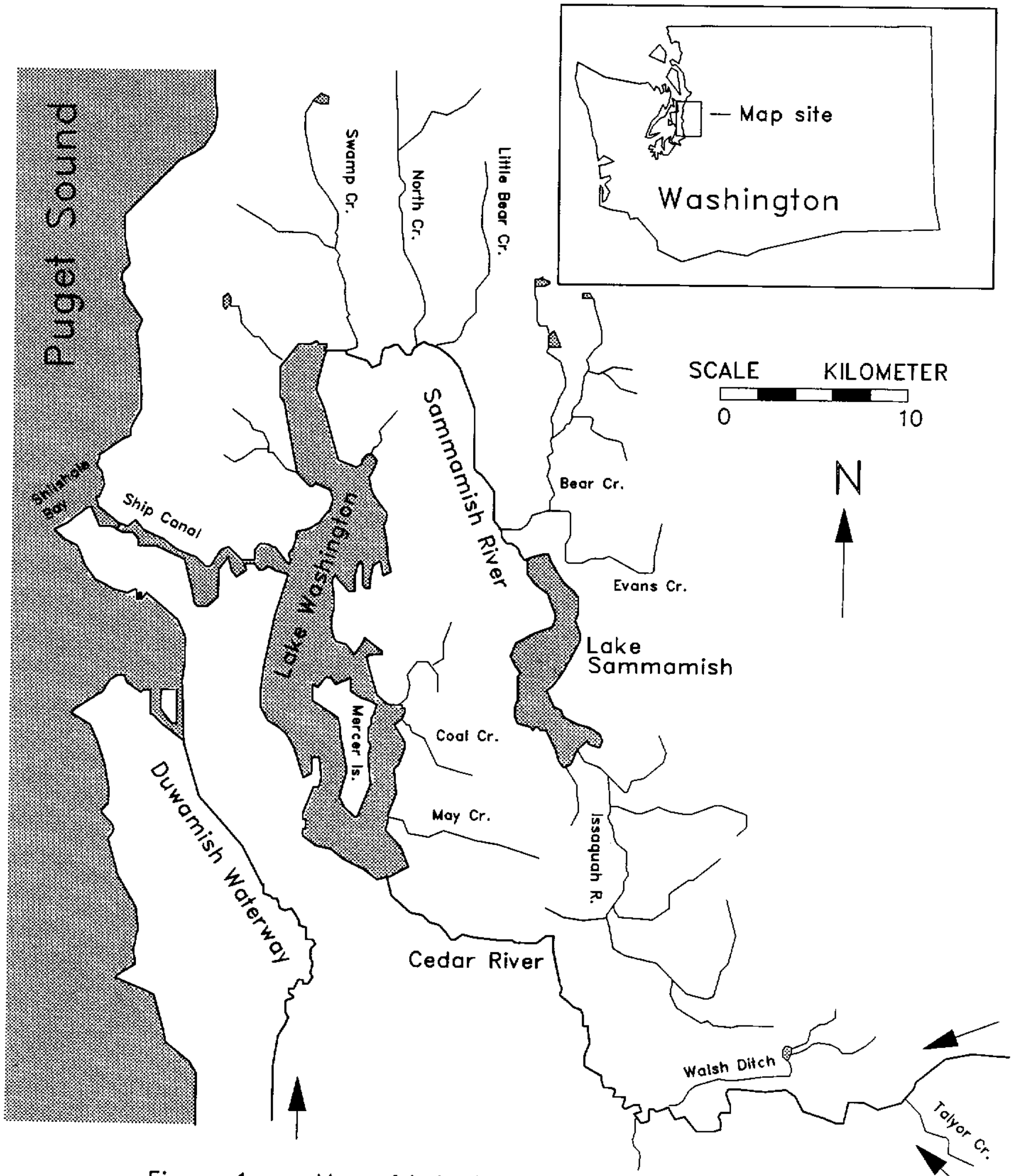

Figure 1. -- Map of Lake Washington drainage basin.

The objectives of the tracking study were to:

1. Determine relatively fine-scale migratory patterns of steelhead directly downstream of the spillway dam and fishway;

2. Assess the time intervals between fish entry into the lower LWSC, entry into the fishway, and ultimate exit from the lock(s) or fishway;

3. Determine the relative proportion of steelhead which use the lock(s) rather than the fishway to pass by the project;

4. Obtain information on depth and salinity preferences of steelhead downstream of the spillway dam and fishway; and

5. Obtain information on the behavior and location of tagged steelhead relative to the number and behavior of foraging sea lions.

The first objective relates principally to identification of the most propitious site(s) for refuges that may be experimentally placed in the future. For example, if the fish tended to mill in discrete, localized areas prior to passage through the fishway or lock(s), those might be logical sites to test an underwater refuge. It is also necessary to know more about the "normal" behavior of the fish before the test environment is modified by placement of a refuge. Finally, since any tests of refuge designs will be costly, and could have serious hydraulic effects on the LWSC or project structures, any test sites chosen must consider both the observed or expected fish behavior as well as the potential impacts on the site. Since hydraulic modeling of prototypical refuges will probably be required (Ad Hoc Technical Committee 1990), selection of the test site(s) is an extremely important consideration.

The second objective relates to the fact that at the Ballard Locks, steelhead are subject to intense predation pressures until they successfully pass through the dam and locks. The fish are largely "safe" from predation from sea lions as soon as they enter the fishway, although harbor seals (*Phoca vitulina*) are becoming more of a concern as a predator on steelhead and can enter the fishway. However, steelhead have been consumed in the locks, therefore fish which pass via the locks are not "safe" until they fully pass the locks. Managers need to know how long the fish must be protected from predation in order to gauge the need for, and assess the best design of any prototype refugia.

Conditions in the locks environment could also affect the time required for fish to enter the fishway or pass through the locks. Salinity in the fishway varies, as does the tide level, the amount and configuration of dam spill, the frequency of lockages, and other factors. Most all of these environmental variables can be monitored and later related to the timing and position of individually tagged steelhead. In some cases, it may be possible to alter locks, spillway dam, or fishway operation to facilitate fish passage. Detailed information on fish behavior is needed to evaluate current locks/dam/fishway operations, and to identify changes in procedure most likely to enhance steelhead passage.

The third objective would enable judgments on experimental refuge location(s), and provide a cross check on other methods used to determine the run fraction which uses the fishway. The relative importance of the two route choices has a bearing on the nature or location of modifications that might be recommended for the dam, locks, or fishway.

There has been substantial concern among the involved agencies that the salinity of fishway attraction flow may affect steelhead fishway entry timing. Since this study would be set up such that the exact time fish entered the fishway (or locks) would be known, these events can be correlated with salinity conditions in the fishway at the time of fish entry. Depth of tagged fish has importance both to questions about salinities and the fish's osmoregulatory needs (to transition from salt to freshwater), and to the design and placement characteristics of an experimental refuge. It would be useful to know, for example, whether individual fish freely move throughout the water column while milling downstream of the fishway or locks, or whether they hold in successively less saline water before passing the locks area.

The intent of the fifth objective is to relate tagged fish behavior (flight or refuge-seeking movements) to concurrently obtained information on sea lion foraging behavior. The technical difficulties of correlating known fish position and the behavior of one or more sea lions are problematic. Nevertheless, this method of tagging and tracking offers the best potential of being able to establish some relationship between fish location and behavior, and sea lion behavior. A comparison of steelhead behavior with and without sea lions present could also be quite valuable.

STUDY SITE

The Ballard (or "Government") Locks and spillway dam are located in northwest Seattle, Washington, at the juncture of the outlet of the Lake Washington watershed and Puget Sound (Figure 1). Lake Washington drains a watershed of 1,564 km^2. The lake has two principal tributaries, the Cedar and Sammamish rivers, as well as numerous smaller streams, to which winter steelhead historically return for spawning and rearing (Figure 1). Besides the Lake Washington basin, flow through Ballard Locks also contains water from Seattle urbanized areas draining to the ship canal and Lake Union.

The locks project was constructed in 1914-16, and constitutes the water level control for both Lake Washington and Lake Union, which are interconnected by the Lake Washington Ship Canal. (See Chrzastowski (1981) and Ajwani (1956) for detailed descriptions of the complex and profound changes that occurred in the location of the outlets of the various lakes in the lower Lake Washington watershed). There is one "large" lock which can be divided into two smaller locks with an intermediate set of gates; this lock has maximum dimensions of 24-m wide, 251-m long, and an average depth of 15 m (Figure 2). The "small" lock is a single chamber measuring 9-m wide, 46-m long, and has an average depth of 15 m. Two long concrete finger piers separate the mouths of the two locks, however a wooden pile and deck extension has been added to the more northerly of the two; fish and sea lions can swim under or through the wooden sideboards of this portion of the longer pier. The spillway dam is approximately 70-m long with six tainter gates equally spaced along the dam.

The level of Lake Washington and Lake Union is maintained within about a 0.6-m range, with a seasonal high level of 6.4-m mean sea level (msl). The dredged LWSC continues immediately below the locks and spillway dam as Salmon Bay, a tidal arm of Puget Sound. Salinities are typically 27-30 ppt, and depths in the immediate vicinity of the locks and spillway dam are approximately 10.7 m at a maximum tide level of about 4.1-m msl. Neap tides may reach as low as -1.0-m msl. Thus, tides may vary as much as 5 m on an exchange cycle, and lockages may at times occur when lake and saltwater elevation differences range from about 1.8 m to over 7.3 m.

Outflow at the locks and spillway dam varies from strictly that volume required for lockages during summer/fall water conservation periods (plus a constant 4.67 m^3/s in the fishway), to flooding conditions where all six Tainter gates have been raised clear of the lake ($\approx$ 425 m^3/s), plus what water can be routed through the large lock via valve adjustments under those extreme conditions. Dam discharges of 60 m^3/s or more are not uncommon during the winter and early spring months when steelhead are returning. However, dam outflow is often zero during March and April when the level of Lake Washington is being brought back up to its summer high level of 6.4-m msl.

There is a complex relationship between lock usage, spillway gate operations, fishway outflow, and the character of the marine environment at the locks/dam/fishway interface. Returning fish are presumed to experience

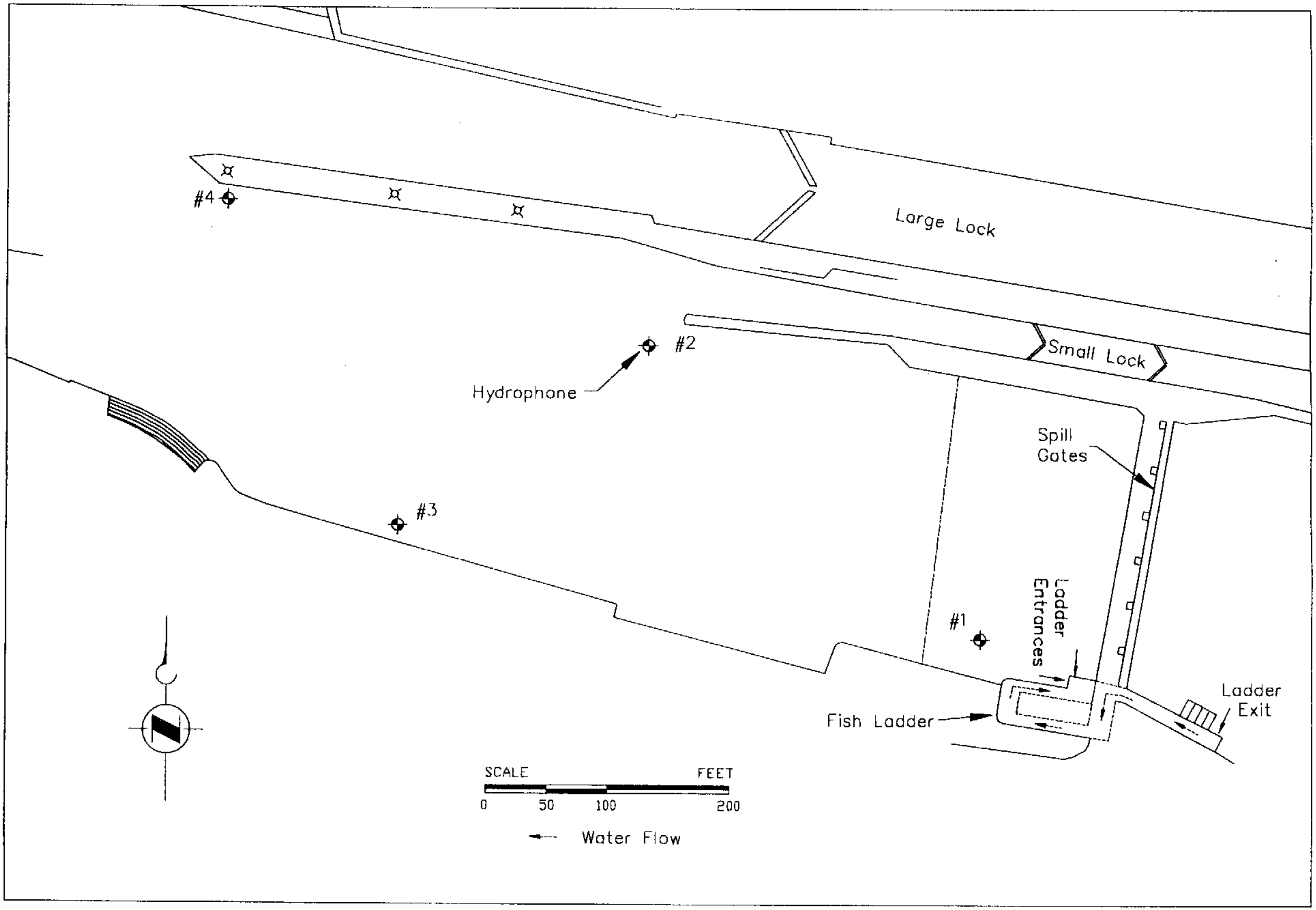

Figure 2 — Map of Ballard Locks and Hydrophone Locations.

LOCKS.DWG

olfactory and tactile (flowing water) cues that vary in intensity and location due to variations in lake water discharge and tide height. For example, relatively large volumes of lake water may be released by frequent large lock lockages at a time of no dam spill and fishway outflow of 15 ppt salinity, which would presumably attract fish to the large lock. At other times infrequent lockages, intermediate dam spill, and near-fresh fishway outflow may guide fish towards the fishway. While the spillway dam releases essentially fresh water, lock and fishway outputs may vary in salinity depending on the amount of salt water in the large lock and its saltwater drain/sump.

Besides steelhead, other anadromous salmonids that migrate through Ballard Locks include, sockeye salmon (*O. nerka*), chinook salmon (*O. tshawytscha*), and coho salmon (*O. kisutch*).

The LWSC below the dam and locks is a dredged channel generally rectangular in cross section below approximately -1.2-m msl, otherwise having gently sloping edges leading to bulkhead or riprapped top-shores. Bottom materials are generally sand or silt with a small percentage of gravel in the lower reaches. There is a concrete apron extending out from the spillway dam to beyond the fishway entrance, and extending from the left bank to the small lock bulkhead. Much of the area in the immediate locks area consists of concrete bulkheads or steeply-sloping riprapped shoreline.

Boat traffic through Ballard Locks is heavy; about 100,000 recreational and commercial vessels and more than two million tons of cargo annually pass through the locks. This level of use has, of course, major implications as to what can be done to provide steelhead refuge(s) in the navigable channel, where substantial predation has been observed in past years.

Typically, the large lock is dewatered for annual maintenance in the winter and the small lock is dewatered in spring. The fishway is dewatered for maintenance in late May.

METHODS

CAPTURE AND TAGGING

Steelhead were captured with a 46-m long, 3.6-m high floating gill net (12.7-cm stretch mesh). One end of the net was anchored onshore and then set perpendicular to shore. The gill net was set at various locations in Salmon Bay (Figure 3) depending on tides, wind, and fishing success. Typically, we fished from 700 to 2100 h depending on the number of tags available. The gill net was closely monitored to ensure steelhead were removed from the net as soon as possible. Immediately after capture, steelhead were put in a 1.1-m long by 20-cm-diameter holding tube and transported to a holding pen.

The acoustic fish tags used for this project were model V3-3H transmitters manufactured by Vemco Ltd.[1] of Nova Scotia, Canada. The specifications for these tags are presented in Table 2. Tags were 58-mm long, 16-mm-diameter width, and weighed 25 g. The two protruding wires were twisted together and soldered. Wires were placed at the end of the tag and covered with 5-minute epoxy. Final length of the tag was approximately 70 mm.

Table 2.-- Specifications of tags used for tracking steelhead at the Ballard Locks during March through April, 1994.

Tag	Serial number	Frequency (kHz)	Pulse width (msec)	Pulse period (msec)	Pulses/ minute	Estimated maximum life (days)
1	9723	69.00	14.84	1009	60	11
2	9724	71.04	14.41	1009	60	11
3	9722	65.54	15.63	1016	59	10
4	9732	50.00	10.24	1505	40	21
5	9733	54.00	9.48	1498	40	22
6	9734	60.00	17.07	1502	40	13
7	9735	63.66	16.09	1496	40	14
8	9736	73.50	13.93	1505	40	15
9	9737	76.80	13.33	1507	40	16

1. Use of trade name does not imply endorsement.

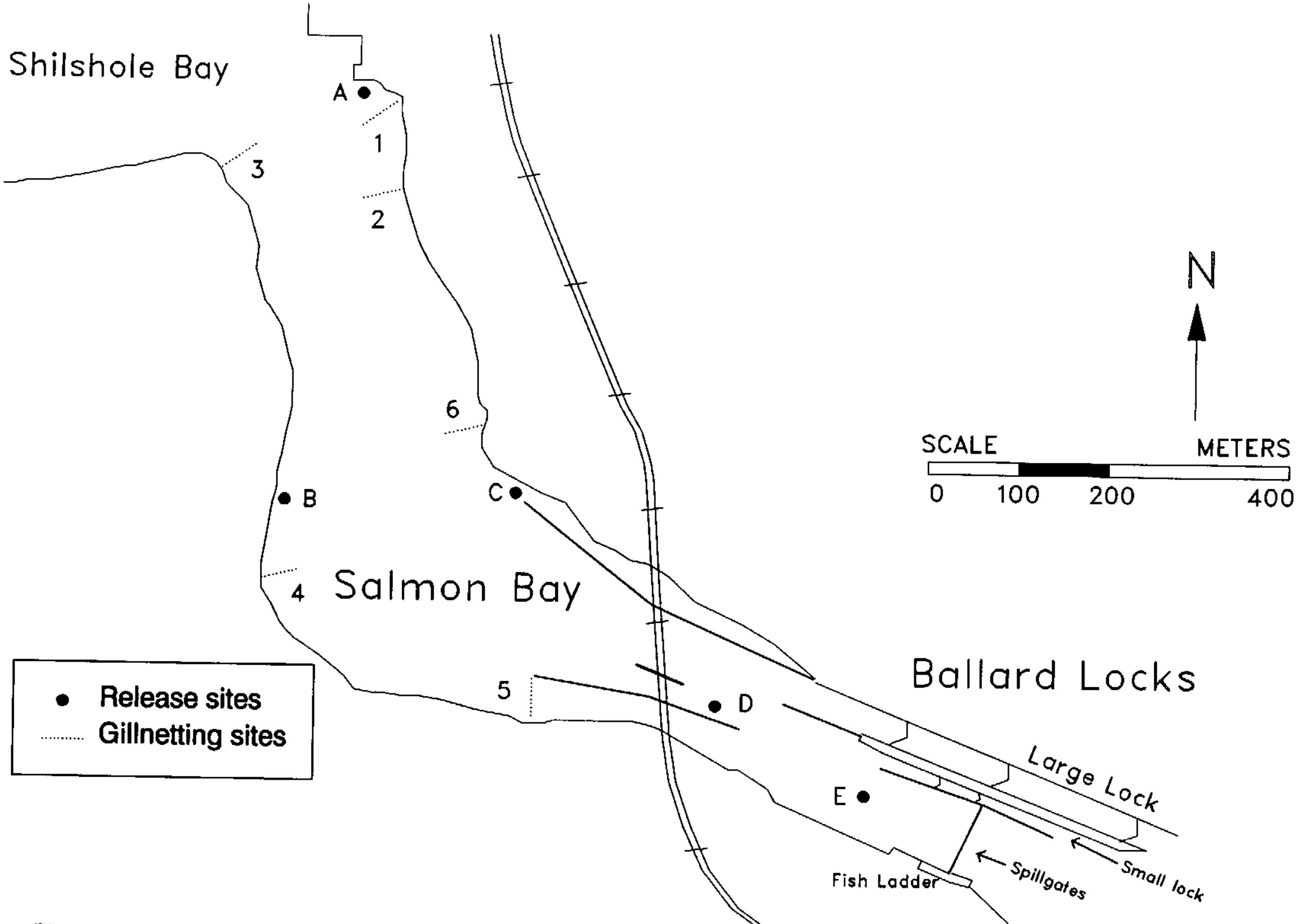

Figure 3. Salmon Bay sites used to capture and release steelhead, March 7 – April 9, 1994. Letters and numbers correspond to specific information in tables 3 and 4.

After the epoxy on the tag had hardened, the fish was removed from the tube and placed in a padded cradle to restrict its movements. Fork length was measured to the nearest 10 mm and sex was noted. Tags were dipped in glycerin for lubrication, and then inserted in the fish's stomach. Fish were returned to the fish tube and allowed to recover from 3.5 to 21.3 h. Most fish were released the evening on the day of capture. However, three fish were held overnight and released the following morning. Fish were released at various sites in Salmon Bay (Figure 3).

MOBILE TRACKING

We attempted to track steelhead for the first few hours after release. In addition, Salmon Bay and inner Shilshole Bay were periodically checked for presence of tags. Typically, the area was checked once each day. Fish were tracked with a hand-held, directional hydrophone and VR-60 Vemco receiver. Fish locations were estimated from either compass readings or approximate distance to navigational buoys and other landmarks. If the fish appeared to be stationary for a period of time, we attempted to triangulate its position.

FIXED HYDROPHONE ARRAY SYSTEM

To track steelhead movements downstream of Ballard Locks, a fixed hydrophone array system was used. The system developed by Pentec Environmental, Inc. and GRD Associates, Inc. and on loan from NMFS, Alaska Fishery Science Center consisted of an array of hydrophones and signal collection and processing hardware and software. To determine the position of the fish, differences in time between the reception of the acoustic signal from the tagged fish by one hydrophone and the reception of the signal by a minimum of two other hydrophones in the array were measured. The position of the fish was then computed from these time differences (taking into consideration the speed of sound in water) using a hyperbolic navigation algorithm (this method is similar in concept to the LORAN-C navigation system used on ships).

There are several factors that affect the positioning accuracy of the system: timing resolution, geometry of the tag relative to the array, and errors in the measurement of the speed of sound. The interaction of these factors determines the overall positioning accuracy of the system.

Timing Resolution: The timing accuracy of the system is determined by the sampling rate of the received acoustic signals used to measure the time differences of arrival between each of the hydrophones. The timing resolution of the sampled waveforms used for localization is 0.4 milliseconds (ms). This equates to approximately 0.6 m at a nominal in-water sound speed of 1,500 m/second. Therefore, based on timing resolution errors alone, the system has the capability to determine range differences to an accuracy of ± 0.6 m.

Geometry: The position solution is computed from the intersection of a series of hyperbolas which are computed from the range differences between each pair of hydrophones. Each hyperbola describes all possible distances (i.e., points) between pairs of hydrophones that can occur from a set of time differences between the pair. When the tag is near the center of the array, these hyperbolas intersect at relatively high angles, which supports higher precision position solutions. However, when the tag is near the edge of the array, the hyperbolas may intersect at rather oblique angles, which equates to less precision in the position solution. Based on the geometric modelling conducted before deployment of the array at the locks, the error bounds around a point within the study area are elliptical in shape. These elliptical error contours are typically about 1 m by 1 m near the center of the array and grow to as large as 2 m by 5 m near the edges. For tags outside the array, error contours may be significantly larger. For tag locations very close to a hydrophone, additional geometric errors will be incurred due to uncompensated three-dimensional effects which are not taken into account in the present localization algorithms.

Speed of Sound: As stated above, the range differences and therefore the position solutions are computed from time differences and speed of sound in water. If the speed of sound is not precisely known, there may be additional errors in the position solution. Estimating the speed of sound below the locks is problematic because the speed of sound changes with temperature and salinity, which vary greatly over short time periods. Based on empirical observations, the error associated with imprecise speed of sound estimation is probably small when compared to the geometric error (probably on the order of ± 2 m).

With the interaction of all of these factors, the overall position accuracy of the system is probably about ± 2-3 m from the actual position.

The major factor that affects system performance (i.e., the ability to track tagged fish) at the Ballard Locks is aerated water caused from water plunging over the spillway. Entrained air bubbles can severely reduce the transmission distance of an acoustic tag. The tags used in this study are detectable to > 370 m in clear water. However, in aerated water, the transmission distance may be reduced to 30 m or less. Since a signal must be received by at least 3 hydrophones for a position solution to be determined, aerated water can greatly affect the ability to track an acoustic tag.

Using the estimated performance characteristics of the system, localization errors versus hydrophone positions were modelled prior to system deployment to determine optimal hydrophone array placement. This resulted in a compromise between desired coverage area, positioning accuracy, and the potential effects of aerated water near the spillway. Four hydrophone locations were selected to limit the geometric errors within the study area and to minimize the potential impact of aerated water near the spillway (Figure 2). Hydrophones were attached to concrete anchors and marked with buoys. Hydrophones were placed 1 m above the substrate.

The site map of the study area was created from an aerial photograph using AutoCAD drafting software. Major features visible in the photograph were traced onto paper by hand. A digitizing tablet and AutoCAD software were then used to draw the master site map from this tracing. Since photographic images are subject to distortion, especially near the edges, due to parallax error, an Electronic Distance Measuring (EDM) laser transit was used to confirm the relative positions of key points on the map. This information was used to correct distortion in the drawing and to increase accuracy of the site map. The coordinates of the hydrophones were documented by surveying them with the EDM. Coordinates for this map were based on a local area coordinate grid system and were used only to show relative positions of objects within the study area. An increasing easting (X) value indicates movement from the west to the east. An increasing northing (Y) value indicates movement from the south to the north. To relate fish location to records of sea lion predation, the study area was also divided into 10 observational cells developed by the sea lion monitoring program (Figure 4).

Acoustic signals transmitted from the tagged animals that entered the study area were received by the array of hydrophones and transmitted to the data acquisition and analysis system by radio telemetry link. As the signal was received from a tag transmission, the data were logged by the data acquisition computer. Backup copies of these data were made on a daily basis. A second computer was linked to the first through a local area network (LAN) and was used to graphically display the position of the tag relative to the hydrophone array as the data were received.

The output from the data analysis contained the tag ID, the X and Y coordinates of the tag relative to the array, and the date and time of the position solution. The position data were filtered using a sliding median value of three data points to reduce variability of the position solutions. To screen out unreliable data due to geometric imprecision, any position that was north of buoy 4, south of buoy 1, more than 30 m east of buoy 1, or more than 30 m west of buoy 4, was considered to be outside of the study area and was rejected.

FISH LADDER DETECTION SYSTEM

A separate monitoring system was installed to monitor the fish ladder for the presence of tags. This system consisted of three hydrophones, one in the lower ladder, one near the upper ladder located in the viewing chamber, and one outside of the ladder above the dam. Positioning of the tag was limited to presence or absence of a signal in the area where each hydrophone was located. This system provided data on how long it took for a tagged fish to move through the ladder with a secondary function of determining if a fish had passed through the locks rather than using the ladder. This latter case would be indicated if a tag was detected on the upstream hydrophone without having been detected in the ladder.

Tag detections, time, and frequency were logged onto a computer dedicated to this monitoring system. Data were downloaded onto floppy disk and reviewed daily for tag detections.

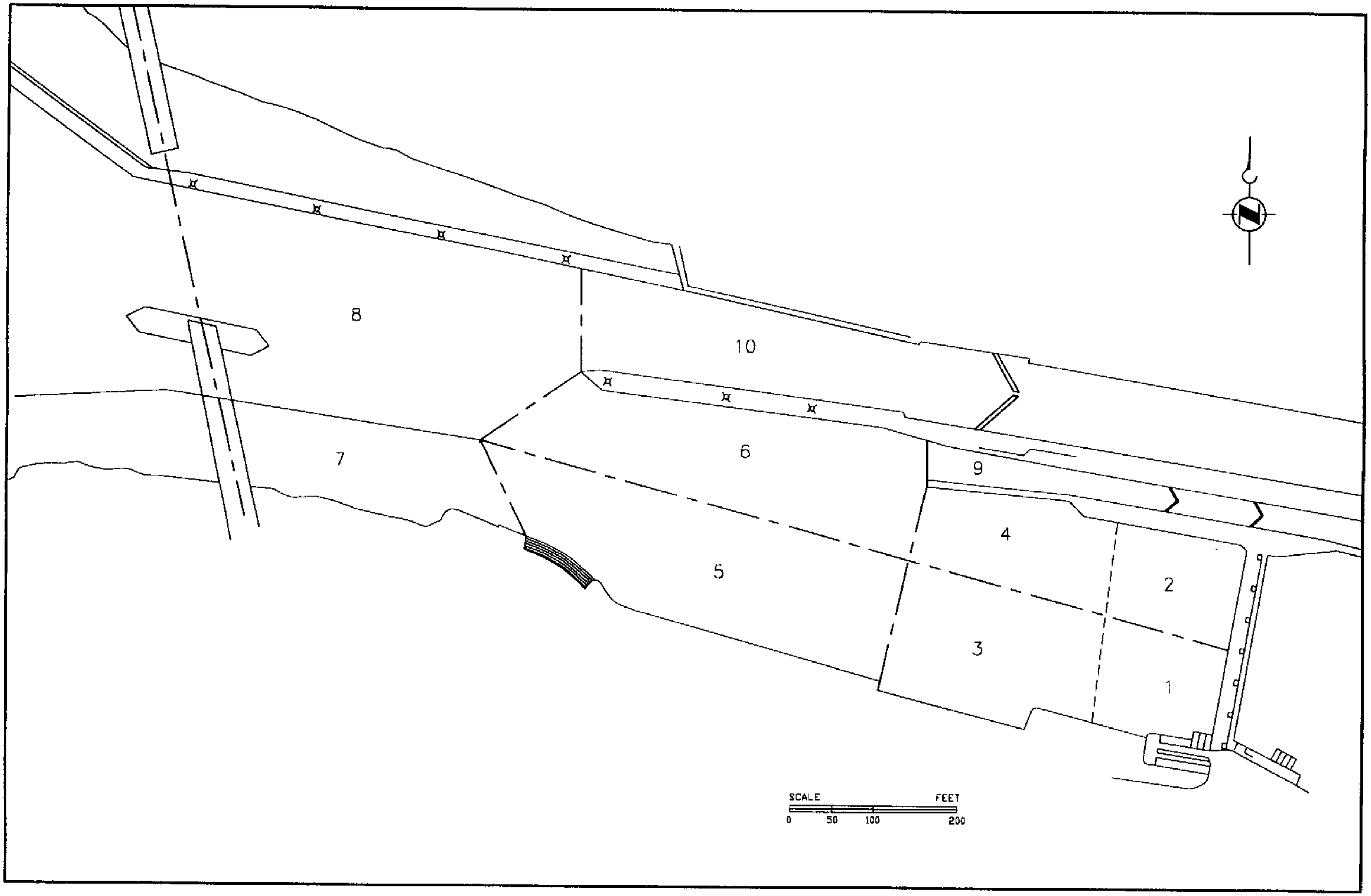

Figure 4 – Observation cells at the Ballard Locks.

RESULTS

CAPTURE AND TAGGING

Total fishing effort was 12 days (118.3 h) from March 7 to April 8 (Table 3). A total of nine steelhead were captured (0.076 fish/h; Table 3). All fish except fish No. 9 were caught on a flood tide. All fish were caught during the day, although we only fished a total of 9 h at night. Fork length ranged from 580 to 870 mm (Table 4). Four females and five males were captured and tagged. All fish appeared to be in good condition when tagged. Two fish bled slightly from the gills, however they appeared to be in good condition when tagged and released.

Table 3. -- Various gill net sets used to capture steelhead in Salmon Bay. Gill net locations are shown in Figure 3.

Date	Start time	End time	Number of hours	Location	Number of Steelhead
March 7	700	1540	8.67	1	0
March 7	1547	2125	5.63	2	0
March 8	740	1130	3.83	3	3
March 18	645	1200	5.25	4	0
March 18	1230	2100	8.50	3	0
March 21	600	615	0.25	3	0
March 21	645	1400	7.25	5	1
March 23	700	1200	5.00	3	0
March 23	1200	1300	1.00	1	0
March 23	1315	1400	0.75	5	0
March 24	600	1200	6.00	5	1
March 29	630	1000	3.50	5	0
March 29	1015	1830	8.25	3	0
March 29	1850	2030	1.67	5	0
March 30	630	1000	3.50	5	0
March 30	1015	1415	4.00	6	0
March 30	1430	1915	4.75	3	1
April 5	700	2145	14.75	3	0
April 6	630	2000	13.50	3	0
April 7	900	1645	7.75	5	1
April 8	800	1230	4.50	5	2

Table 4. -- Summary of steelhead captured in Salmon Bay with gill nets. Capture sites are shown in Figure 3.

Tag	Date	Time	Site	Fork Length (mm)	Sex
1	March 8	1110	3	770	M
2	March 8	1035	3	870	F
3	March 8	900	3	--	M
4	March 21	820	5	800+	F
5	March 24	1145	5	--	M
6	April 8	1220	5	660	F
7	March 30	1615	3	580	M
8	April 7	1230	5	770	F
9	April 8	845	5	870	M

Table 5. -- Summary of tagging and release of steelhead with acoustic transmitters in Salmon Bay. Recovery time is the time from when the fish was tagged to when it was released. Release sites are shown in Figure 3. Time in Salmon Bay is the amount of time the fish remained in Salmon Bay after release.

Tag	Tagging date	Tagging time	Recovery time (h)	Release date	Release time	Site	Mobile tracking?	Time in Salmon Bay (min)
1	March 8	1230	5.9	March 8	1824	A	no	-
2	March 8	1235	5.9	March 8	1830	A	no	-
3	March 8	1230	6.1	March 8	1835	A	no	-
4	March 21	1230	9.5	March 21	2201	B	no	< 10
5	March 24	1430	9.2	March 24	2342	D	yes	23
6	April 8	1952	11.0	April 9	649	C	yes	20
7	March 30	2105	9.6	March 31	643	E	yes	32
8	April 7	1400	3.5	April 7	1730	C	yes	7
9	April 8	1255	21.3	April 9	1010	C	no	> 77

FISH TRACKING

After fish were released, they generally left Salmon Bay in a short time and returned to Puget Sound (Table 5). We were able to successfully track four fish with mobile tracking equipment. All four steelhead left Salmon Bay within 32 min of release. We did not obtain the mobile tracking equipment in time to track the first three fish immediately after their release. The other two fish were lost immediately after release by mobile trackers. Two fish did move upstream after release and were detected by the fixed hydrophone array for 73 and 10 min, respectively, but later they moved back downstream.

Only one tagged fish remained in Salmon Bay after 24 h of release. This tag remained stationary downstream of the railroad bridge for nine consecutive days. The tag may have been regurgitated or the fish died in that location. After the initial mobile tracking efforts, six fish were never detected again. Two steelhead returned to Salmon Bay and passed through the fish ladder.

A summary of tracking for each tagged fish is as follows:

Fish No. 1

Fish No. 1 left Salmon Bay sometime within 20 h of release. No detections of this tag were recorded.

Fish No. 2

Fish No. 2 moved upstream after release and was detected by the fixed hydrophone array for 10 min. The tagged fish was released at 1830 and was detected by hydrophone 4 between 1908 and 1917 and again from 1936 to 1937. Twenty hours after release, Salmon Bay was searched for the presence of tags with mobile tracking equipment for the first time. The tag was detected in the middle of the ship channel approximately 200 m below the railroad bridge. Afterwards, the area was typically checked once or twice each day and the tag appeared to be stationary in this position for nine consecutive days. The fish was presumed to have regurgitated the tag or died in that location.

Fish No. 3

Fish No. 3 left Salmon Bay sometime within 20 h of release. No detections of this tag were recorded.

Fish No. 4

After release, fish No. 4 appeared to swim off rapidly and the signal was quickly lost. Salmon Bay and inner Shilshole Bay were thoroughly checked during the next 2 h with no detections of the tag. Fish No. 4 apparently left Salmon Bay immediately after release. No further detections of this tag were recorded.

Fish No. 5

Fish No. 5 was released approximately 50 m upstream of the railroad bridge and 100 m downstream of hydrophone 4 (Figure 3). After release, the fish remained near the release site for approximately 5 min. The tag was detected by both hydrophone 4 and mobile tracking equipment. Afterwards, the fish moved steadily downstream. Within 30 min after release the fish had left Salmon Bay (Figure 5). The last known location of the fish was in inner Shilshole Bay, southwest of Salmon Bay (Figure 5).

Fish No. 6

Fish No. 6 left Salmon Bay after release and was followed with mobile tracking equipment south around West Point to the south end of Discovery Park (Figure 5). The last known location is approximately 5.3 km from the release site. Tagged fish No. 6 was followed for a total of 3 h and then abandoned. No further detections of this tag were recorded.

Fish No. 7

Fish No. 7 was released near the spill gates in the middle of the fixed array. The fish immediately moved downstream and left Salmon Bay within 20 min after release (Figure 6). The fish spent approximately 30 min in Shilshole Marina before moving to open water. The fish was slowly swimming in a northerly direction. It was visually seen at the water surface on three occasions for a total of 50 min. The signal was lost approximately 6.2 km from the release site (Figure 6). Fish No. 7 was followed for a total of 7.8 h.

After the initial tracking efforts, Tag No. 7 was detected again 45.8 h later at 1220 on April 2. The tagged fish was first detected with mobile tracking equipment on the south side of the ship channel, opposite of the entrance to Shilshole Marina. The signal was picked up for about 15-30 seconds and then lost. The tag was first detected by the fixed array tracking system at 1244 on hydrophone 3. The tide height at the time of first detection in the fixed array was 1.1 m and was ebbing (Figure 7). Detections continued on one or two hydrophones until a position solution was obtained at 1256 in the area approximately 7.5 m downstream of the small lock. Nearly continuous positioning data were collected from 1256 until 2045. The plot of all data is presented in Appendix Plot 1 showing each data point. Plot 2 shows the data points connected with a line, and Plots 3-24 show the plotted data in 15 min time intervals or until a time gap occurred of > 10 min.

During the 8 h that this tag was tracked, there were several time gaps of 10 min or more when the position of the tag could not be automatically determined by the tracking software. These periods range from 12 to 27 min and are due to the acoustic signal from the tag being received on fewer than three hydrophones. These gaps were most likely a result of the fish occupying aerated water (near the fish ladder or downstream of the small or large locks), leaving the area covered by the hydrophone array, or being in other

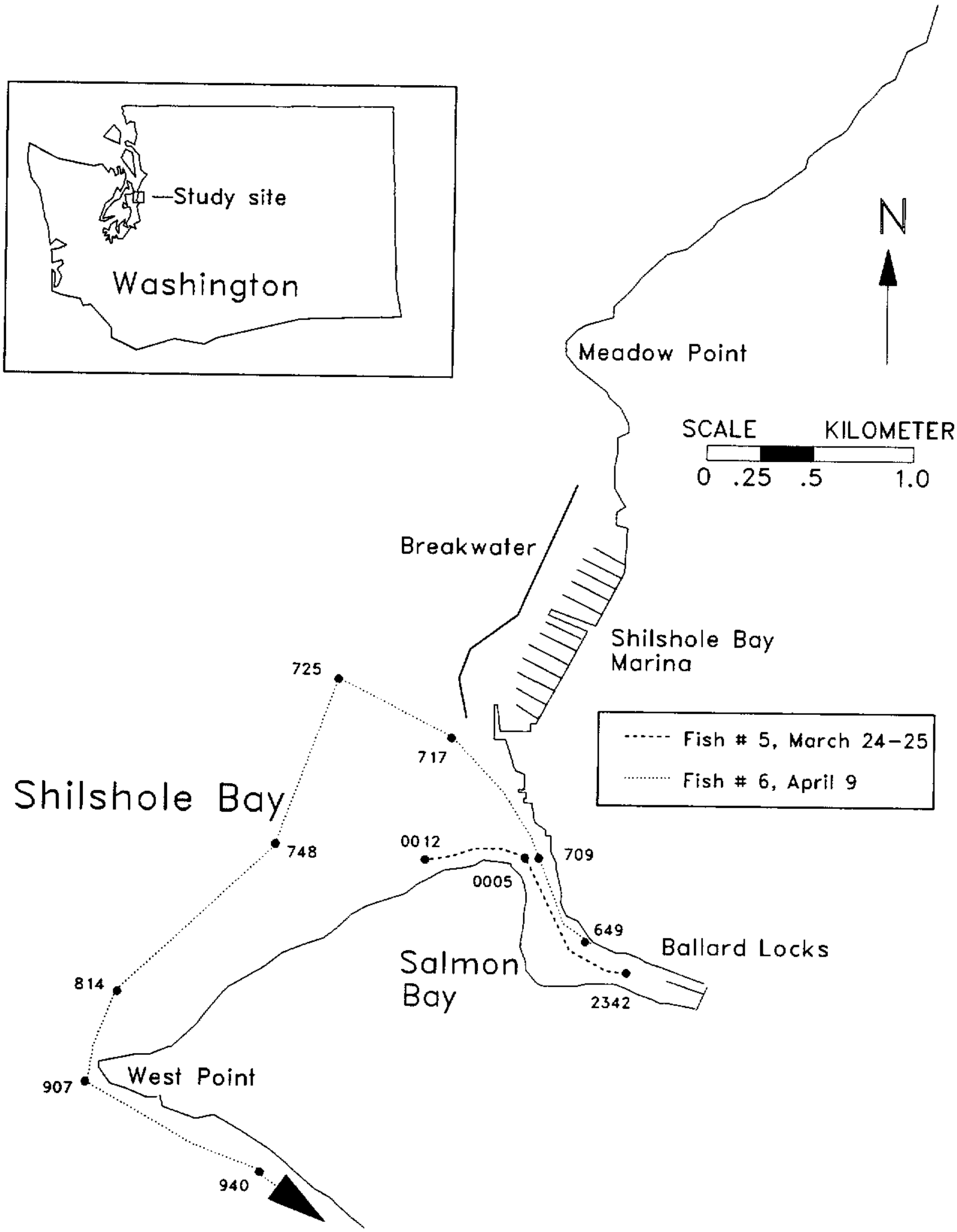

Figure 5. Movements of tagged fish No. 5 and No. 6 immediately after release.

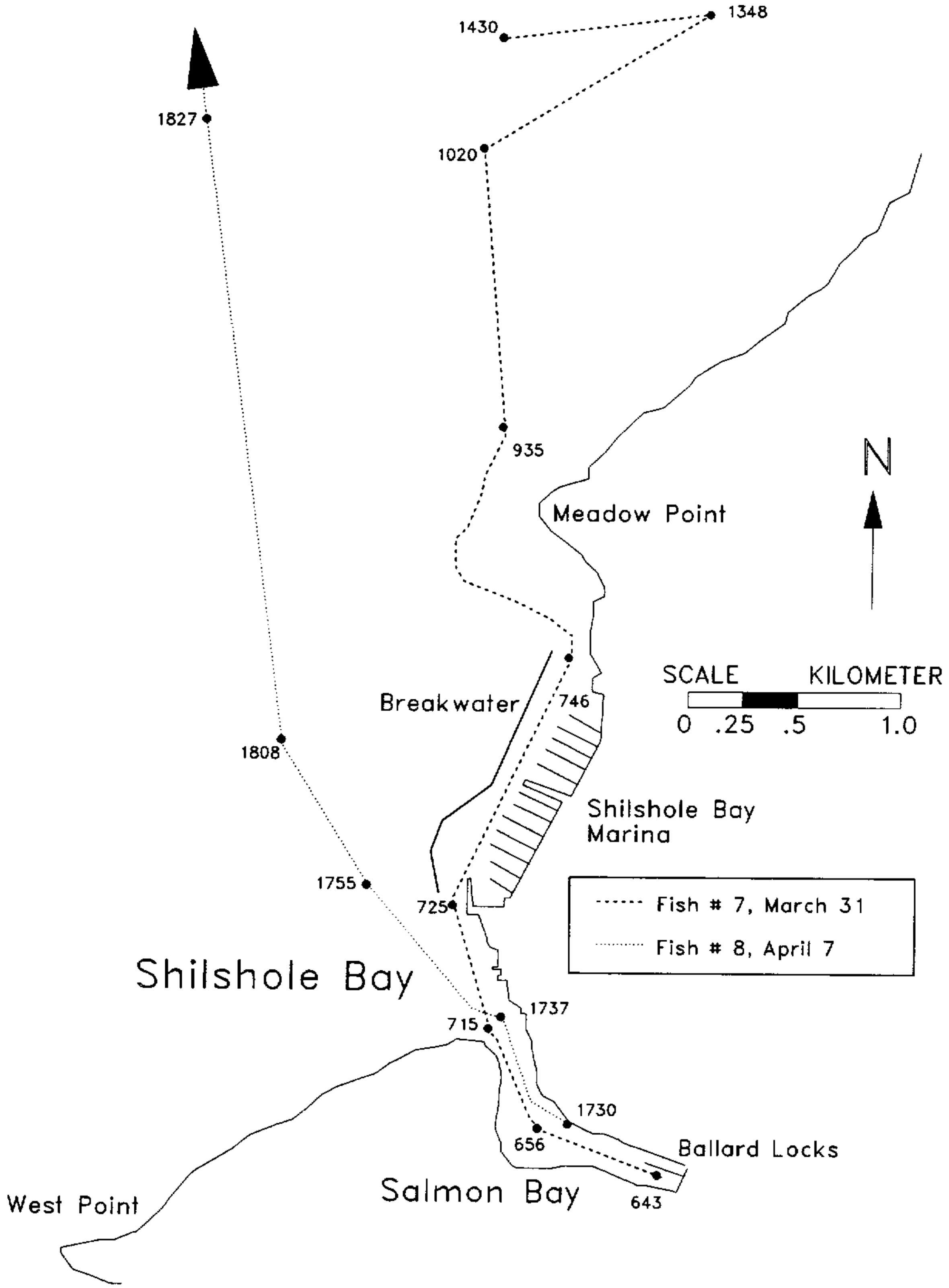

Figure 6. Movements of tagged fish No. 7 and No. 8 immediately after release.

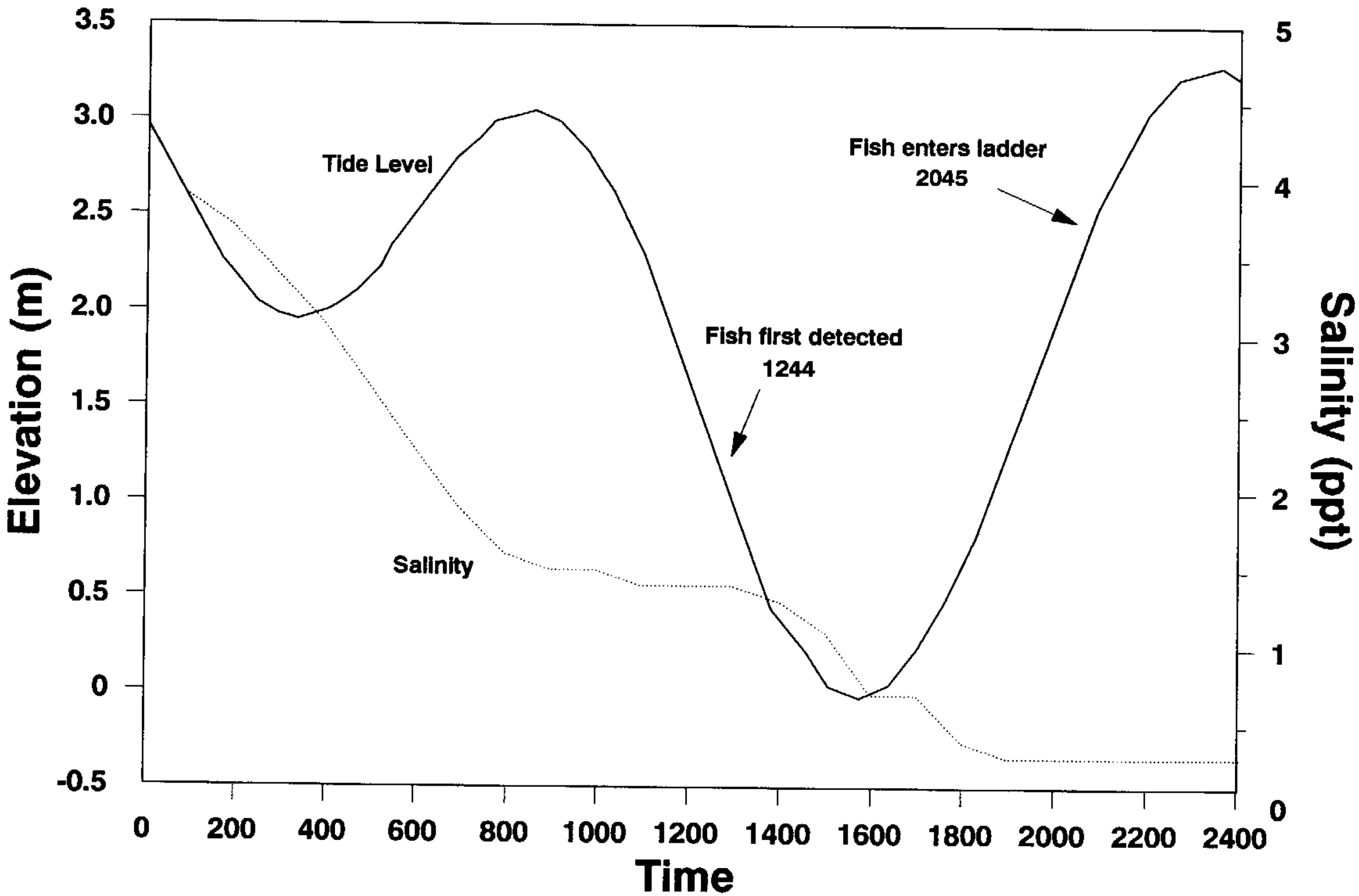

Figure 7. Relationship of salinity (entrance pool of fish ladder) and tide levels to fish movements for Tag No. 7 on April 2, 1994.

locations where the signal was not received by a least three hydrophones. These gaps are shown in Table 6. By manually inspecting the raw tracking data files, it was possible to add some data points within these gaps and estimate the probable location of the fish during the time gaps (Table 6). Location estimates were performed by looking at which hydrophones were receiving data and the signal strength measured by the hydrophone electronics. The estimated total time that the tagged fish spent in each observation cell (identified in Figure 4) below the locks is presented in Table 7 and Figure 8a. We were able to account for ≈94 % of the time the fish was in the array. The remaining time was when the fish moved between observation cells.

The fish spent over 65 percent of the time downstream of the locks in three observation cells (1, 6, and 10). It is interesting to note that each of these cells has a source of freshwater; cell 1 is adjacent to the fish ladder, cell 6 is below the small lock, and cell 10 is below the large lock.

Table 8 and Figure 8b present the time that the fish spent in each of the observation cells when down lockings were occurring. If the fish was attracted to the water being discharged during a down locking event, it would be expected that the time spent in cell 6 would be higher than time spent in the other cells. There does not appear to be any correlation between small lock operations (specifically down lockings) and the distribution of the tagged fish, indicating that there is not any special "attraction" to the small lock during down lockings. However. there may be a period of delay from when the lock adds attraction flow to when the fish is attracted to the flow. The large lock was also in operation during this time. However, because freshwater can be pumped out on both up and down lockings, it is difficult to assess when freshwater attraction flow would be present.

The tag was detected by the ladder monitoring system at 1920 for a 2-min period. This signal was weak, indicating that the fish was outside of the ladder entrance and did not actually enter the ladder. The tag was tracked until 2037 when position data were lost at a location near the center of the dam. Eight minutes later, at 2045, the fish entered the ladder for the first time. The length of time between when the fish entered the study area and when the fish first entered the ladder was 8 h and 1 min. There was no spill during this entire time period.

When the fish entered the ladder, the tide was flooding at a height of 2.5 m and salinity in the entrance pool to the fish ladder was low (0.3 ppt; Figure 7). The signal at the hydrophone in the bottom of the ladder was lost at 2057 when the fish exited the ladder at the downstream end. The fish reentered the ladder 14 min later at 2111. The signal was again lost at 2121 when the fish moved farther up the ladder.

Weak signals from the tag were detected by the fish ladder tracking system while the fish was inside ladder, and the last detection on the tracking system occurred at 2121. The ladder monitoring system detected a weak signal at the downstream hydrophone at 2141 for 2 min. These signals are thought to have been transmitted through the concrete walls of the fish ladder.

Table 6. -- Gaps of 10 min or greater in positioning data for Tag No. 7, frequency 63.6 kHz, on April 2, 1994 (see Figure 4 for cell locations).

Easting	Northing	Time	Time difference	Event	Last known location	Probable location during gaps
		1244		First detection of tag		Cell 8
9707	10037	1256		Start tracking	Cell 6	
9501	10056	1344		Lose track	Cell 6	Cell 10
9501	10056	1405	0:21	Plot single position point	Cell 6	
9634	10054	1425	0:19	Plot single position point	Cell 6	
9682	10032	1450	0:24	Resume track	Cell 6	
9600	10036	1505		Lose track	Cell 6	Cell 10
9600	10043	1517	0:12	Plot single position point	Cell 6	Cell 10
9373	10226	1525	0:07	Three detections outside of study area	Cell 10	Cell 10
9583	10077	1534	0:09	Resume track	Cell 6	
9865	9868	1544		Lose track	Cell 3	Cell 3
9879	9868	1556	0:12	Resume track	Cell 3	
10009	9805	1741		Lose track	Cell 1	Cell 1
9899	9859	1758	0:16	Resume track	Cell 3	
9567	10136	1803		Lose track	Cell 6	Cell 10
9588	10101	1821	0:18	Resume track	Cell 6	
10092	9907	1921		Lose track	Cell 2	Cell 1
10092	9917	1939	0:18	Resume track	Cell 2	
9971	9831	2008		Lose track	Cell 1	Cell 1
9971	9831	2035	0:27	Resume track	Cell 1	
10068	9866	2037		End tracking	Cell 2	Cell 1
		2045	0:07	Fish enters ladder		
		2057		Fish exits ladder		Cell 1
		2111	0:14	Fish reenters ladder		In Ladder
		2215	1:04	Fish exits top of ladder	Above dam	
		2225	0:10	End detection of tag		Above dam

Table 7. -- Total time and percentage of time spent by Tag No. 7 in observation cells at the Ballard Locks.

Observation cell	Total time spent in observation cell (hh:mm:ss)	Percentage of time spent in observation cell
1	1:35:27	21.5
2	0:49:03	11.0
3	0:41:23	9.3
4	0:47:20	10.7
5	0:21:12	4.8
6	1:28:32	19.9
7	0:00:00	0
8	0:00:00	0
9	0:00:15	0.1
10	1:41:00	22.7

Table 8. -- Total time and percentage of time spent by tag No. 7 in observation cells during small lock down locking events at the Ballard Locks.

Observation cell	Total time spent in observation cell (hh:mm:ss)	Percentage of time spent in observation cell
1	0:11:01	8.4
2	0:21:17	16.1
3	0:09:39	7.3
4	0:26:22	20.0
5	0:01:48	1.4
6	0:23:42	18.0
7	0:00:00	0.0
8	0:00:00	0.0
9	0:00:00	0.0
10	0:38:00	28.8

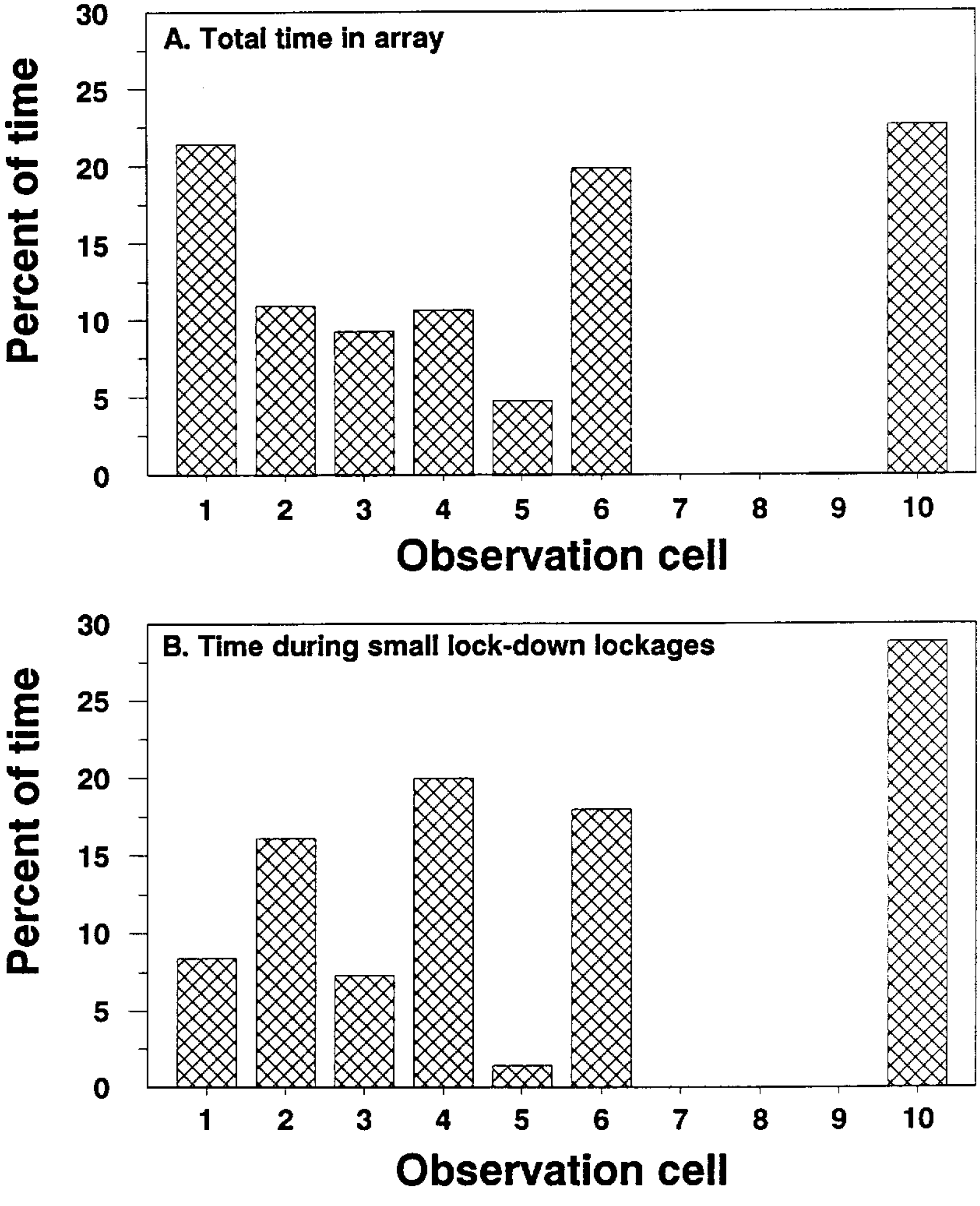

Figure 8. Percentage of time spent by tag No. 7 in observation cells at Ballard Locks. A) percentage of total time spent in observation cells near the fixed hydrophone array and B) percentage of time spent in observation cells during small lock-down lockage. Observation cells are shown in Figure 4.

The tag was next detected upstream of the ladder between 2215 and 2225. The transit time between the tag entering the ladder the second (final) time and exiting the ladder was 1 h and 4 min. No further detections of this tag occurred.

The tag was never detected by the hydrophone in the viewing chamber. A check of the ladder monitoring system showed that the hydrophone was functioning but that it was fouled with a large mass of algae which was blocking the acoustic signal. The hydrophone was repositioned to avoid further fouling problems.

Tag No. 8

Fish No. 8 left Salmon Bay within minutes of release. The fish was followed northwest approximately 7 km to the middle of Puget Sound (Figure 6). Fish was followed for 1.6 h and then abandoned.

Tag No. 9

Tagged fish No. 9 was released at 1010 on April 9. The fish swam away rapidly after release and was lost within a minute by mobile trackers. Four minutes after release the tag was however, detected upstream near the fixed hydrophone array. The tag was detected by two hydrophones between 1014 and 1127. No position data were obtained because the signal was received by less than three hydrophones.

The fish returned to the study area and passed through the fish ladder five days later on April 14. The first detection of the tag by the tracking system occurred at 1214 on hydrophones 3 and 4. This was prior to ebb slack tide at 0.38 m (Figure 9). The signal from the tag was erratically detected by one or two hydrophones with several detection gaps occurring until 1634 hrs when the signal was finally lost. No position data could be obtained due to turbulent water conditions. The length of time between the first detection of the tag and when the fish was detected in the fish ladder at 1655 was 4 h and 41 min. During this time interval, spill volume varied from 0 to 32.5 m^3/s (Table 9). Entrance pool head was visually estimated and varied from 35 to 26 cm (Figure 9).

The fish entered the ladder on the flooding tide at 1.28-m msl and salinity in the entrance pool to the fish ladder was relatively low (Figure 9). Spill volume was 13.0 m^3/s (the second and third gates closest to the fish ladder were each open 0.15 m) when the fish entered the ladder. The tag was detected in lower fish ladder for 9 min ending at 1704. The hydrophone in the viewing chamber then picked up the signal between 1744 and 1754. Next, the tag was detected upstream of the fish ladder from 1757 to 1821 and from 1845 to 1909. Total transit time through the ladder was 1 h and 2 min.

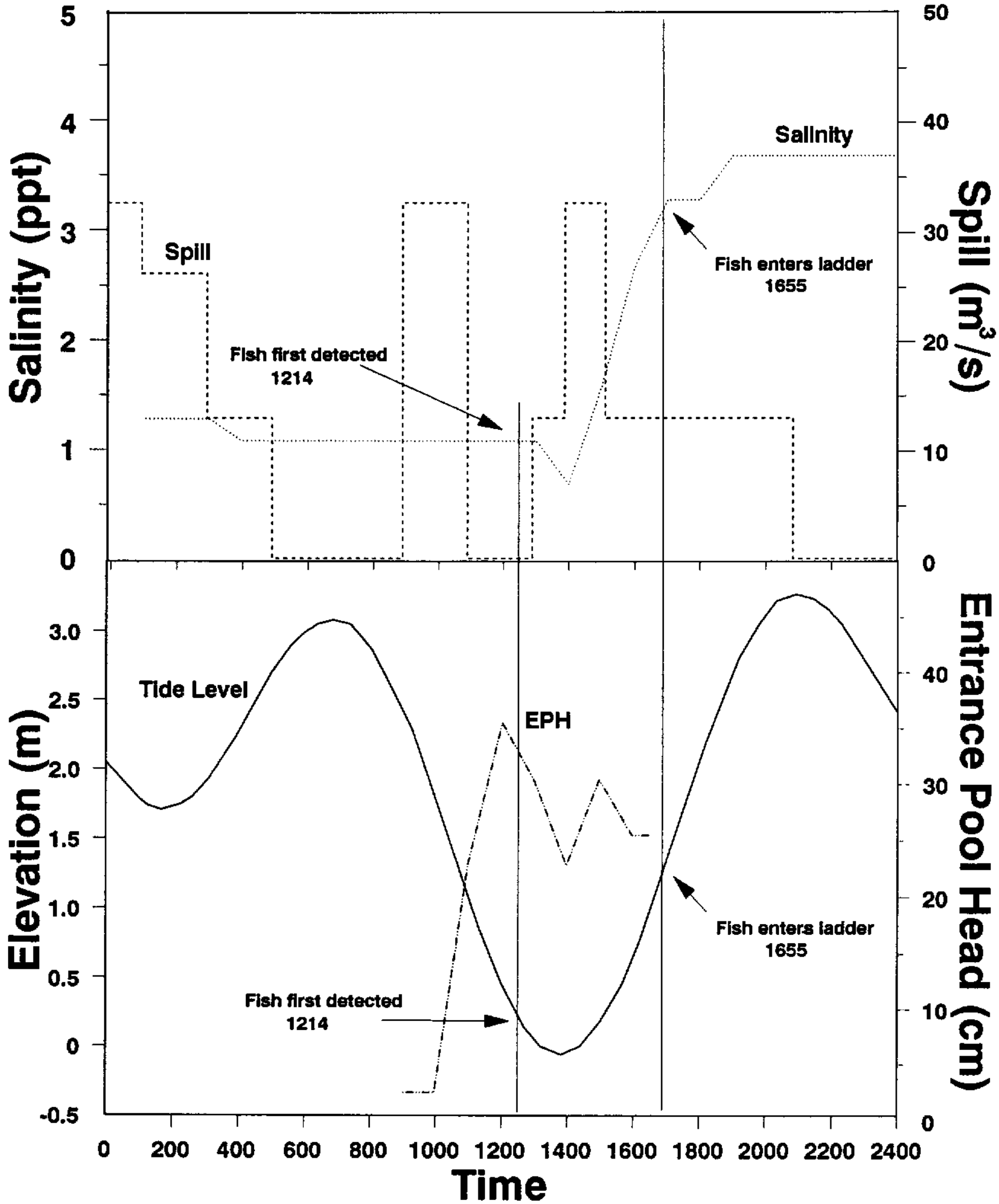

Figure 9. Relationship of salinity (entrance pool of fish ladder), spill, tide level, and entrance pool head to fish movements for Tag No. 9 on April 14, 1994.

DISCUSSION

LOSS OF FISH

Most tagged steelhead moved downstream and left Salmon Bay a short time after release and were not detected again. Downstream movements after tagging are most likely steelhead destined for other watersheds or a result of handling stress.

Handling stress, such as from tagging and gill netting, can have important effects on the physiology and behavior of fishes. Barton et al. (1986), and Sigismondi and Weber (1988) have demonstrated that acute handling stresses can also have a cumulative effect on their physiology and behavior. Steelhead we collected were handled twice plus some additional stress may have occurred when the fish were released. Three of the fish were also transported a short distance to a release site. Each stressor may have affected the fish's behavior, and the effects were probably cumulative. Stressed fish often have general lethargic behavior, stop feeding, seek cover (Mesa and Schreck 1989), and have increased susceptibility to predation (Herting and Witt 1967). Tagged steelhead released in streams often move downstream or remain near the release site (Burger 1983, Wampler 1984, Snohomish County P.U.D. District 1 1989). Adult tagged steelhead (Ruggerone et al. 1990) and salmon (Quinn et al. 1989, Ogura and Ishida 1992) released in open marine areas often make steep dives to deep water for the first 30-60 min after release. Afterwards, they appeared to have more typical movements near the surface. Most steelhead we tagged moved downstream rapidly, which may indicate a stress response to move to deeper, more open waters. Stressed steelhead may also have had increased susceptibility to sea lion predation. Fish No. 7 was visually observed at the surface and appeared somewhat stressed due to its lethargic behavior and on one occasion it was easily approached by a sea gull. Lethargic behavior was not noted in the other fish tracked.

The amount of recovery time needed before releasing the tagged steelhead is not known. Recovery time can vary widely depending on environmental conditions and the amount and type of stress. Fried et al. (1976) recommended a recovery period of 8 h for tagged Atlantic salmon smolts (*Salmo salar*). Mesa and Schreck (1989) found wild cutthroat trout (*O. clarki*) that have been electroshocked need 24 h to recover. Fish that have undergone multiple acute stress may take over 24 h to fully recover (Sigismondi and Weber 1988). We held steelhead from 3.5 to 21.3 h after tagging. Because both fish that returned to Salmon Bay were held overnight (recovery time of 9.6 and 21.3 h), there was some preliminary indication that a long recovery period is needed.

If some steelhead had a protracted recovery period, they may have passed through the fish ladder after their tag batteries were expired. Everest (1973) found some steelhead were delayed as much as 31 days in the estuary after tagging. The battery life of our tags ranged from 10 to 24 days and thus could have been too short. However, the two steelhead that did return to Salmon Bay, came back in 5 days or less. Longer battery life would certainly be preferable. Battery life can be increased if pulse rate or signal strength is reduced, but the likelihood of detection is reduced. Tag size can also be increased to increase battery life but can easily exceed the appropriate size to fit in the fish's stomach.

The size of tag in relation to the fish's size can affect recovery time (Moser et al. 1990). Based on experiments with juvenile coho salmon, Moser et al. (1990) recommended a recovery time of 4 h for tags weighing up to 5% of the fish's body weight and 36 h for tags of 9% of the fish's body weight. McCleave and Stred (1975) found dummy transmitters representing up to 5% of the body weight did not significantly reduce swimming performance of Atlantic salmon. Based on length to weight relationships for steelhead, we estimated our tags ranged from 0.4 to 1.3% of the fish's weight. Thus tag weight did not appear to be a major problem in recovery time. The length of the tag (58 mm) appeared to only be a potential problem in the smallest fish (580 mm FL), however this fish did return to Salmon Bay and pass through the fish ladder. Depth tags (90 mm length) could probably be used in steelhead larger than 800 mm FL.

Besides the effects of handling stress, the downstream movement and loss of steelhead can also be attributed to fish movements to other river systems. The upstream migration of steelhead and salmon often involves a certain amount of testing or "proving" in non-natal streams (Ricker 1972). Fish may ascend the wrong stream a certain distance, return downstream, and then eventually migrate to the home stream (Taft and Shapovalov 1938, Labelle 1992). Steelhead in the Columbia and Snake rivers commonly make temporary detours into tributaries with cooler waters (Bjornn and Peery 1992). Strays may also remain in a non-natal stream and spawn there. In other river systems the percent of steelhead strays is often low (Everest 1973, Leider et al. 1985). However, the percent of strays in Salmon Bay may currently be high because the number of steelhead returning to Salmon Bay has declined to precariously low numbers while stocks in neighboring river systems (Green River and Snohomish River) have remained healthy (SASSI 1993). The 1994 escapement through Ballard Locks was estimated to be 70 fish over a 4 month period (0.58 fish/day; Pfeifer, unpublished data). Our catch rate of 0.75 fish/day appears somewhat higher than expected, considering that we only fished 10 h/day and only used one 46-m net. However, our fishing effort may have simply coincided with pulses of fish movements.

FISH TRACKING SYSTEM

Use of the fixed hydrophone system proved to be a valuable tool in tracking steelhead at Ballard Locks. The major limitation of the system is entrained air that occurs during spill conditions. Alleviating this problem would probable require deploying a system with more hydrophones. Currently three of the four hydrophones are required to determine a fish's location. As more hydrophones are added, and the distance between them is reduced, the likelihood of getting detections would increase. Additionally, a system which can simultaneously scan for several tags would also increase the chance of determining a fish's location. The current system can only search within single 2 kHz-wide channels for deployed tags. Consequently, the receiver must scan several channels if the tag frequencies are not within the same 2 kHz band, which means that simultaneous, continuous tracking of all tags is not possible.

Continuously following tagged fish with mobile tracking gear in Puget Sound proved to be difficult. We followed the fish to get a general idea of their movement patterns after release. If their return times are 2-5 days or longer, continuous mobile tracking would require a larger boat and excessive personnel time to continuously track fish. Because the main objective is to track fish as they move through Ballard Locks, the most efficient use of funds would be to develop an improved fixed hydrophone array and limit the amount of mobile tracking. One fixed hydrophone at the entrance to Salmon Bay would probably be adequate to detect tagged fish leaving and reentering Salmon Bay.

FISH PASSAGE AND DELAY

Both steelhead that eventually passed through the Ballard Locks area appeared to be somewhat delayed. Fish No. 7 moved from Shilshole Bay to the fixed array (≈1.3 km) in 24 min, but then took 8 h to enter the fish ladder. Fish No. 9 spent 4 h and 41 min near the fixed array before entering the fish ladder. Similarly, steelhead in the Columbia and Snake rivers migrate rapidly between dams but are delayed below each dam (Bjornn and Peery 1992). Fish passage at dams is most efficient when 1) there are suitable attraction flows to lead fish to the fish ladder entrances, 2) the entrances to fish ladders can be found and entered without difficulty, and 3) fish migrate rapidly through the fish ladders (Bjornn and Peery 1992).

Salinity in the entrance pool may influence the quality of attraction water for fish. During the periods when tagged steelhead were in the array, salinities in the entrance pool were low (≤ 3.3 ppt) and thus did not appear to be an important factor in delaying their passage. An analysis of fishway salinity and hourly steelhead passage rates indicates there may be a threshold of 9-10 ppt salinity, above which steelhead passage is inhibited (Infometrix 1994, Pfeifer 1994). Data and evidence are not conclusive on this point, and fishway salinities at or above 10 ppt occurred in only 4.3% of 3771 near-consecutive hours sampled in the winter-spring of 1992-93.

Another quality influencing attraction for fish to the ladder is velocity. Discharge through the fishway is maintained at a constant rate, however water velocities exiting the fishway vary widely depending on the tidal stage. At some low tides, the elevation difference between the entrance pool and the saltwater can cause high velocities which may delay passage. At some high tides, current velocities may be very low and difficult to detect by fish. Entrance pool head (EPH) dictates the water velocities exiting the fishway's west and north entrance slots. In general, low tide stages are associated with large EPH values and high water velocities, and higher tides are associated with low EPH levels and low water velocities. Cross-tabulation of 1992-93 steelhead passages and fishway EPH suggests that steelhead do not enter the fishway when the EPH is less than 10 cm, or more than 43 cm (Infometrix, Inc. 1994). EPH was < 10 cm or > 43 cm 33.6% of the time in a sample of 378 separate hourly EPH measurements in 1994 (Pfeifer, unpublished data). Movements of sockeye salmon into the fishway at Ballard Locks can be delayed during tidal stages above 1.8 m when freshwater velocities are reduced (M. Mahovlich, Muckleshoot Tribe, unpublished data) . In this study, both tagged fish entered the fishway at intermediate tide stages. Thus, fish passage appears to most efficient at intermediate tidal elevations.

Besides tidal stage, the direction of the tide may also be important. The two tagged fish that passed through Ballard Locks entered the fishway during afternoon-evening flood tides. Analysis of hourly fish passages in the fishway in comparison to tide levels indicate a preference by steelhead for early morning-to-midday flood tides (Infometrix, Inc. 1994).

Spill discharge patterns at dams often affect fish passage rates. During high river flow conditions fish can be delayed (e.g. Haynes and Gray 1980). However, fish are often attracted to spillgate discharges, which may be beneficial if they are led to fish ladder entrances (Bjornn and Peery 1992). At Columbia and Snake river dams which have separate fish ladders near the spillgates and powerhouses, the relative use of each fish ladder will shift depending on the flow patterns (Bjornn and Peery 1992). The overall rate of fish passage can be increased when even a small amount of water is spilled to attract fish (Junge and Carnegie 1973). At Ballard Locks, a specific spillgate flow pattern has been developed to attract fish to the fishway. However, during low flow periods there is often no spill to help guide the fish to the fishway. A high percentage of the freshwater flow will come from the small and large locks. This may in part explain the difference in delay between the two tagged steelhead. Passage rates could potentially increase during low to moderate spill conditions which would guide the fish to the fishway but not cause significant delays due to high flows. However, the analysis performed by Infometrix, Inc. (1994) failed to show any strong correlation between spill volumes and steelhead passages up the fishway at the Ballard Locks.

Unlike at most dams, anadromous salmonids that migrate past Ballard Locks must move from saltwater to freshwater. Steelhead may be delayed due to the operation and design of the fishway or they may spend time below the fishway to acclimate to freshwater. Steelhead and salmon must undergo physiological changes as they approach freshwater. However, the amount of time required to acclimate to freshwater is not well known. Everest (1973) visually observed that large schools of steelhead moved rapidly through the bay and estuary, and into the Rogue River. This may indicate that steelhead are ready to enter freshwater as they approach the estuary and require little time to acclimate to reduced salinities. At Ballard Locks however, there is a sharp gradient between saltwater and freshwater and fish may spend some time below the fish ladder adjusting to the abrupt change in salinity.

Both fish passed through the fish ladder in slightly over an hour. Although passage time through the fish ladder did not appear to be a problem, changes in water velocities could alter passage time. Passage through the fish ladder accounted for only 11 and 18% of the total delay time. Likewise, passage through fish ladders on the Columbia and Snake river dams makes up a small percentage of the delay time at each dam (Bjornn and Peery 1992).

When fish No. 7 was in the array, it appeared to spend most of the time near the three freshwater sources. These same areas are also where a substantial amount of steelhead have been preyed on by sea lions (Pfeifer 1989, 1991a, 1991b). However, during the 8 h that fish No. 7 was in the array, no sea lions were present. Therefore, the observed movements of fish No. 7 do not necessarily reflect steelhead behavior when sea lions are present. Steelhead behavior may be significantly altered when sea lions are present. Predators often have profound effects on the behavior of fishes (Stein 1979, Helfman 1986).

RECOMMENDATIONS

1. Due to the small sample size in 1994, further tagging is recommended to 1) further refine tracking techniques, 2) test fish passage under a variety of conditions and 3) make more definitive conclusions.

2. Due to the small run size of wild steelhead, we recommend using hatchery steelhead or another species such as coho salmon to refine techniques prior to further studies directly on wild steelhead.

3. Deploying a fixed hydrophone array system with more hydrophones to increase the likelihood of getting detections during spill conditions.

4. Upgrade the current fixed hydrophone array system to simultaneously scan for several tags and thus increase the chance of determining a fish's location.

5. Deploy a fixed hydrophone at the entrance to Salmon Bay to detect tagged fish leaving and reentering Salmon Bay. Mobile tracking should done on a limited basis.

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REFERENCES

Ad Hoc Technical Committee. 1990. Report of the committee on feasibility of structural additions or modifications to limit sea lion predation in the Lake Washington Ship Canal. USDC-NOAA. Nat. Mar. Fish. Serv. Northwest Region. 27 pp. mimeo.

Ajwani, S. 1956. A review of Lake Washington watershed, historical, biological, and limnological. Master of Science thesis, Univ. Wash.

Barton, B.A., C.B. Schreck, and L.A. Sigismondi. 1986. Multiple acute disturbances evoke cumulative physiological stress responses in juvenile chinook salmon. Transactions of the American Fisheries Society 115:245-251.

Bjornn, T.C., C.A. Peery. 1992. A review of literature related to movements of adult salmon and steelhead past dams and through reservoirs in the lower Snake River. Technical report 92-1, U.S. Army Corps of Engineers, Walla Walla, Washington.

Burger, C., M. Scott, and M. Small. 1983. Overwintering and spawning areas of steelhead trout (*Salmo gairdneri*) in tributaries of the Upper Copper River, Alaska. Final report. U.S. Fish and Wildlife Service, Anchorage, Alaska.

Chrzastowski, M. 1981. Historical changes to Lake Washington and route of the Lake Washington Ship Canal, King County, Washington. Water Resources Investigation Open-File Report 81-1182, U.S. Geological Survey, USDI. 8 pp.

Everest, F.H. 1973. Ecology and management of summer steelhead in the Rogue River. Oregon State Game Commission, Fishery Research Report No. 7.

Fried, S.M., J.D. McCleave, and K.A. Stred. 1976. Buoyancy compensation by Atlantic salmon (*Salmo salar*) smolts tagged internally by dummy telemetry transmitters. Journal of the Research Board of Canada 32:559-563.

Haynes, J.M. and R.H. Gray. 1980. Influence of Little Goose Dam on upstream movements of adult chinook salmon. Fisheries Bulletin 78:185-190.

Helfman, G.S. 1986. Behavioral responses of prey fishes during predator-prey interactions. Pages 135-156 *in* M.E Feder and G.V. Lovder, editors. Predator prey relationships. University of Chicago Press, Chicago.

Herting, G.E., and A. Witt. 1967. The role of physical fitness of forage fishes in relation to vulnerability to predation by bowfin (*Amia calva*). Transactions of the American Fisheries Society 96:427-430.

Infometrix, Inc. 1994. Statistical and pattern recognition multivariate analysis of winter steelhead passage rate, environmental and operational variables at the Lake Washington Ship Canal/Ballard Locks fishway. Final Report, Infometrix, Inc., Seattle, Washington.

Junge, C.O. and B.E. Carnegie. 1973. Operational studies (1972-73). Fish Commission of Oregon, Clackamas, Oregon.

Labelle, M. 1992. Straying patterns of coho salmon (*Oncorhynchus kisutch*) stocks from southeast Vancouver Island, British Columbia. Canadian Journal of Fisheries and Aquatic Sciences 49:1843-1855.

Lieder, S.A., M.W. Chilcote, and J.J. Loch. 1985. Kalama River studies final report, Part III, adult life history and movement studies. Washington Dept. of Game, Fish Management report No. 85-13, Olympia.

McCleave, J.D. and K.A. Stred. 1975. Effect of dummy telemetry transmitters on stamina of Atlantic salmon (*Salmo salar*) smolts. Journal of the Fisheries Research Board of Canada 32:559-563.

Mesa, M.G., and C.B. Schreck. 1989. Electrofishing mark-recapture and depletion methodologies evoke behavioral and physiological changes in cutthroat trout. Transactions of the American Fisheries Society 118:644-658.

Moser, M.L., A.F. Olson, and T.P. Quinn. 1990. Effects of dummy ultrasonic transmitters on juvenile coho salmon. American Fisheries Society Symposium 7:353-356.

Ogura, M. and Y. Ishida. 1992. Swimming behavior of coho salmon, *Oncorhynchus kisutch*, in the open sea as determined by ultrasonic telemetry. Canadian Journal of Fisheries and Aquatic Sciences 49:453:457.

Pfeifer, B. 1989. Monitoring of the 1988-89 California sea lion control program in the Lake Washington estuary. Fishery Management Report 89-12, Washington Department of Wildlife, Mill Creek, Washington.

Pfeifer, B. 1991a. Monitoring of the 1989-90 California sea lion control program in the Lake Washington estuary. Fishery Management Report 90-17, Washington Department of Wildlife, Mill Creek, Washington.

Pfeifer, B. 1991b. Monitoring of the 1990-91 California sea lion control program in the Lake Washington estuary. Report 91-19, Fisheries Management Division, Washington Department of Wildlife, Mill Creek, Washington.

Pfeifer, B. 1994. Analyses of winter steelhead passage through the Hiram Chittendon Locks fishway in relation to environmental conditions and steelhead run sizes, 1989-1994. Washington Department of Wildlife, Mill Creek, Washington.

Quinn, T.P., B.A. Terhart, and C. Groot. 1989. Migratory orientation and vertical movements of homing adult sockeye salmon, *Oncorhynchus nerka*, in coastal waters. Animal Behaviour 37:587-599.

Ricker, W.E. 1972. Hereditary and environmental factors affecting certain salmonid populations. Pages 27-160 *in* R.C. Simon and P.A. Larkin, editors. The stock concept in Pacific salmon. H.R. MacMillan Lectures in Fisheries, University of British Columbia, Vancouver.

Ruggerone, G.T., T.P. Quinn, I.A. McGregor, and T.D. Wilkinson. 1990. Horizontal and vertical movements of adult steelhead trout, *Oncorhynchus mykiss*, in the Dean and Fisher channels, British Columbia. Canadian Journal of Fisheries and Aquatic Sciences 47:1963-1969.

SASSI. 1993. 1992 Washington state salmon and steelhead stock inventory. Washington Dept. of Fisheries, Wash. Dept. of Wildlife, and Western Wash. Treaty Indian Tribes, Olympia, Washington.

Scordino, J. and B. Pfeifer. 1993. Sea lion/steelhead conflict at the Ballard Locks. History of the control effort to date, a bibliography of technical reports, November 1993. Unpublished manuscript, Washington Department of Fish and Wildlife, Mill Creek, Washington.

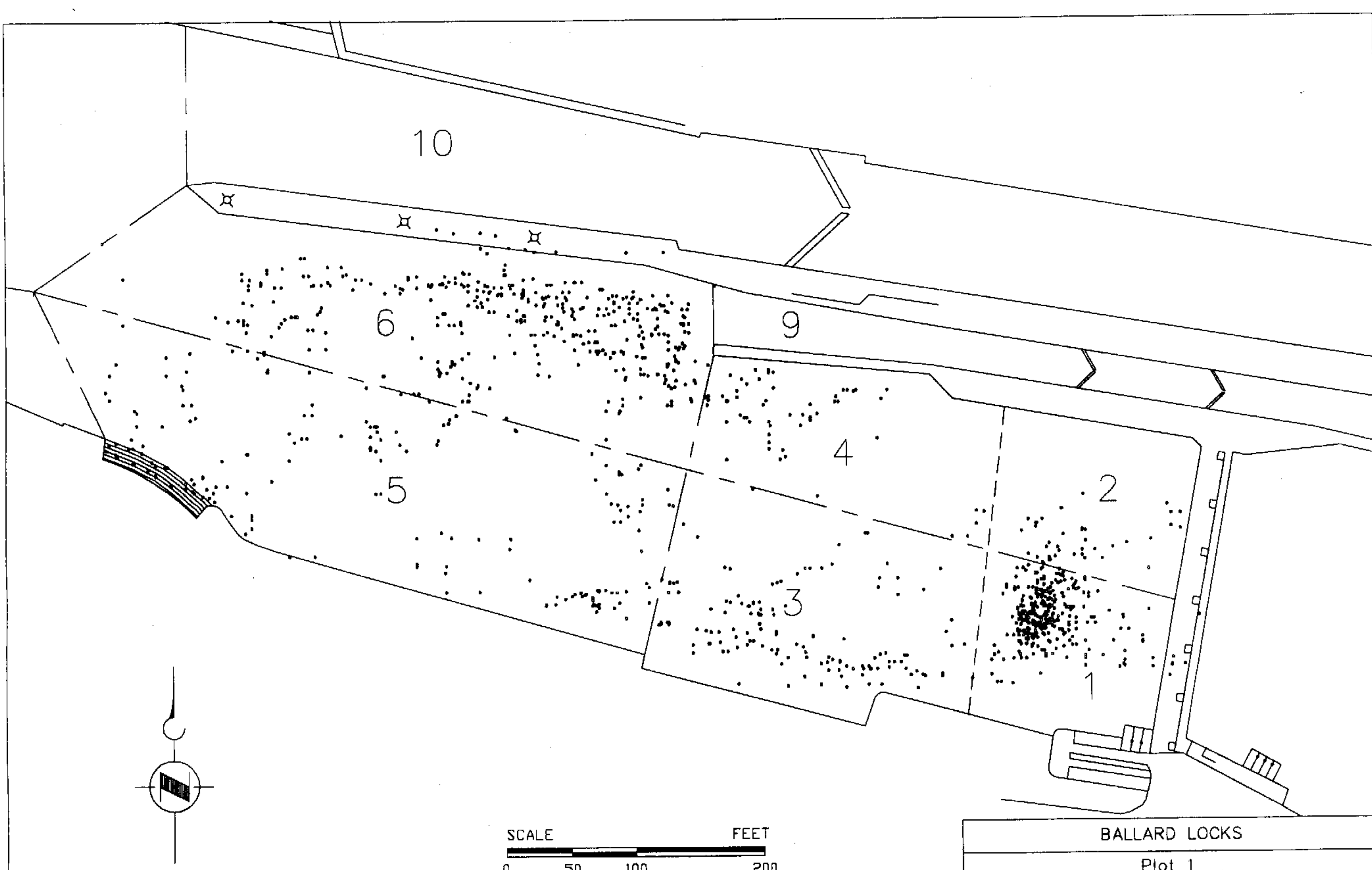
Sigismondi, L.A. and L.J. Weber. 1988. Changes in avoidance response time of juvenile chinook salmon exposed to multiple acute handling stresses. Transactions of the American Fisheries Society 117:196-201.

Snohomish County P.U.D. District 1. 1989. Adult fish passage (powerhouse berm) study. Final report. Henry M. Jackson (Sultan River) hydroelectric project, FERC Project No. 2157, Everett, Washington.

Stein, R.A. 1979. Behavioral response of prey to fish predators. Pages 343-353 *in* H. Clepper, editor. Predator-prey systems in fisheries management. Sport Fishing Institute, Washington, D.C.

Taft, A.C. and L. Shapovalov. 1938. Homing instinct and straying among steelhead trout (*Salmo gairdneri*) and silver salmon (*Oncorhynchus kisutch*). California Fish and Game 24:118-125.

Wampler, P.A. 1984. Radio telemetry assessment of adult summer run steelhead behavior following release in the upper Elwha River. Miscellaneous report. U.S. Fish and Wildlife Service, Fisheries Assistance Office, Olympia, Washington.

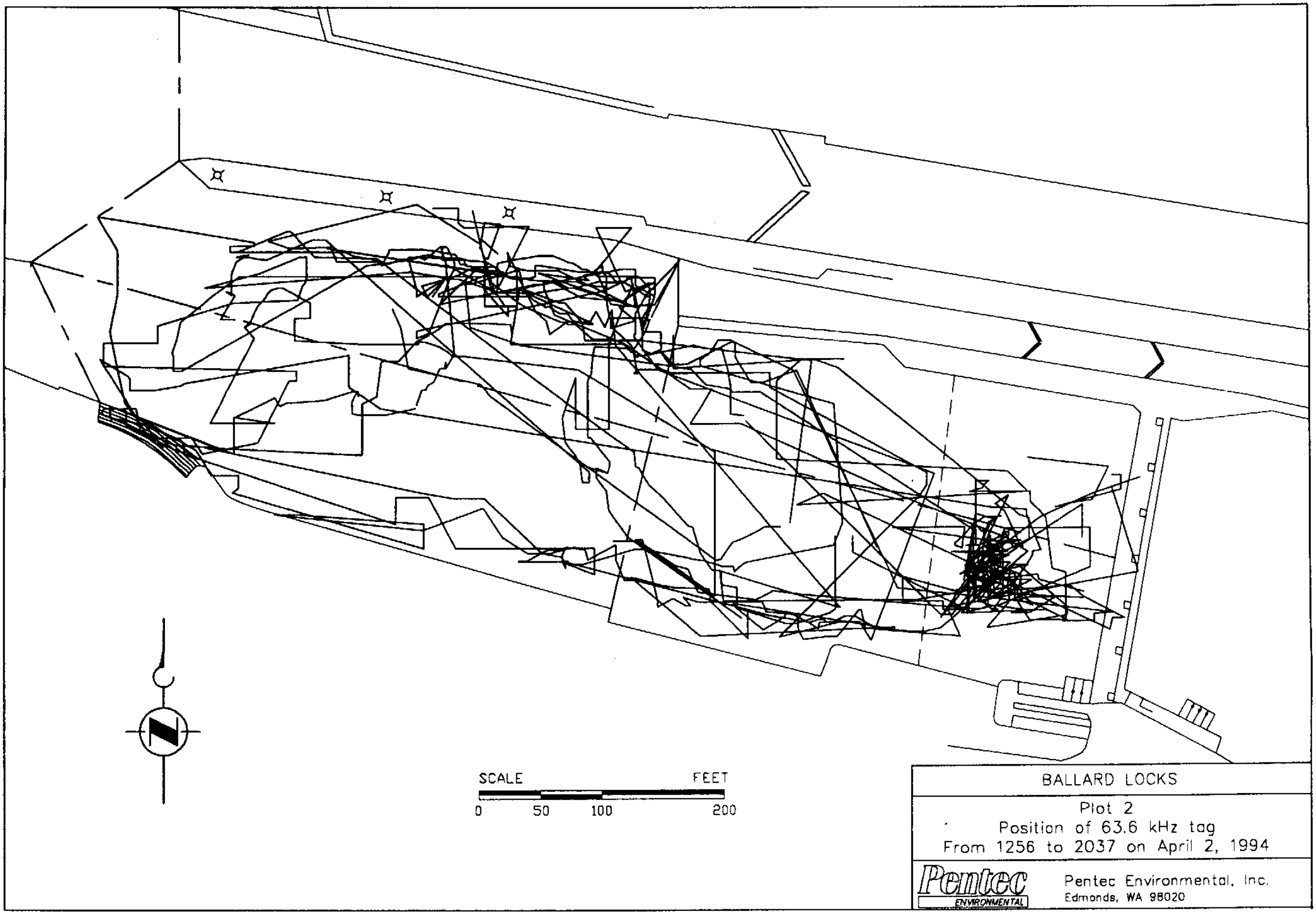


BALLARD LOCKS

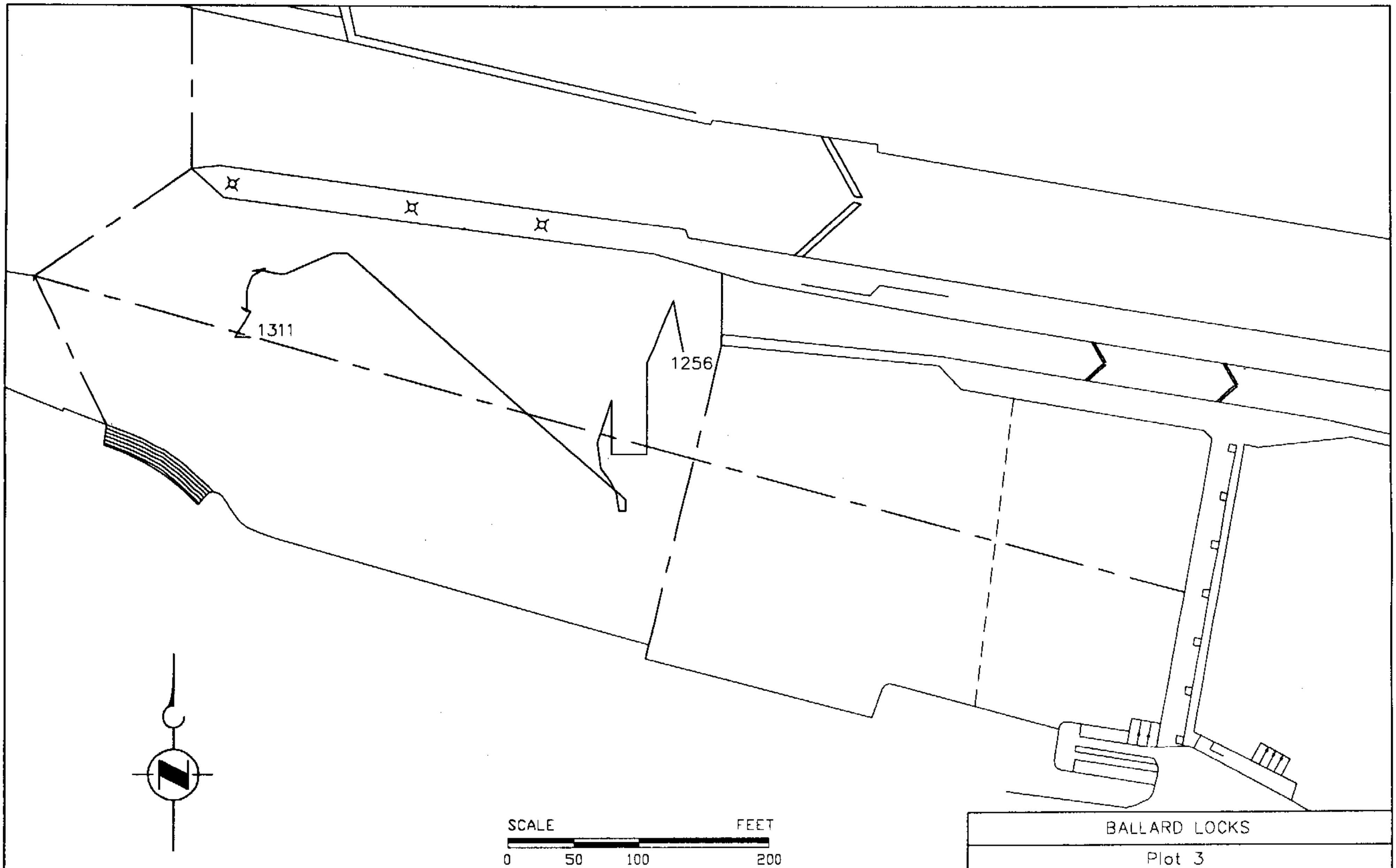
Plot 1
Position of 63.6 kHz tag
From 1256 to 2037 on April 2, 1994

Pentec ENVIRONMENTAL

Pentec Environmental, Inc.
Edmonds, WA 98020



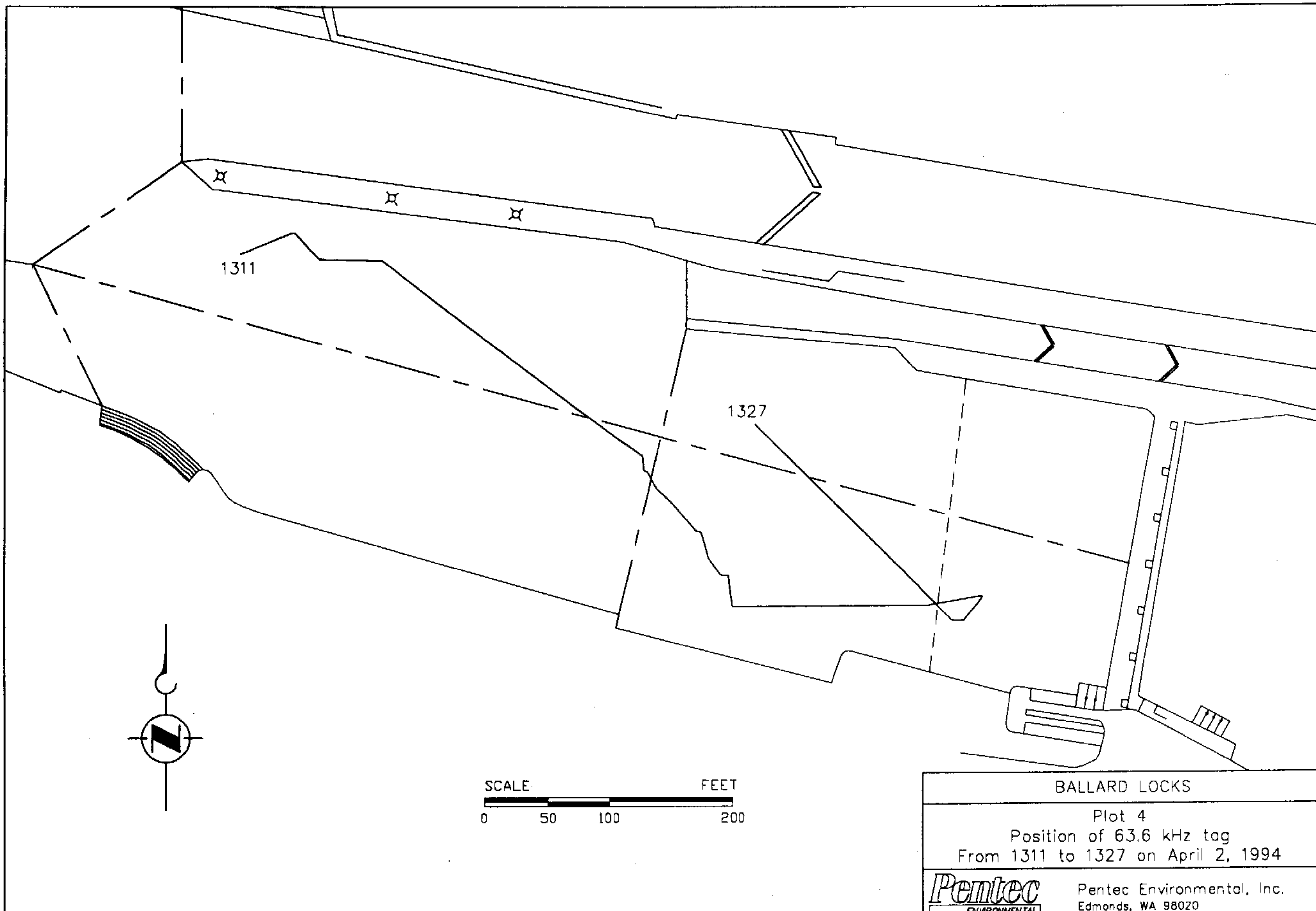
SCALE
FEET
0
50
100
200
BALLARD LOCKS
Plot 2
Position of 63.6 kHz tag
From 1256 to 2037 on April 2, 1994
Pentec ENVIRONMENTAL
Pentec Environmental, Inc.
Edmonds, WA 98020



BALLARD LOCKS

Plot 3
Position of 63.6 kHz tag
From 1256 to 1311 on April 2, 1994

Pentec Environmental, Inc.
Edmonds, WA 98020

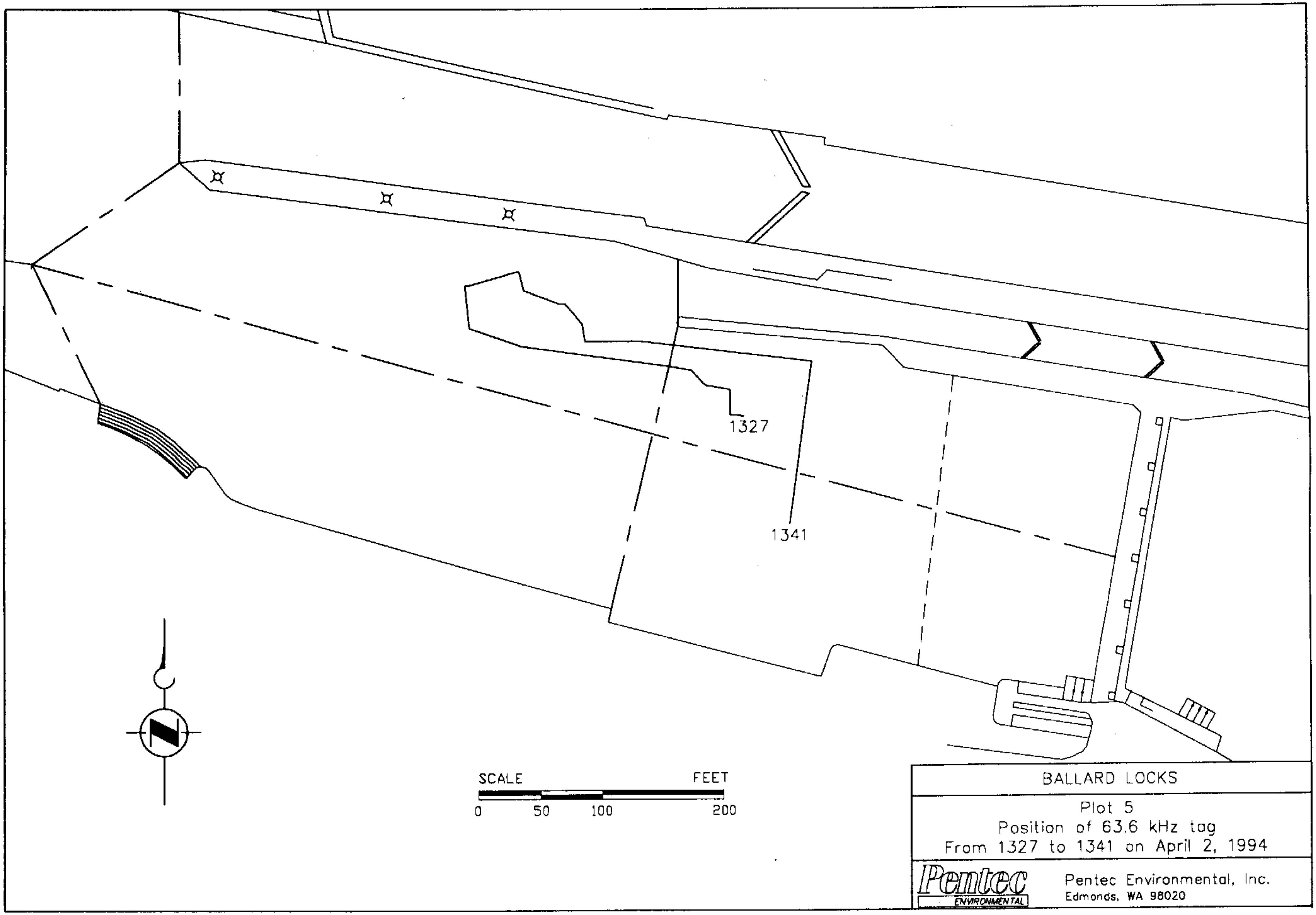


BALLARD LOCKS

Plot 4
Position of 63.6 kHz tag
From 1311 to 1327 on April 2, 1994

Pentec ENVIRONMENTAL

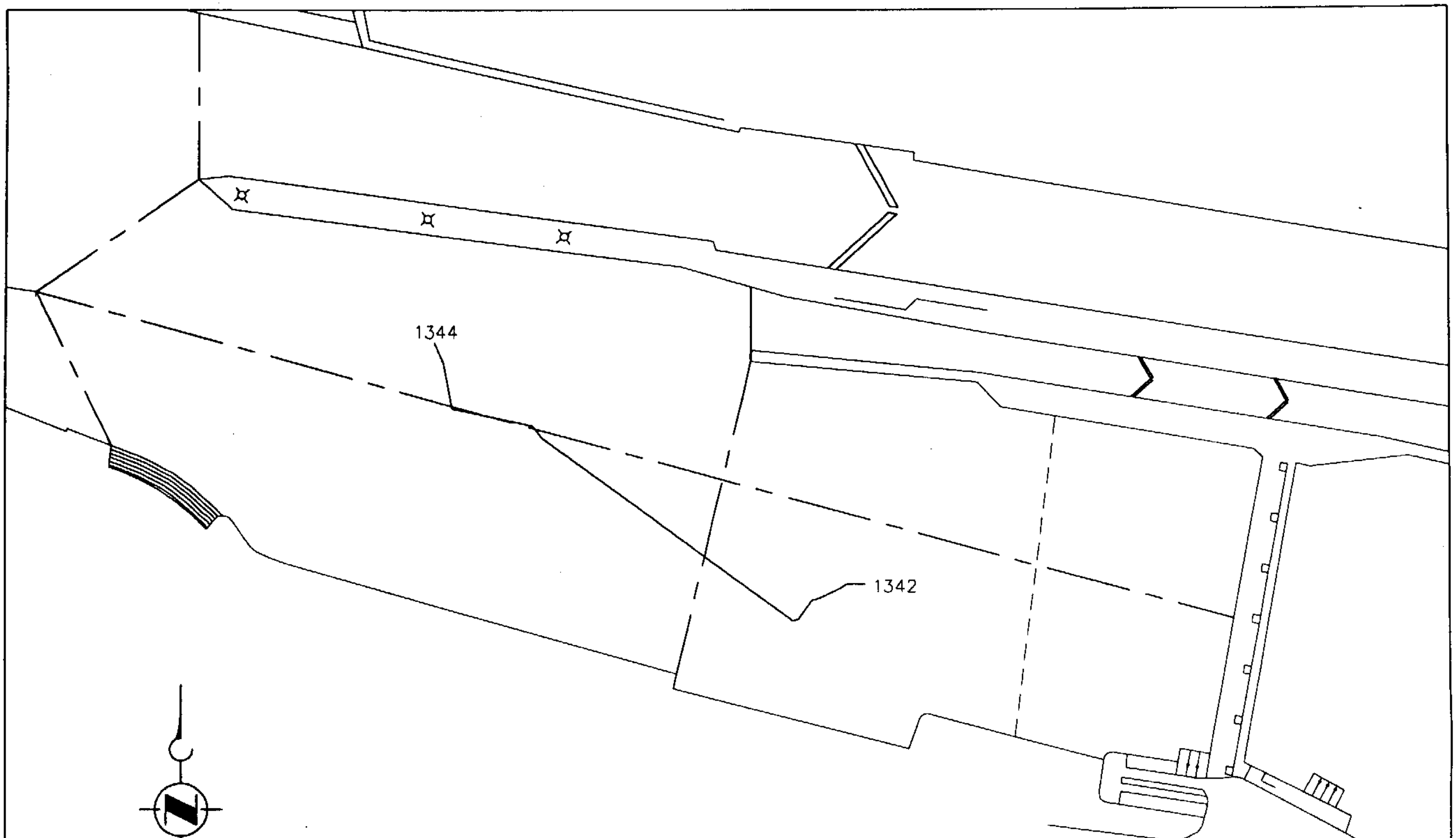
Pentec Environmental, Inc.
Edmonds, WA 98020



BALLARD LOCKS

Plot 5
Position of 63.6 kHz tag
From 1327 to 1341 on April 2, 1994

Pentec Environmental, Inc.
Edmonds, WA 98020

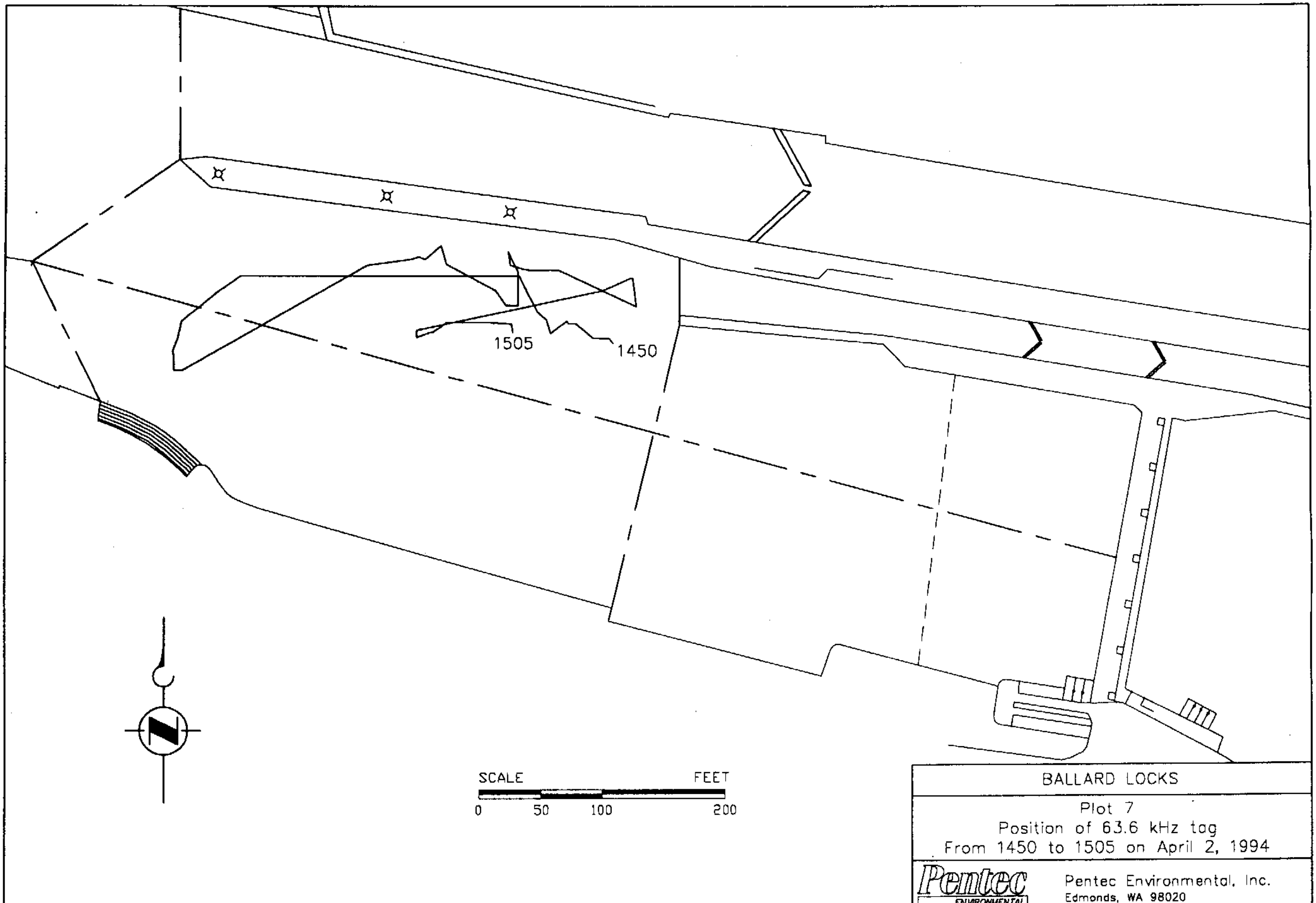


BALLARD LOCKS

Plot 6
Position of 63.6 kHz tag
From 1342 to 1344 on April 2, 1994

Pentec ENVIRONMENTAL

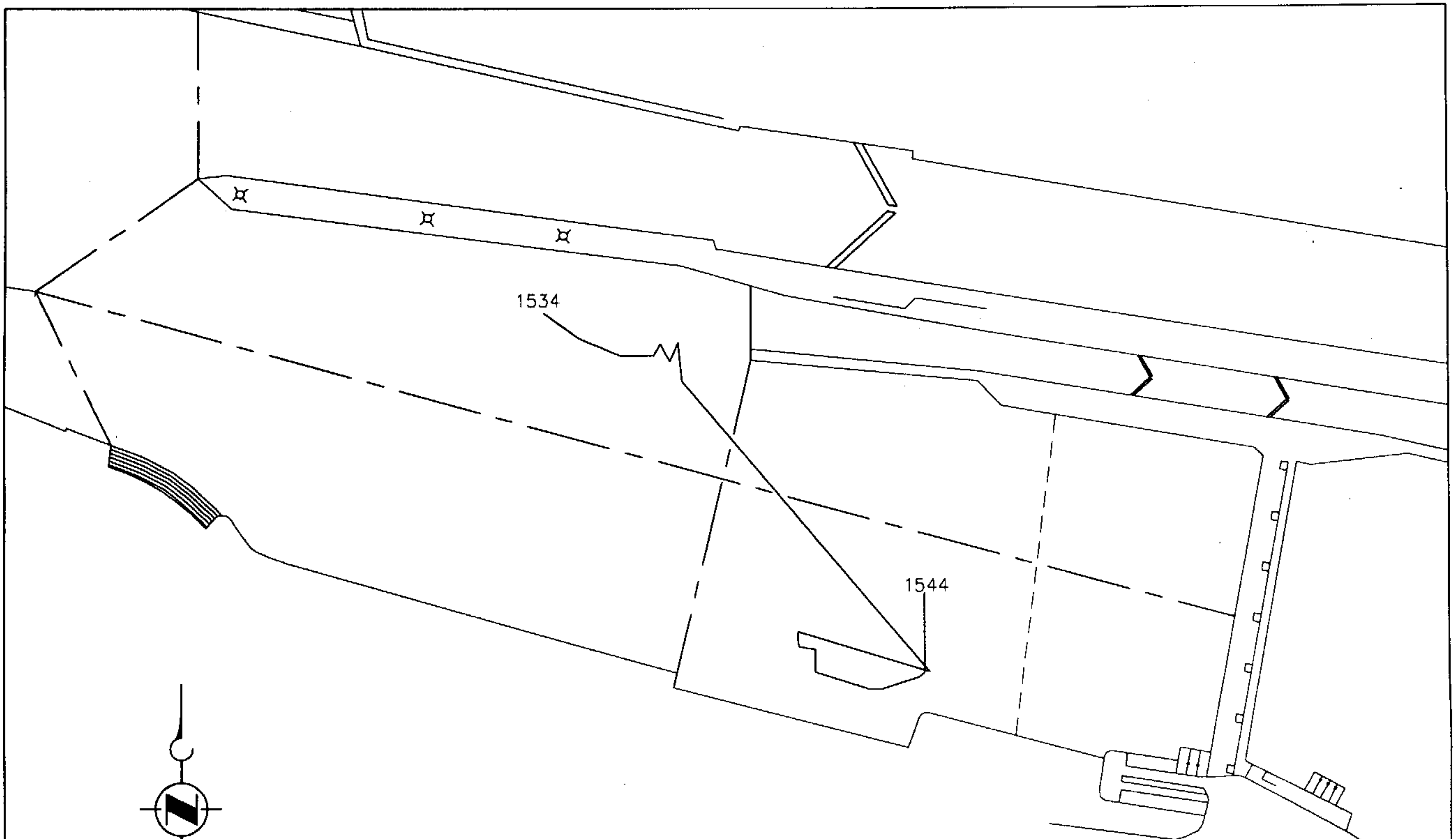
Pentec Environmental, Inc.
Edmonds, WA 98020



BALLARD LOCKS

Plot 7
Position of 63.6 kHz tag
From 1450 to 1505 on April 2, 1994

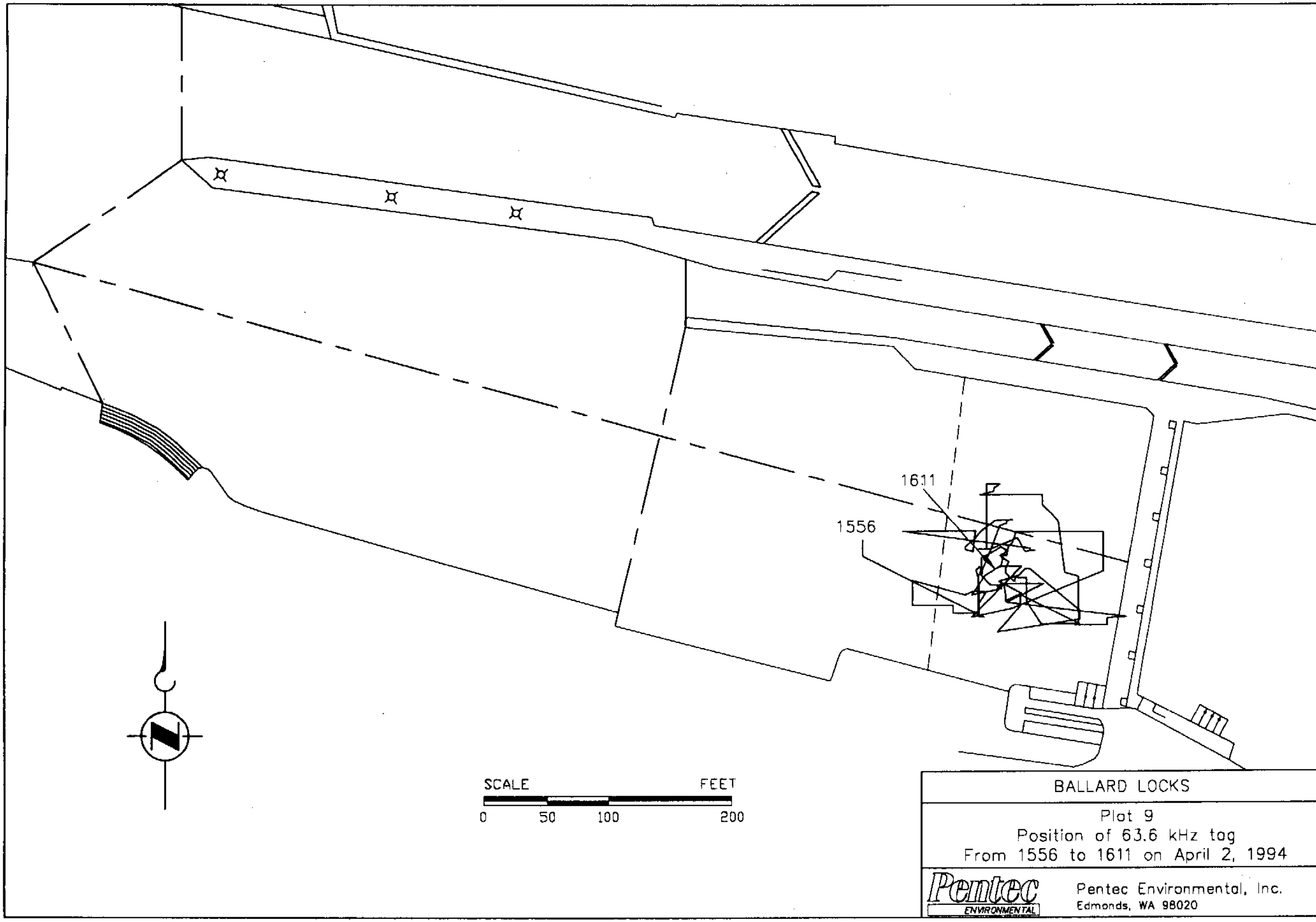
Pentec Environmental, Inc.
Edmonds, WA 98020



BALLARD LOCKS

Plot 8
Position of 63.6 kHz tag
From 1534 to 1544 on April 2, 1994

Pentec Environmental, Inc.
Edmonds, WA 98020

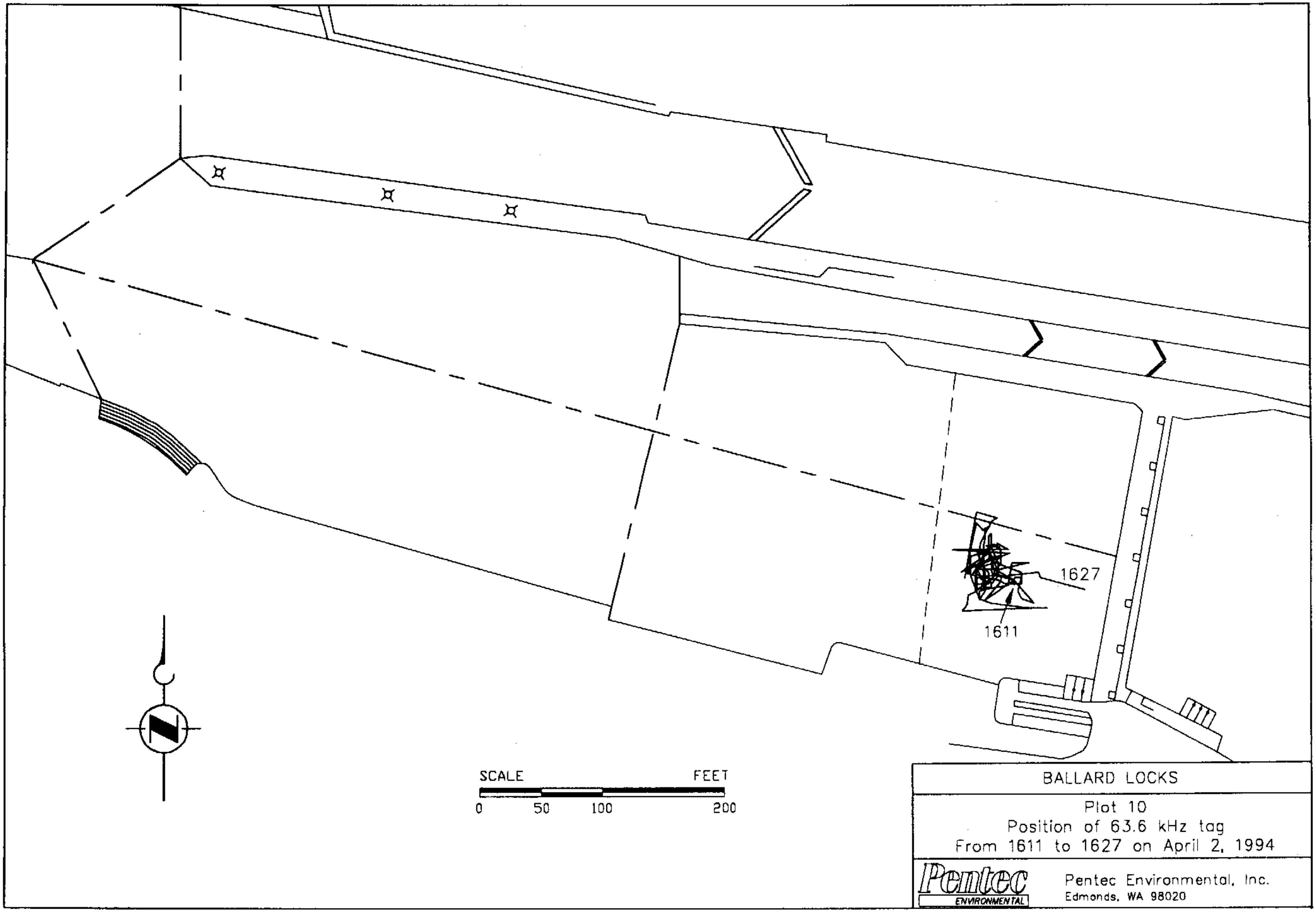


BALLARD LOCKS

Plot 9
Position of 63.6 kHz tag
From 1556 to 1611 on April 2, 1994

Pentec ENVIRONMENTAL

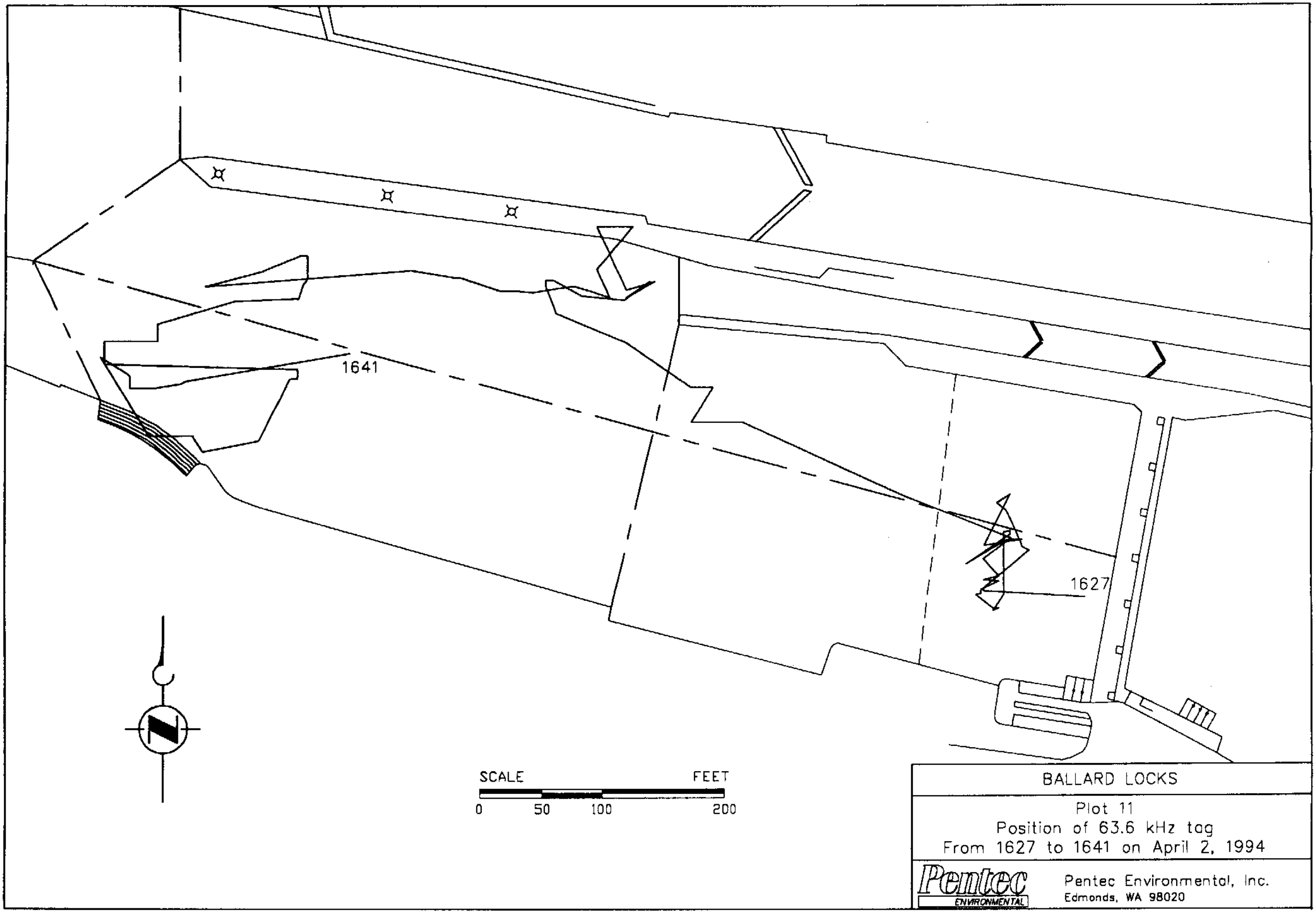
Pentec Environmental, Inc.
Edmonds, WA 98020

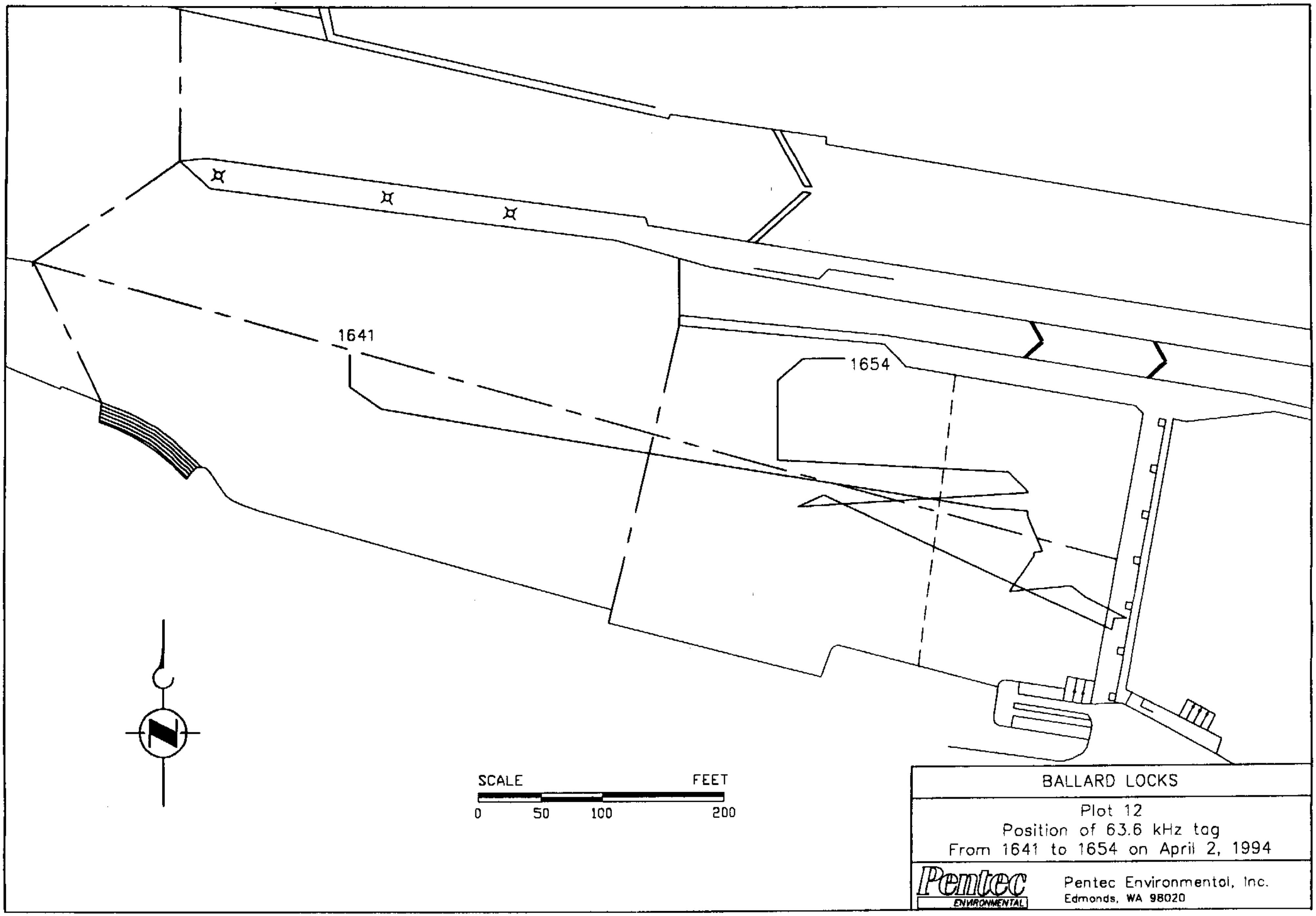


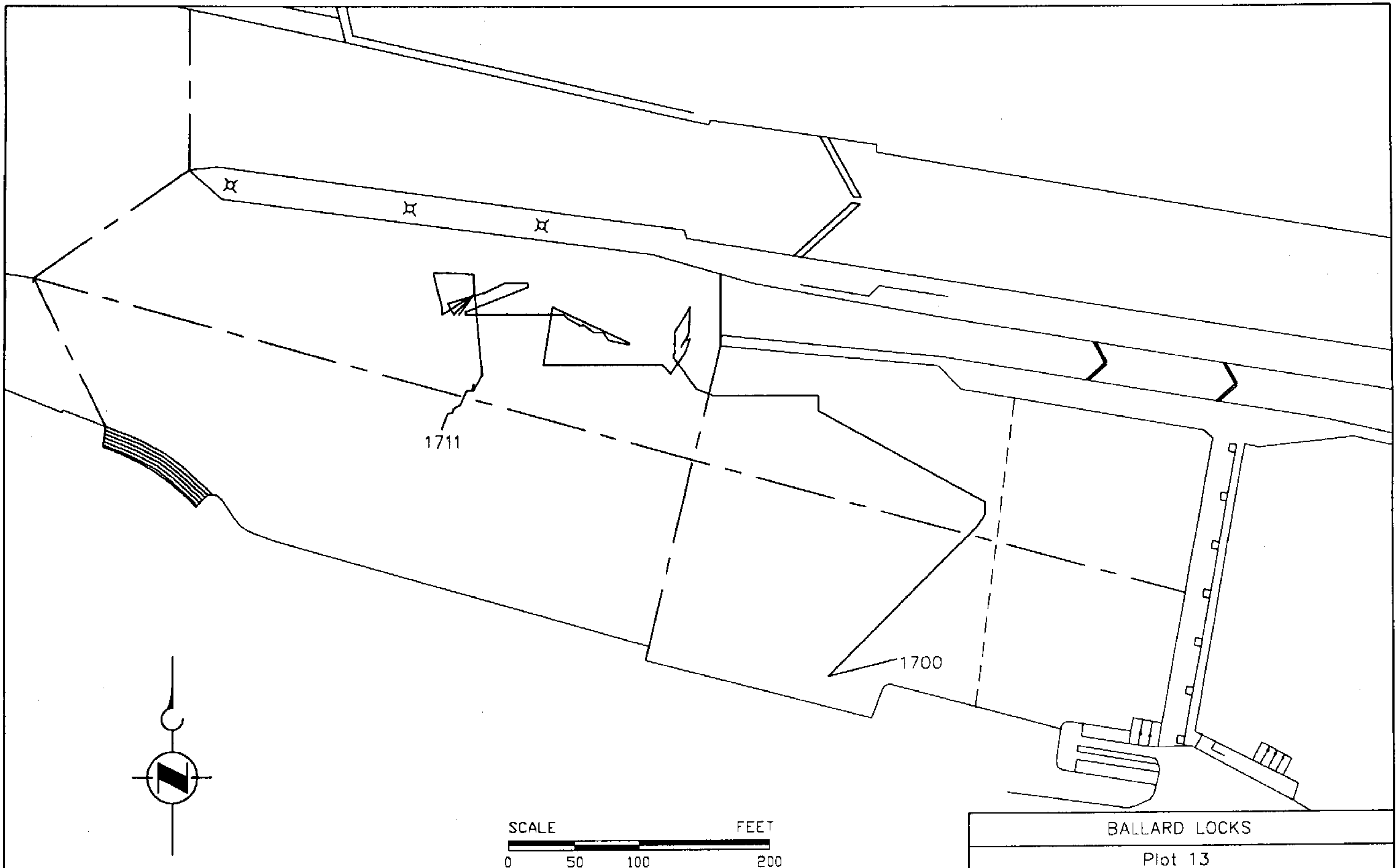
BALLARD LOCKS

Plot 10
Position of 63.6 kHz tag
From 1611 to 1627 on April 2, 1994

Pentec Environmental, Inc.
Edmonds, WA 98020


1627
1641
SCALE
FEET
0
50
100
200
BALLARD LOCKS
Plot 11
Position of 63.6 kHz tag
From 1627 to 1641 on April 2, 1994
Pentec
ENVIRONMENTAL
Pentec Environmental, Inc.
Edmonds, WA 98020


1641
1654
SCALE
FEET
0
50
100
200
BALLARD LOCKS
Plot 12
Position of 63.6 kHz tag
From 1641 to 1654 on April 2, 1994
Pentec
ENVIRONMENTAL
Pentec Environmental, Inc.
Edmonds, WA 98020

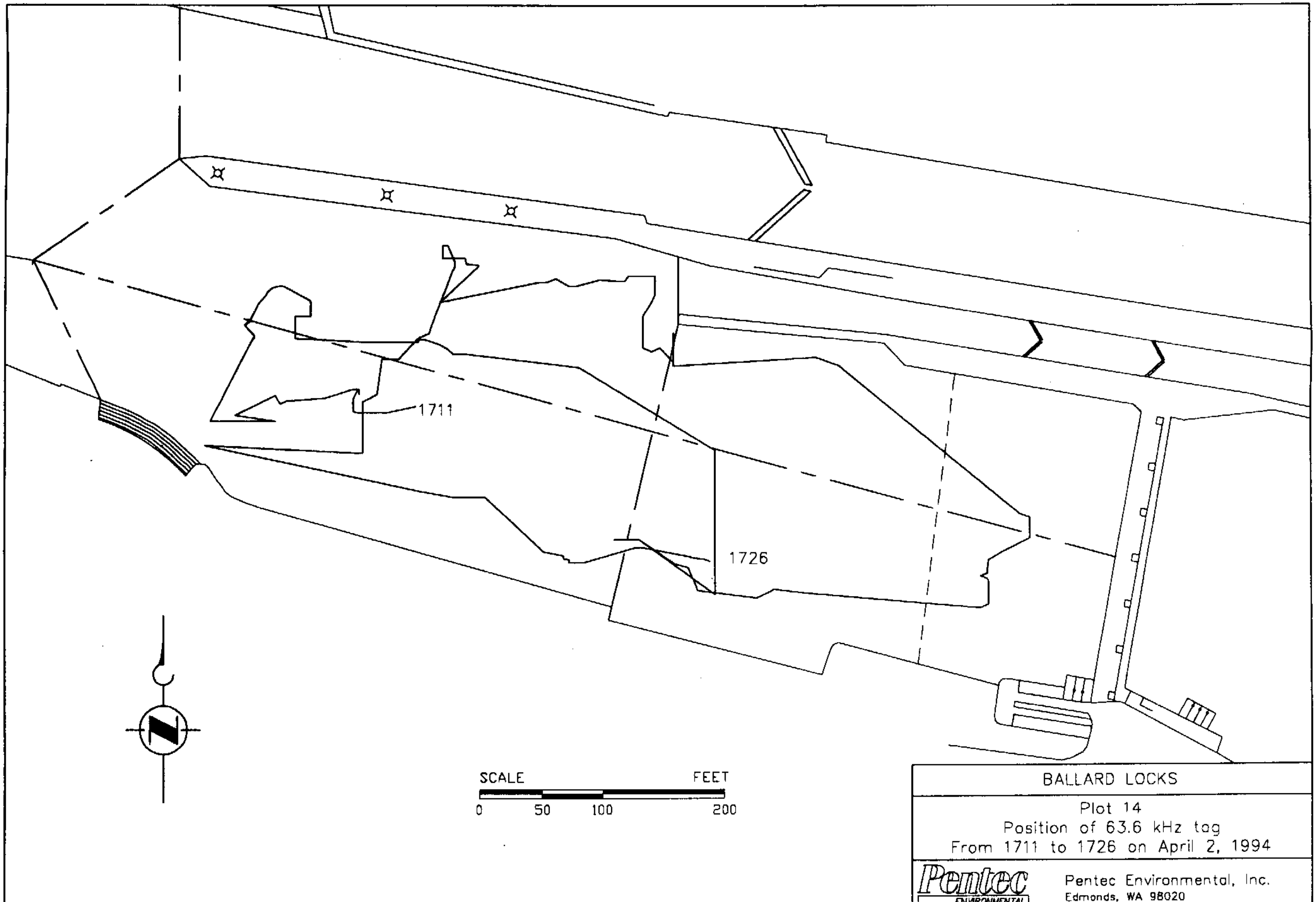


BALLARD LOCKS

Plot 13
Position of 63.6 kHz tag
From 1700 to 1711 on April 2, 1994

Pentec ENVIRONMENTAL

Pentec Environmental, Inc.
Edmonds, WA 98020

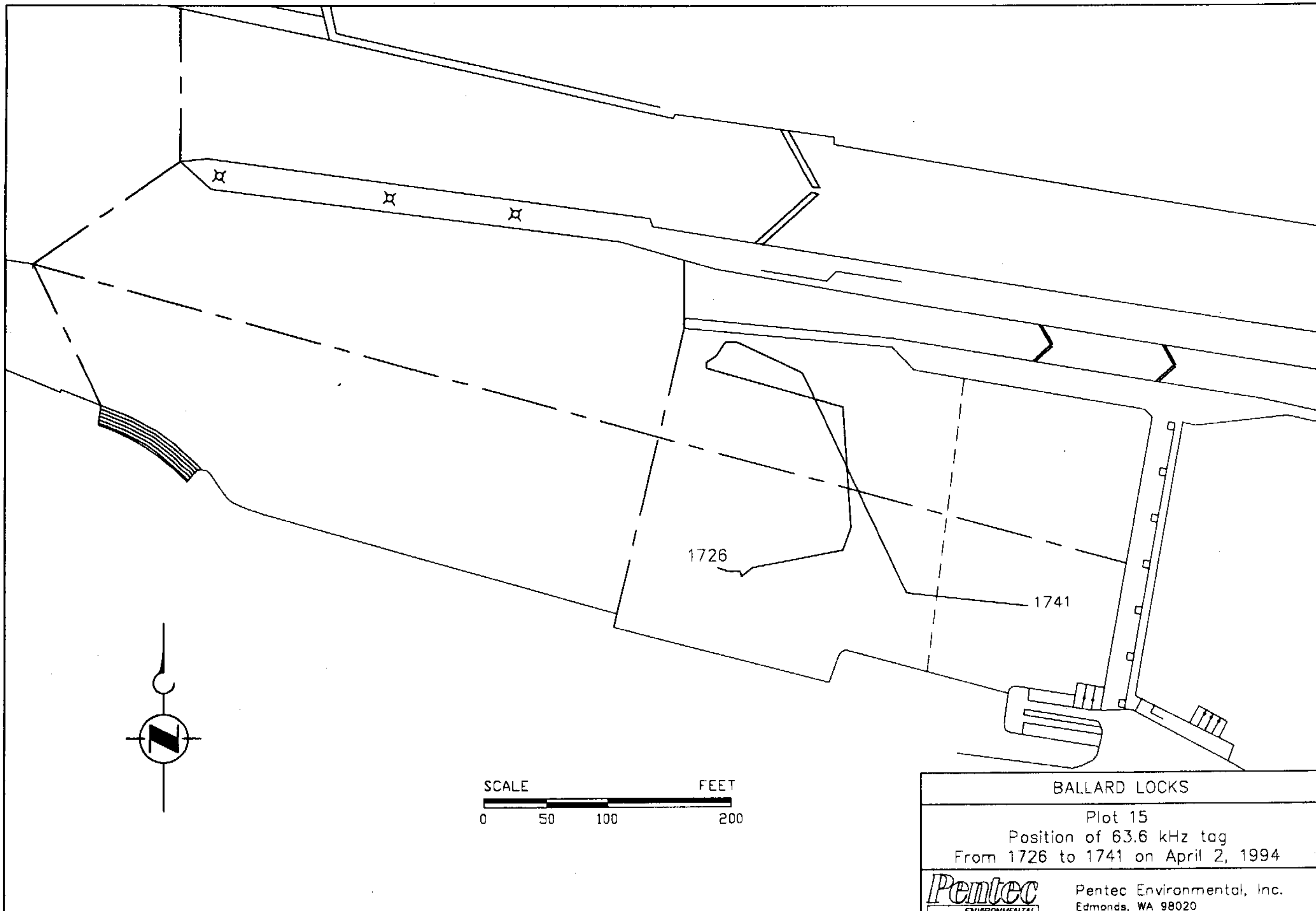


BALLARD LOCKS

Plot 14
Position of 63.6 kHz tag
From 1711 to 1726 on April 2, 1994

Pentec ENVIRONMENTAL

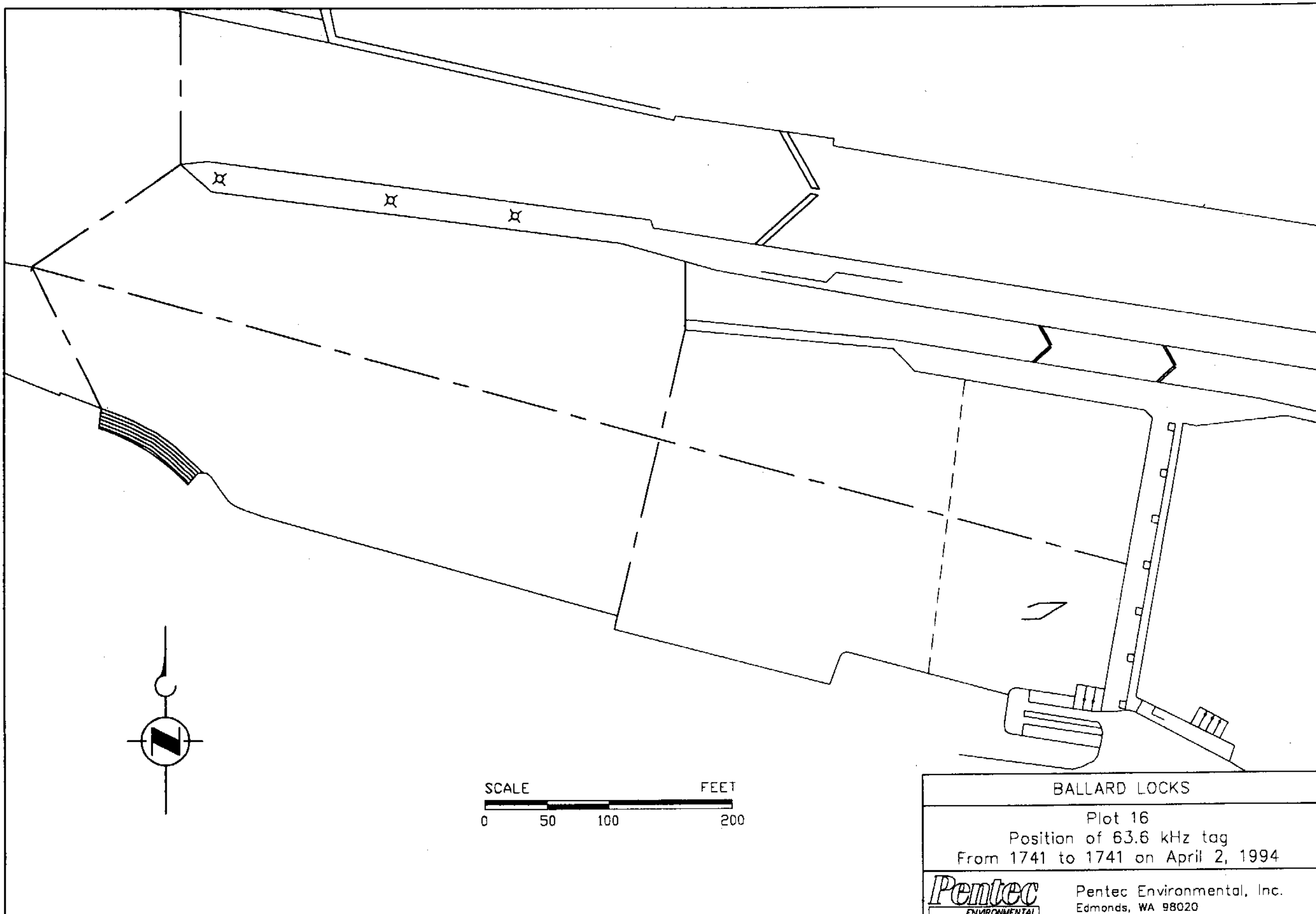
Pentec Environmental, Inc.
Edmonds, WA 98020



BALLARD LOCKS

Plot 15
Position of 63.6 kHz tag
From 1726 to 1741 on April 2, 1994

Pentec ENVIRONMENTAL
Pentec Environmental, Inc.
Edmonds, WA 98020

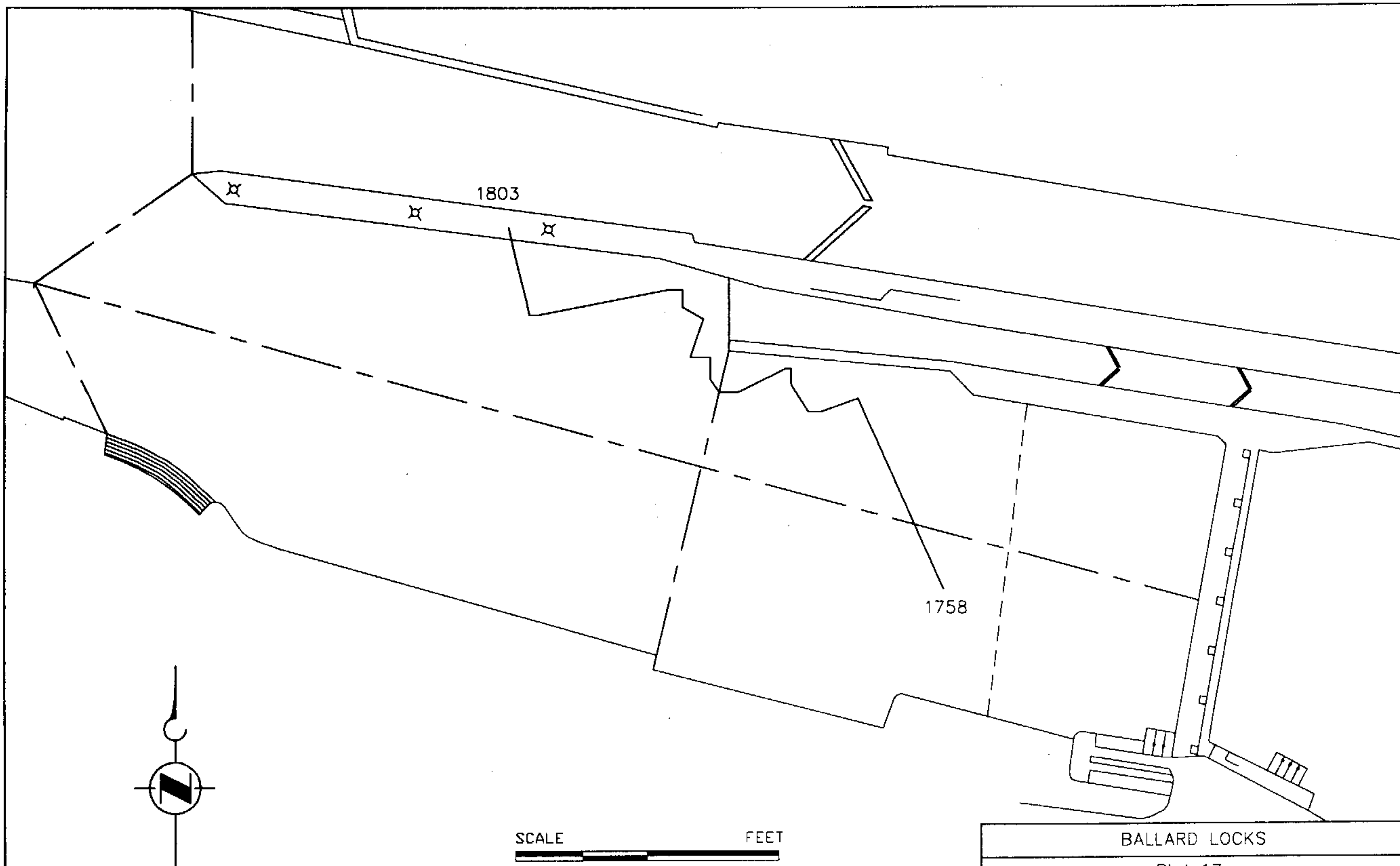


BALLARD LOCKS

Plot 16
Position of 63.6 kHz tag
From 1741 to 1741 on April 2, 1994

Pentec ENVIRONMENTAL

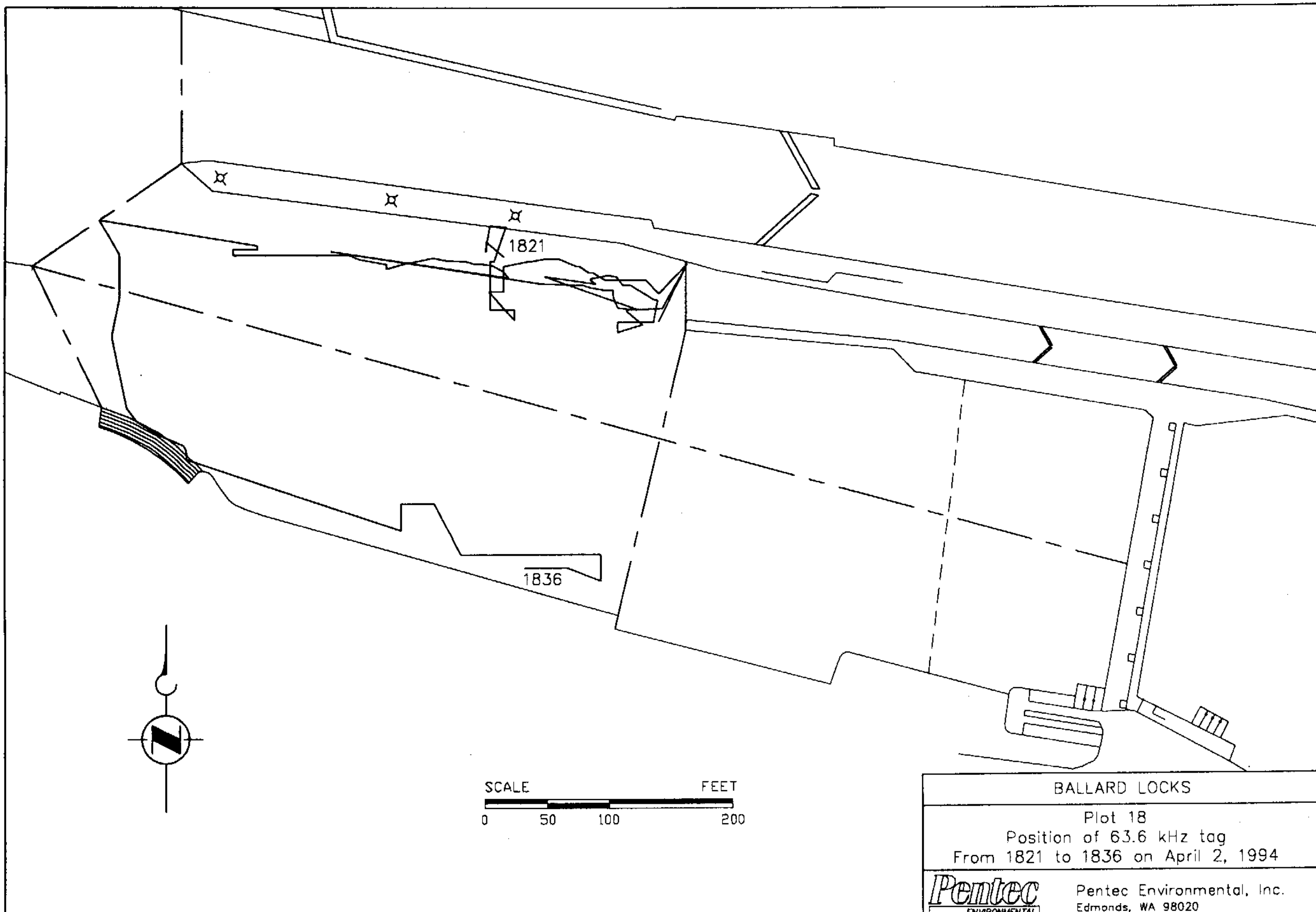
Pentec Environmental, Inc.
Edmonds, WA 98020



BALLARD LOCKS

Plot 17
Position of 63.6 kHz tag
From 1758 to 1803 on April 2, 1994

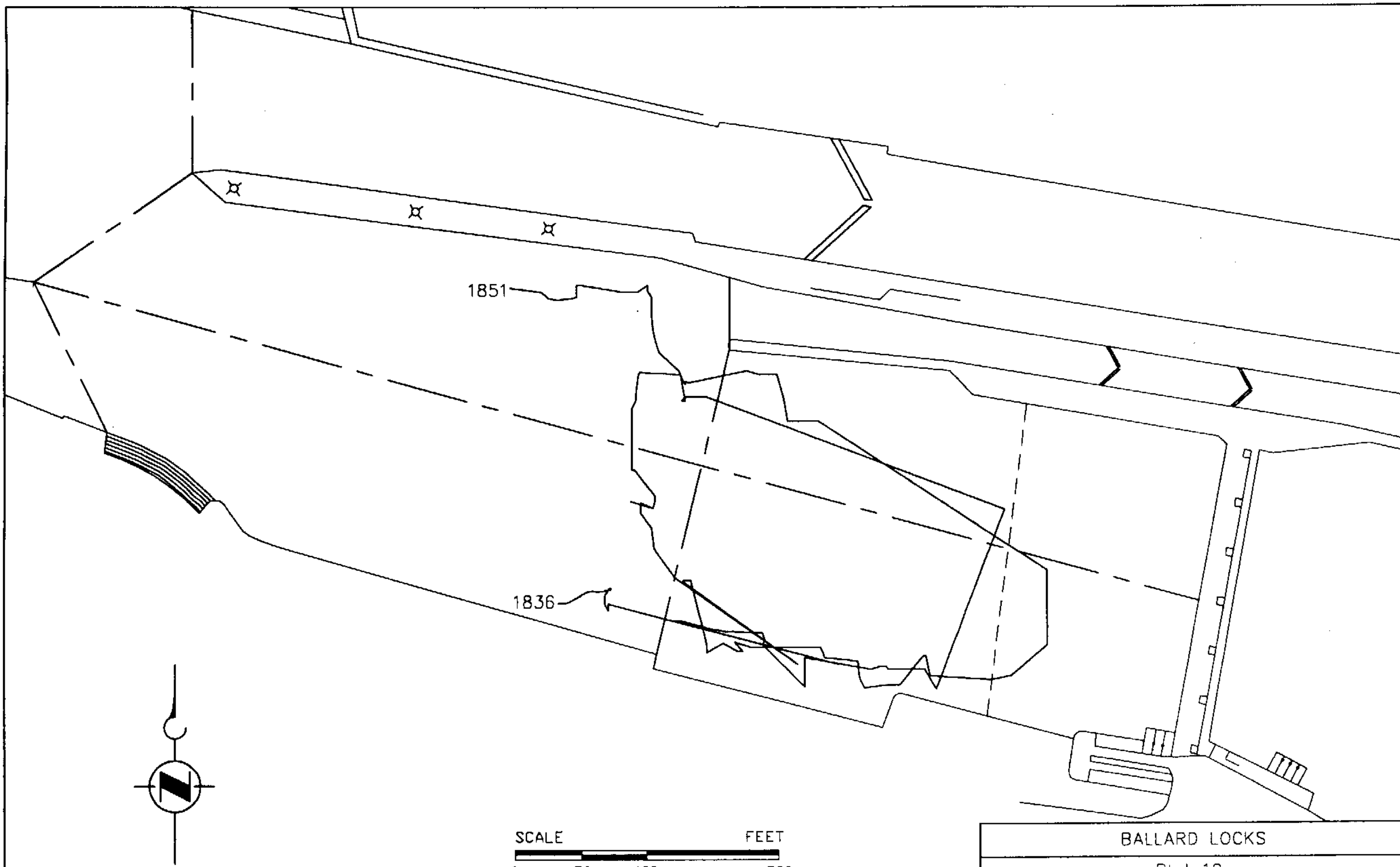
Pentec Environmental, Inc.
Edmonds, WA 98020



BALLARD LOCKS

Plot 18
Position of 63.6 kHz tag
From 1821 to 1836 on April 2, 1994

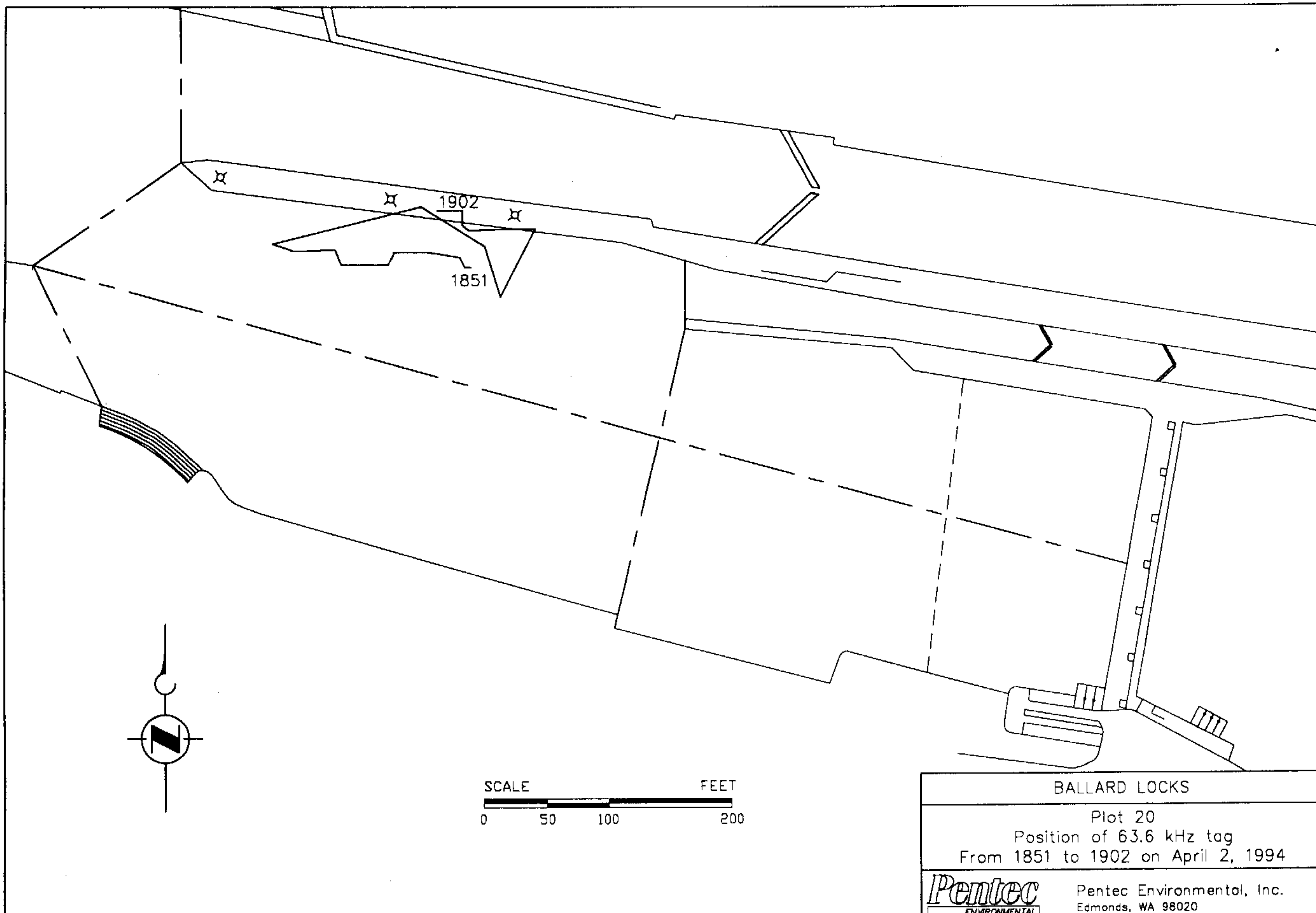
Pentec Environmental, Inc.
Edmonds, WA 98020



BALLARD LOCKS

Plot 19
Position of 63.6 kHz tag
From 1836 to 1851 on April 2, 1994

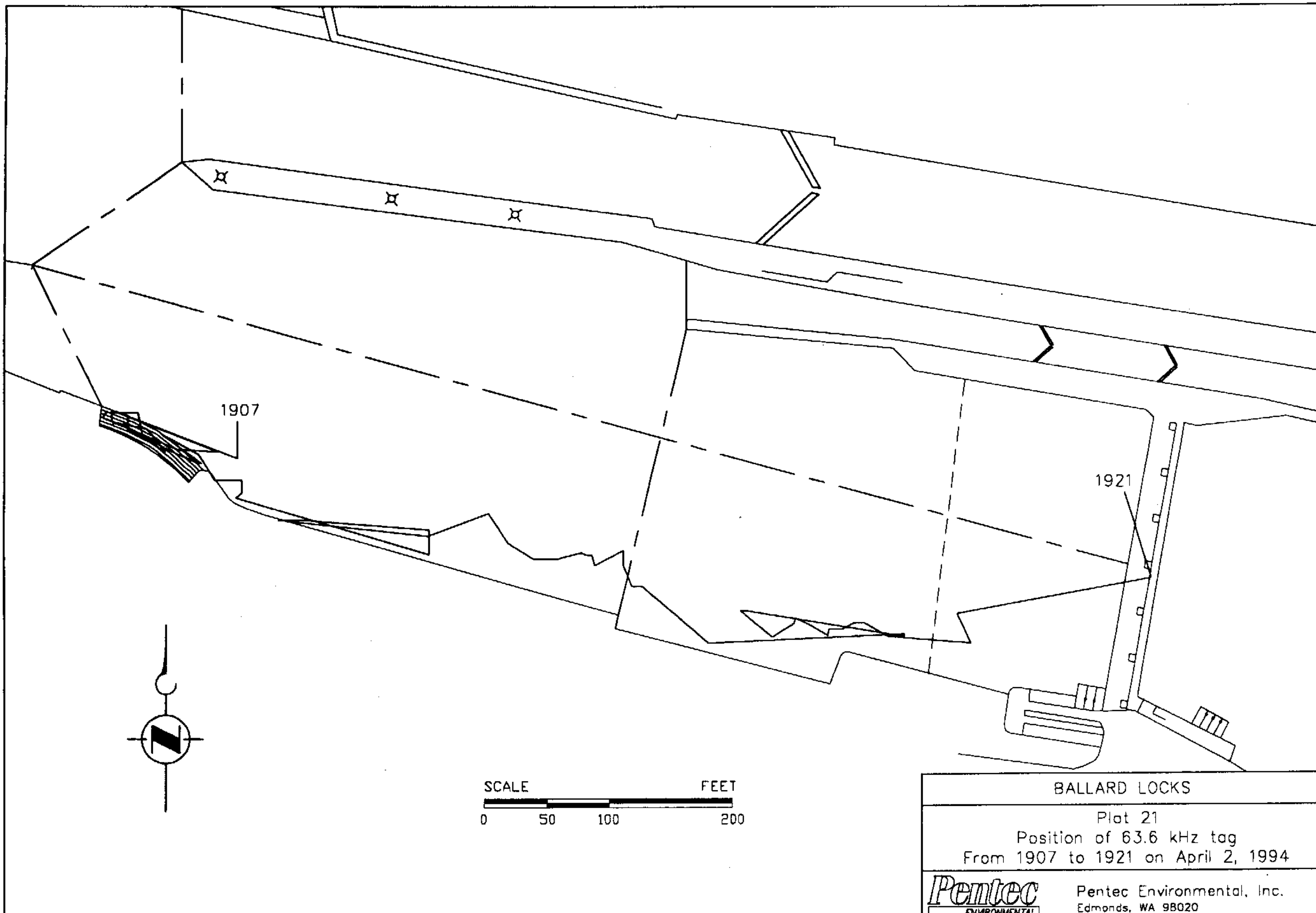
Pentec Environmental, Inc.
Edmonds, WA 98020



BALLARD LOCKS

Plot 20
Position of 63.6 kHz tag
From 1851 to 1902 on April 2, 1994

Pentec Environmental, Inc.
Edmonds, WA 98020

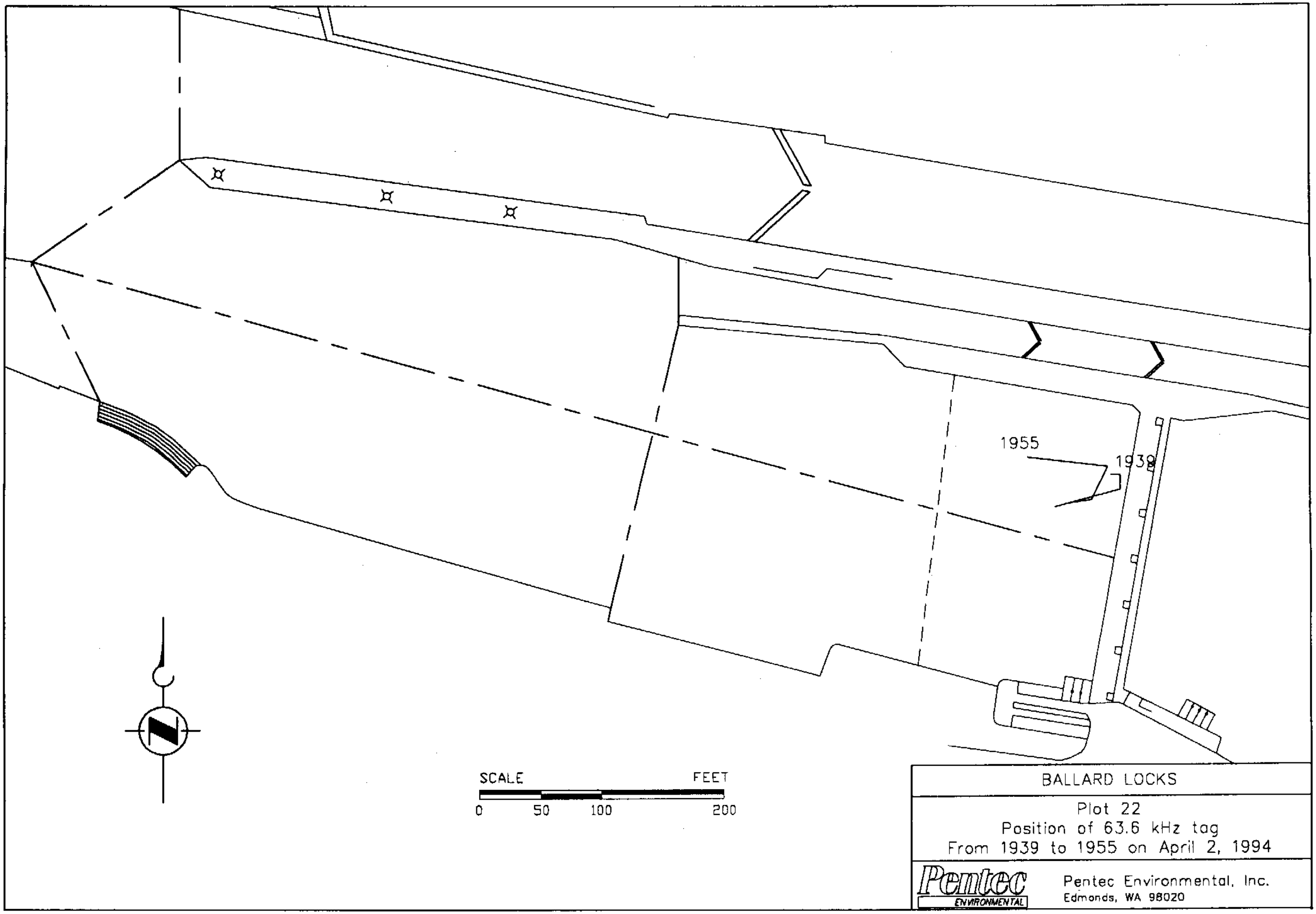


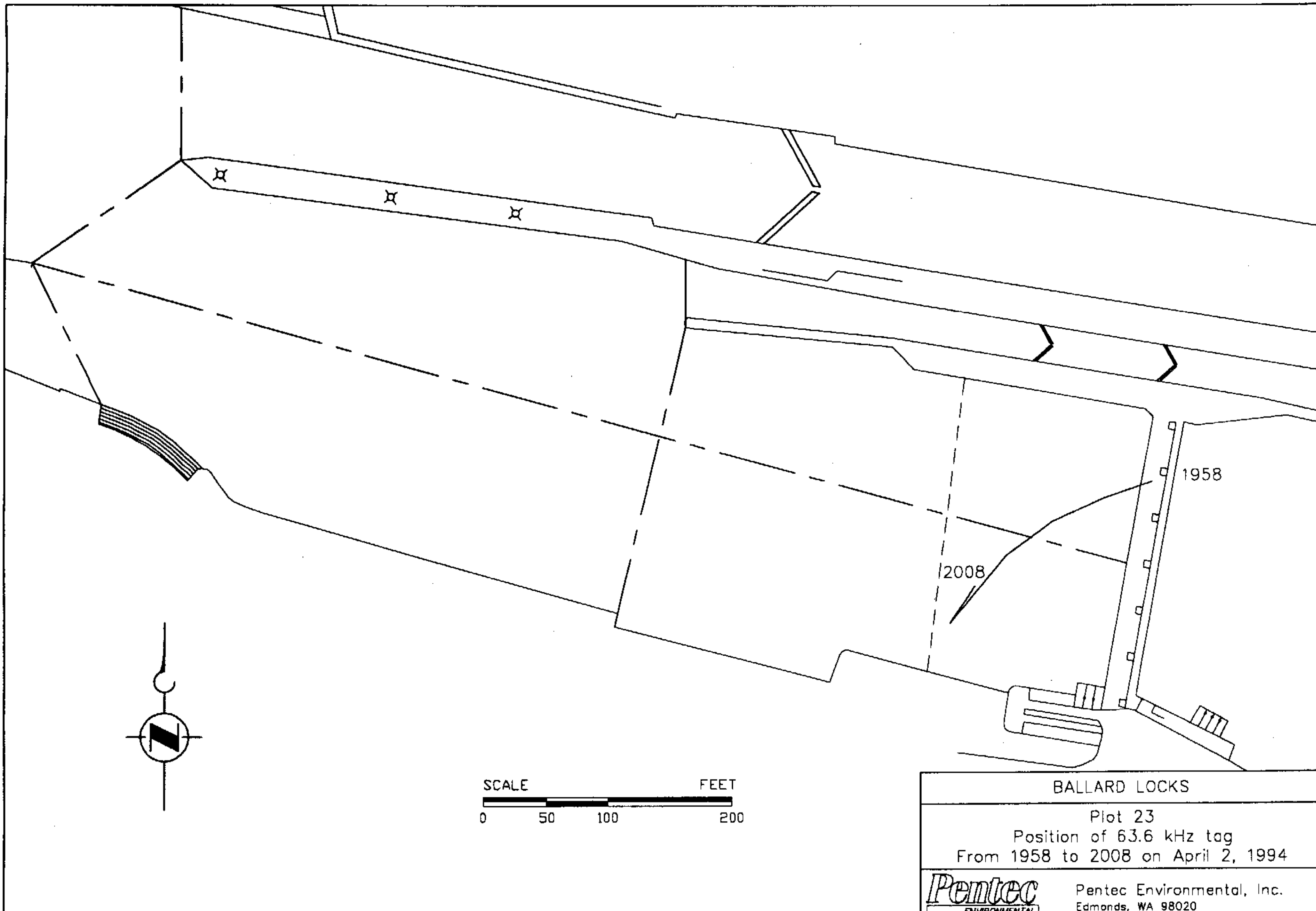
BALLARD LOCKS

Plat 21
Position of 63.6 kHz tag
From 1907 to 1921 on April 2, 1994

Pentec ENVIRONMENTAL

Pentec Environmental, Inc.
Edmonds, WA 98020

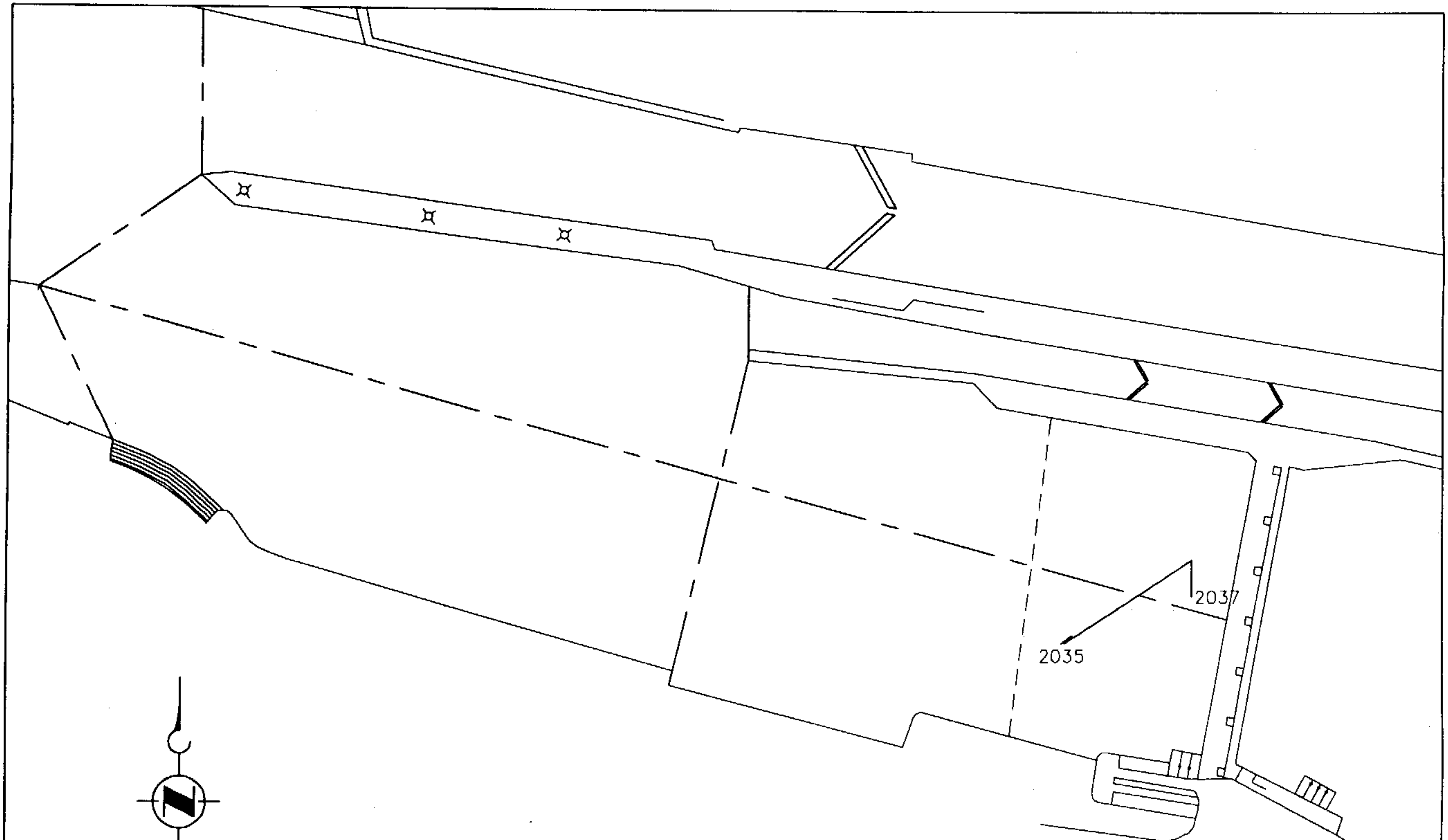

1955
1939
SCALE
FEET
0
50
100
200
BALLARD LOCKS
Plot 22
Position of 63.6 kHz tag
From 1939 to 1955 on April 2, 1994
Pentec
ENVIRONMENTAL
Pentec Environmental, Inc.
Edmonds, WA 98020



BALLARD LOCKS

Plot 23
Position of 63.6 kHz tag
From 1958 to 2008 on April 2, 1994

Pentec Environmental, Inc.
Edmonds, WA 98020



BALLARD LOCKS

Plot 24
Position of 63.6 kHz tag
From 2035 to 2037 on April 2, 1994

Pentec Environmental, Inc.
Edmonds, WA 98020