Biological Testing

of Effects of

EnCurrent Model ENC-005-F4 Hydrokinetic Turbine

On

juvenile Atlantic salmon and adult American shad

By

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And

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INTRODUCTION

Hydroelectric power development has historically been problematic for migration, passage, and restoration of diadromous and other riverine migratory fishes. Dams are typically required to maintain the hydraulic head necessary to efficiently drive turbines, and these dams pose barriers to movement in both up- and downstream directions. Downstream migrants are confronted with additional risks, incurring injuries and mortality as they pass through turbines and other routes; even delays associated with passage in either direction can reduce fitness. Fishways and bypass structures can provide safe passage routes, but the structures are costly, and their performance is often poor. Because of these and related factors, hydropower development associated with dams is often blamed for declining populations of migratory and other riverine fish species.

Recently, there has been renewed interest in so-called hydrokinetic turbines. These are devices that are placed in locations such as rivers or tidal zones where the kinetic energy of flowing water drives turbines in free flow without requiring construction of dams or other obstacles.

Questions remain, however, as to whether such devices are indeed safe for fish passage. Even without a dam, the potential still exists for fish to be injured by moving turbine blades. Mechanical injury is not the only concern, however. Fish may avoid moving structures in flowing water, and so not be exposed to mechanical injury. In the process, however, they may refuse to pass the structure, or exhibit migratory delay (Castro-Santos and Haro 2003). When this happens, populations of fish concentrate above or below the structures, where they may become attractive to predators, suffer energetic depletion, disease risk, etc. Also delays can alter run timing and prevent fish from accessing essential habitat during key time windows (McCormick et al. 1998; McCormick et al. 2009). Because of this, evaluations of effects of hydrokinetic devices on fish should not be limited to immediate mechanical injury, but avoidance and delay behaviors should also be quantified (Castro-Santos et al. 2009; Castro-Santos and Haro 2009).

In 2010 we performed a series of studies designed to assess these effects – mechanical injury, avoidance behaviors, and migratory delay—of migratory fish passing a hydrokinetic device in a large-scale, semi-controlled laboratory setting. This report summarizes the findings of those studies and identifies areas where further work is needed.

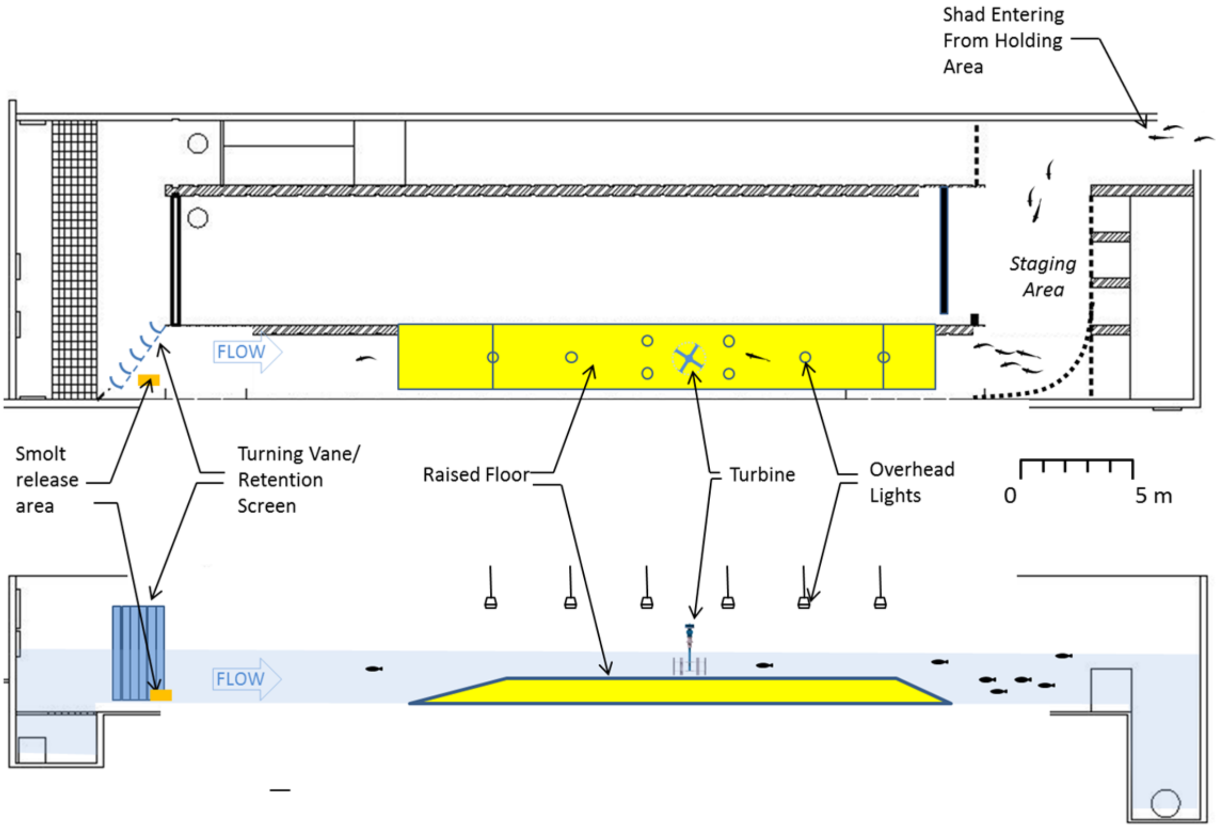

Figure 1a. Test flume facility at the Conte Lab in plan view (upper panel) and elevation view (lower panel). Note placement of the turbine, as well as release and staging locations: shad staging area was also the recovery area for smolts. Lower panel shows elevation view of raised floor and inlet and outlet structures.

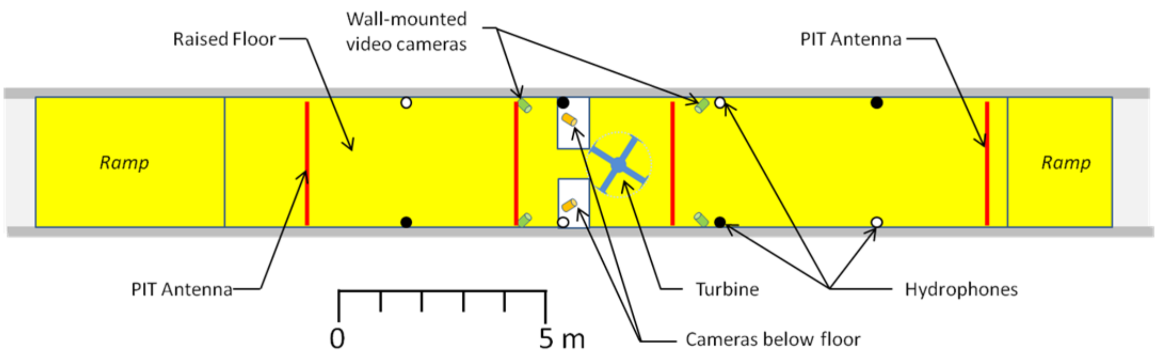

Figure 1b. Detail of test area with locations of turbine, cameras, hydrophones, and PIT antennas. Hydrophones were placed on walls at alternating heights of 30 cm (open circles) and 80 cm (closed circles) above the floor—this creates the optimal conditions for 2-dimensional positioning. For smolt tests, no hydrophones were placed at the downstream location; instead the uppermost hydrophones were moved to the downstream location for shad tests.

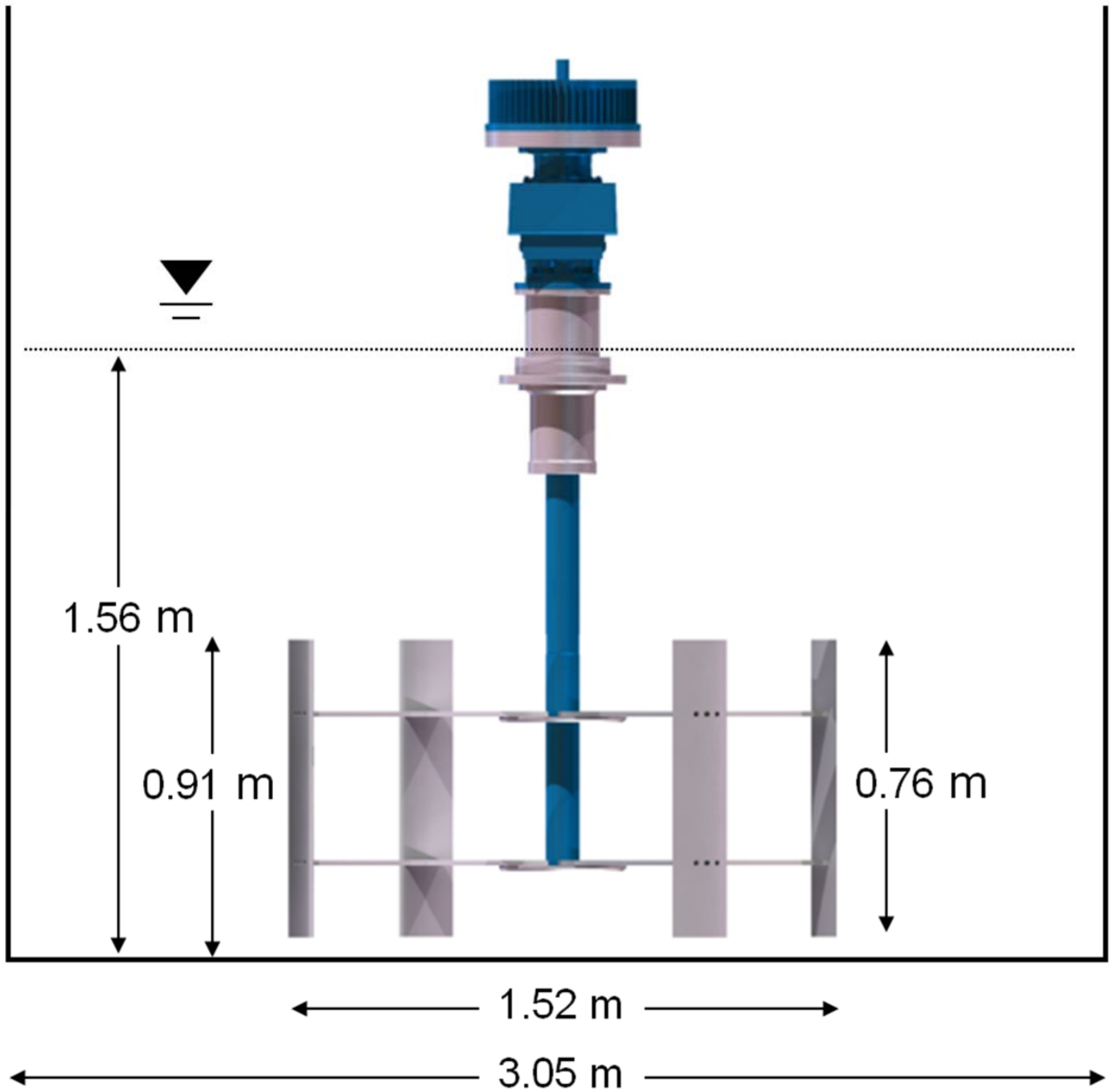

Figure 1c. Encurrent Model ENC-005-F4, vertical axis hydrokinetic turbine (elevation view)**.** Heavy lines indicate floor and walls of the test flume. The turbine blades were 76 cm tall by 152 cm diameter, and the device was mounted 15 cm above the floor. Water level shown is upstream of the turbine (Table 1).

METHODS

The Flume and Turbine

We performed a series of experiments in the flume facility at the S.O. Conte Anadromous Fish Research Center (Conte Lab), located on the Connecticut River in Turners Falls, MA (Figure 1). This is a flow-through facility, capable of passing up to 10 m^3s^{-1} of river water through the flumes. The flow was diverted from an adjacent power canal and returned to the river downstream of the associated hydropower dam.

We tested live, actively migrating Atlantic salmon (*Salmo salar*) smolts and adult American shad (*Alosa sapidissima*) passing through one of these flumes outfitted with a functional hydrokinetic turbine (Encurrent model ENC-005-F4, New Energy Corp, Inc., Calgary, AB, Canada; Figure 1c.). This is a vertical axis-type turbine capable of producing 5 kW of power in flow velocities of 3 m s^{-1}. The turbine measures 1.52 m diameter with rotor height of 0.76 m. Given that the flumes at the Conte Lab measure 3.05 m wide and that flow depths of 1.56 m were required to efficiently drive the turbine actual flow velocities averaged only about 2.25 m s^{-1}, producing a power equivalent of approximately 3 kW (Table 1) at a total discharge of 8.50 m^3s^{-1}. This is a realistic condition for many locations where these units are designed to be deployed however, and so was deemed acceptable for biological testing.

Because we were interested in volitional behavior, it was necessary to create velocity zones both upstream and downstream of the turbine that were low enough to allow fish to voluntarily approach and pass it. This was accomplished by raising the floor of the flume by 60 cm for a distance of 10 m upstream and downstream of the turbine. The greater depth upstream and downstream of this raised floor caused velocities to be reduced in those sections by approximately 40% (Table 1). A larger area was also provided downstream to serve as a recovery area for Atlantic salmon smolts and as a resting and staging area for the upstream migrants (American shad). This comprised a large screened corral measuring 6.1 m wide by 6.1m long adjacent to the test flume (Figures 1 and 2). Flow was discharged through a set of screens and gates 10.3 m wide by 2.1 m tall. The screen immediately downstream of the turbine testing flume was built on a curve with a 3 m radius; this created a sweeping cross-flow that kept fish from being impinged there after passing through the turbine. Screens were constructed of galvanized steel, with 1.0 cm clear opening to allow for maximum flow while minimizing risk of escapement or impingement.

Figure 2. Downstream staging and recovery area. Discharge is toward the left; test flume is out of sight in background, behind the concrete wall to the right. The screen continues to arc toward the back wall as shown in Figure 1a. Note the slack water condition, which provided suitable resting conditions for both Atlantic salmon and American shad.

The flume was illuminated with 6-400 W mercury vapor lamps placed 2.5 m above the water surface. These were configured in such a way as to provide uniform lighting around the turbine and to avoid strong shadows from the turbine and associated mounting hardware. The intent was to at once avoid startling the fish while providing sufficient illumination for the view monitoring system (see below).

For the treatment condition, the turbine was mounted with the lower portion of its blades 15 cm above the floor and the upper portion 80 cm below the water surface (Figures 1c and 3a & 3b). Note that the total swept area of the turbine was 1.15 m^2, or 24.3% of the flume cross-section (4.76 m^2). For comparison, a control condition was also run with the turbine removed (Figure 3d). Telemetry and monitoring systems remained in place, allowing for direct comparison of movement patterns with the turbine present and absent.

Figure 3a-c. Test flume with turbine in (panels a and b) and out (panel c). Visible in panel a are the turbine, lights, PIT antennas, cameras, and hydrophones (see schematic, Figure 1). Note that the turbine created some head differential, which affected flow velocities in those zones (Table 1, Figure 4.)

Instrumentation

Because of the novel nature of this study, we used several methods to monitor passage of fish past the turbine (test conditions) or the unimpeded flume (control condition), knowing that it was likely that not all monitoring methods would be effective. Passive integrated transponder (PIT) telemetry was used to monitor gross movements up or down the flume, video cameras monitored passage by the turbine itself, and an integrated hydrophone array and acoustic tracking system (Model HTI-290; Hydroacoustic Technology Inc., Seattle, WA; hereafter termed the HTI system) monitored movements in 2-dimensional (horizontal) space with a mean time resolution of 220 ms.

A single PIT antenna was used to monitor downstream movements of Atlantic salmon smolts; this was primarily to reference passage times to allow for identification of smolts as they passed the video cameras (see below). For upstream migrants (shad) a total of 4 antennas were used, allowing for quantification of distance of ascent and delays as shad approached the turbine location.

Video cameras were deployed below the false floor, angled upward through clear acrylic panels to provide a ventral perspective of fish as they passed the turbine. Later, cameras were moved above the floor to provide a lateral perspective of the fish. .

The HTI system works by integrating input from an array of hydrophones that record the difference in arrival times of acoustic transmissions from each tag as they pass through the array. This information is used to triangulate a 2- or 3-dimensional position for the tag at each transmission time. Eight hydrophones were deployed and interfaced with the HTI system (Figure 1b). These were positioned upstream and downstream of the turbine to provide optimum 2-dimensional coverage of fish as they approached and passed the test area. Hydrophones were placed at alternating heights of 30 and 80 cm above the false floor. For smolt tests, 4 hydrophones were placed upstream of the turbine, two in-line with the turbine, and 2 downstream of the turbine. This provided optimal coverage of the upstream end as smolts approached the turbine and were situated to maximize our ability to detect behavioral responses to the turbine before passing it. For shad, the two most upstream hydrophones were moved to the downstream location, in this case providing better coverage of the shad as they approached the turbine from the downstream direction.

Flow velocities were also monitored continuously throughout each run using acoustic Doppler current profilers (ADCP’s: Sontek Argonaut, model SL3000; Sontek/YSI, San Diego, CA, USA) deployed 2.45 m upstream and 2.45 m downstream of the turbine location. Velocities were measured in 10 discrete cells, each measuring 0.28 m long. Cells were distributed laterally and uniformly across the flume channel and velocities were recorded every 60 seconds. Representative velocity conditions were also recorded at several locations along the flume, creating full, 2-dimensional profiles of flow velocity to which test animals were subjected.

For each of these systems, PIT, Video, HTI, and ADCP, clocks on the associated instruments were synchronized to the nearest second at the beginning of each trial. This allowed for later comparisons and verification among the various types of data.

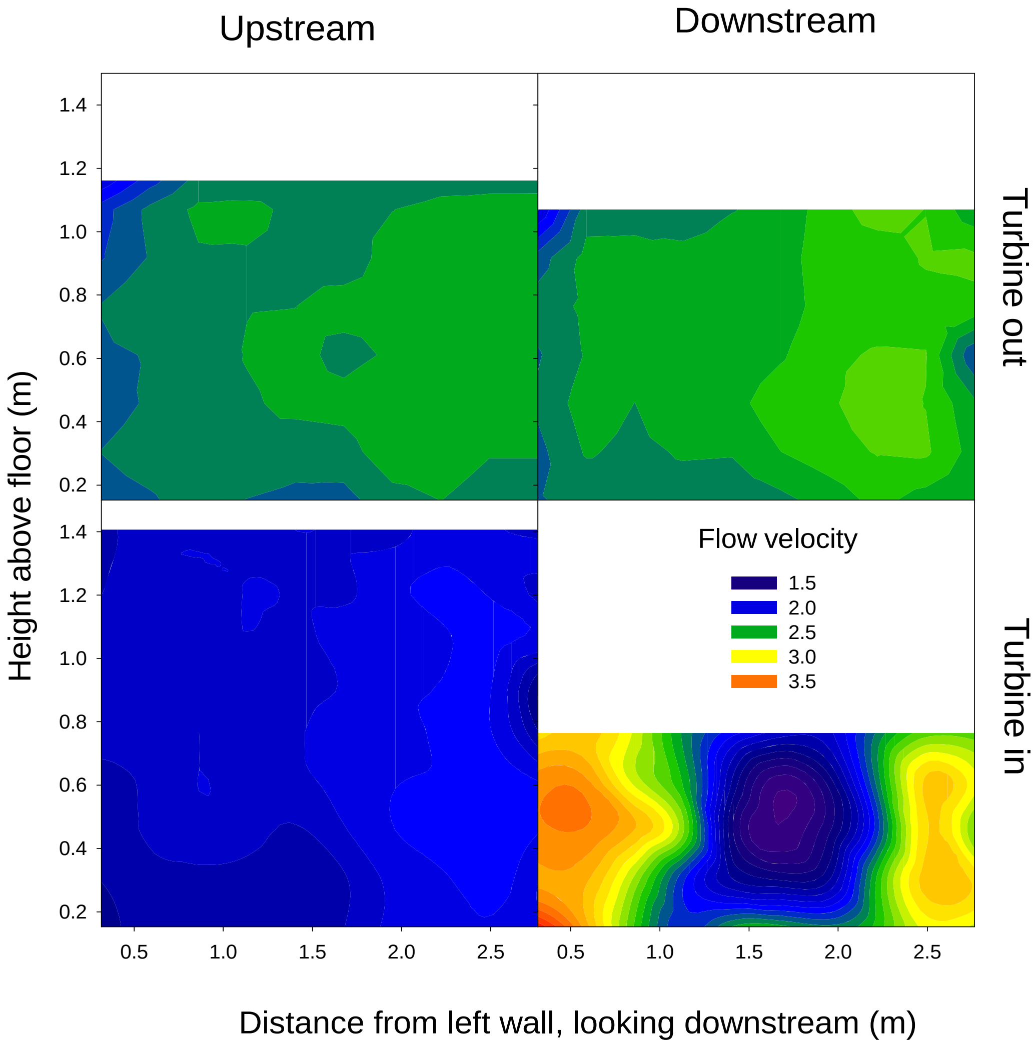

Figure 4. Flow velocity contours looking downstream, taken 2.45 m upstream and 2.45 m downstream of the turbine hub. Upper panels show conditions with turbine removed, and lower panels show conditions with turbine running. Note the low velocity zones upstream and immediately downstream of the turbine, and the high velocity zones near the walls. This represents the wake shed by the turbine while running.

Study Animals

Because hydrokinetic devices such as the Encurrent Model ENC-005-F4 are meant to be deployed in locations with anadromous migrant fishes, we wanted to explore effects on both the upstream migrant (adult) and downstream migrant (juvenile or smolt) phases. Some of the proposed siting locations, like the Yukon and Mackenzie Rivers have important populations of migratory salmonids, so our first choice was to select a salmonid species. Because our laboratory discharges directly to the Connecticut River, however, we are unable to test non-native fish that might escape and colonize the river or transmit disease. Atlantic salmon are available in this system, but because this is a population under restoration only hatchery-reared juveniles were available for testing. For this reason we used Atlantic salmon smolts as our representative species for the juvenile life stage. The Connecticut River also has a large native population of anadromous American shad. Adults of this species are large, averaging around 435 mm in length, or about the adult size of many large salmonids. Shad are also susceptible to handling, which makes them a good indicator species—any injury that would harm an adult salmonid would almost certainly have a greater effect on American shad. Furthermore, shad are known as a 'nervous' fish, one that is easily deterred from passing obstacles or conditions that might be perceived as unnatural. This is also a useful characteristic because it means that behavioral effects of the turbine would likely be easier to observe in shad than in some other species. Thus shad were chosen as a surrogate species for adult salmonids and other anadromous fish, providing conservative estimates of both injury and behavioral effects of the turbine. Note that throughout this text we use the term 'conservative' to imply greatest sensitivity to effects and to interpretations of data that will support precautionary management strategies.

Atlantic salmon smolts

209 Atlantic salmon smolts were obtained from the Dwight D. Eisenhower National Fish Hatchery in Pittsburgh, VT and transported by truck to the Conte Lab. Upon arrival, smolts were immediately transferred to 2 m diameter round tanks, where they were held and fed to satiation twice daily. Two days after arrival, feeding was withheld, and all smolts were anaesthetized and tagged with 23 mm passive integrated transponders (PIT tags; Castro-Santos et al. 1996). At this time smolts were divided equally into two new 2 m diameter tanks and allowed to recover. Two days after tagging smolts from one of these tanks were transferred to a 23 m long open-channel swim chamber (Haro et al. 2003; Castro-Santos 2005). This chamber, originally designed for studying sprinting performance, is outfitted with a low-velocity staging area downstream. Flows were regulated such that the flume maintained a depth of 50 cm and a mean flow velocity of 0.5 $m\ s^{-1}$. These conditions were provided to give the smolts opportunity to exercise and swim in an open-channel environment, and so hopefully be better able to swim at speeds representative of wild fish when exposed to the turbine test arena. Throughout this holding period smolts were fed twice daily and monitored for mortality. Only healthy individuals were used for testing.

On the day of a test, smolts were transferred to the upstream end of the flume facility, and once test flows were established, the fish were tagged with acoustic telemetry tags, which had been outfitted with steel loops and suture threads for this purpose (Figure 5). Tags were set to transmit at a very rapid rate (4-5 transmissions per second). This transmission rate limited tag life, and in order to maximize sample size tags were activated and attached just before beginning each test. This timing also meant that anesthesia could not be used when tagging smolts as it would likely have affected their ability to respond to the turbine. Instead, smolts were restrained without anesthesia and tagged by passing the suture thread through the skin just behind the dorsal fin and tying it off to the loop. This technique prevented the suture thread from cinching down on the skin and possibly ripping it—in this way we simultaneously avoided injuring the fish and reduced the risk of losing the tags. Also at this time each fish was inspected visually for any signs of injury. This information was recorded and used for comparison with post-run condition assessments (see below)

After tagging, smolts were transferred to a recovery tank where they were held for 1-5 minutes before being released into the test flume. Once they had recovered (as evidenced by upright swimming and active response to researchers) smolts were transferred to the test flume by bucket and released in a slack-water zone about 20 m upstream of the turbine (Figure 1a). Structures were placed in this zone on the floor and walls to create flow refugia in which smolts were able to hide before volitionally entering the flume. In this way we hoped to have smolts approach the turbine under their own control, and in a way that was as close to the natural environment as could be achieved in our laboratory.

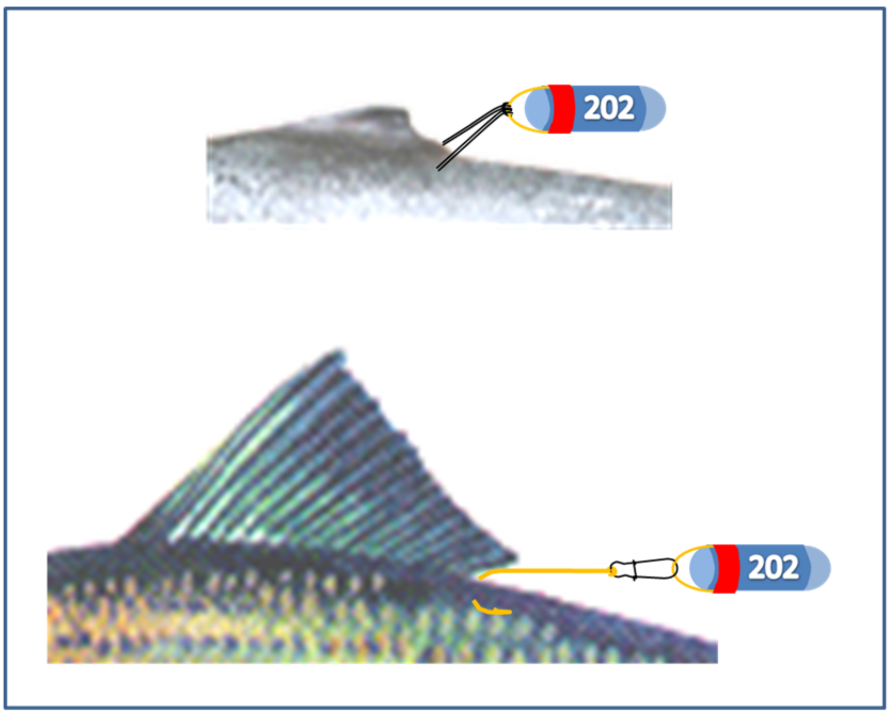

Figure 5. Tag attachment methods for smolts (upper image) and adult shad (lower image)

Once a trial was complete, and all smolts had been released and passed the turbine or control condition, flow through the flume was reduced and smolts were collected with dip nets and transferred by bucket to 1 m holding tanks for recovery. There they were fed *ad libidum* and monitored several times daily for a minimum of 48 h. Time of death was recorded to the nearest h. Survivors were either euthanized or, when possible, released into the Connecticut River to supplement ongoing restorations efforts there. Before euthanasia or release, all smolts were visually inspected and any signs of injury were recorded. Any change in condition was noted and included as a result.

Adult American shad

Adult, actively migrating American shad were collected from a fishlift at Holyoke Massachusetts and transferred by truck to holding facilities at the Conte Lab. The truck was outfitted with a 4.2 m^3 round tank specifically designed for transporting shad, with a recirculating pump and supplementary oxygen provided at a rate of 10 L $minute^{-1}$. Water for transport was treated with a simulated seawater solution diluted to 7.5 ppt. This solution is standard for shad transportation and helps reduce stress and disease associated with transport.

Upon arrival at the Conte Lab shad were PIT-tagged (IP) and deposited in groups of 20 into large flow-through holding tanks adjacent to, and hydraulically connected with the flume facility (Burrows and Chenoweth 1970). The following day, a subset of each collection was fitted with acoustic transmitters. The attachment differed from that used for smolts. In this case, the acoustic tags were fitted with #6 Aberdeen style gold-plated fishhooks coated with epoxy. This method allows for rapid tagging and detagging so that tags could be used repeatedly on successive experiments (Castro-Santos et al. 1996). Once this subset was tagged, all shad from a given holding pond were seined into the staging area downstream of the test flume. A screen situated at the downstream end of the flume kept shad from entering while flow levels were raised to the test condition. Once test conditions were established, the screen was raised and shad were allowed to enter and ascend the flume volitionally. Throughout each trial, shad had free access to the flume and the staging area. Often shad would ascend the flume, fall back downstream, and then hold in the staging area. In other cases shad remained in the upstream end for the duration of the trial. At the end of each trial, flows were reduced and shad were returned to the staging area and seined back into the holding ponds, where they were monitored several times a day for mortalities. For each mortality, PIT ID and time were recorded and the animal was assessed for injuries. Survivors were likewise inspected before release.

Analysis

Post-trial condition and survival

Survival rates for both salmon and shad were compared using Kaplan-Meier survivorship curves and statistical comparisons using Wilcoxon and LogRank tests (Allison 1995; Hosmer and Lemeshow 1999; Kaplan and Meier 1958). These are well-established, nonparametric methods for comparing survival rates for treatment and control animals and are superior to logistic and other forms of binomial comparison of two groups because they explicitly include a time component and allow for testing of differences in mortality over time. These methods are also robust against unequal time intervals for monitoring such as happens, for example, when lab personnel were absent overnight. Thus the multiple observations per day act to improve resolution of the tests and are unaffected by the comparatively longer gaps that typically occurred at night. This technique also allowed us to include data from animals that were held for greater than 48 hours. Furthermore, the two tests applied have different sensitivities, with the Wilcoxon test being more sensitive to differences in survival early in the time series (left side of the distribution) and Log-Rank tests being more sensitive to the later part of the time series (right side of the distribution).

Movement behaviors
Video was recorded continuously throughout each trial by 4 cameras interfaced with a multiple input digital video recorder (Tyco Model TVR-08025; Tyco Video, Boca Raton, FL). Passage events were identified using PIT records (recorded separately), and video was reviewed for several seconds before and after each recorded event. If a fish was identified, its position was documented, along with any observations of strike, avoidance behavior, passage route, etc.

PIT data were compiled in a database containing ID, location, and time to the nearest 0.01 s. For salmon smolts, passage times were recorded along with any observations of fish returning upstream. The data for shad were more complex. Here it was possible to identify individual ascent attempts, and in many cases more than one attempt was made. Likewise, not all shad staged attempts. For each condition, proportion attempting was recorded and compared using Logistic regression between treatment and control conditions. Distributions of number of attempts staged were compared using a Kolmogorov-Smirnov test. Because each antenna had a known location, it was also possible to use the PIT array to estimate maximum distance of ascent (Haro et al. 2004).

HTI Data were summarized as location information on a horizontal plane, with position resolved to the nearest second. Because our primary interest was in determining a) whether fish actively avoided the turbine, and b) whether the turbine created a barrier to movement, we focused our analysis on changes in movement rate relative to the ground.

RESULTS

A total of 173 salmon smolts and 208 adult American shad were introduced to the flume structure (Table 1). For both species, more individuals were subjected to the treatment condition (turbine in) than the control (turbine out). This allowed us to improve our estimates of survivorship for those individuals that were exposed to the turbine, while still including enough data from control fish for performing statistical comparisons between treatment and control groups.

In the case of the salmon smolts, flow velocities exceed the swimming ability of the fish and so all individuals ultimately passed downstream. Typically, smolts passed the turbine within about 30 s of release time, although a few individuals were able to hold position upstream for as long as 90 s (see HTI tracks, Appendix A).

Flume conditions varied by trial condition (Table 1 and Figure 5). With the turbine in place, water was held back, creating a head drop across the turbine. A zone of high-velocity flow occurred along the walls downstream of the turbine, and a zone of low-velocity flow occurred immediately downstream of the turbine. Flow downstream of the turbine was also visibly quite turbulent, although we have not quantified the intensity of turbulence as of this writing. Flow velocities in the upstream and downstream staging areas were not measured. As mentioned above, hydraulic conditions in the upstream staging area were sufficiently energetic that all smolts moved downstream shortly after release. The downstream area was much more tranquil, however, and smolts and shad could be easily observed during the trials resting and holding station without any indication of stress or fatigue. Moreover, no fish of either species were impinged on the discharge screens under either treatment or control conditions, providing further evidence that the staging area provided suitable resting habitat.

Instrumentation

Performance of instrumentation varied between the two species. For the salmon smolts, only a single PIT antenna was in place—this was intended primarily for identifying passage times to facilitate video viewing. Turbid conditions and bubbles obstructed much of the video, however we were able to characterize spatial distribution of 33 smolts (Figure 6) and 14 shad passing the turbine zone.

Table 1. Trial test conditions and sample sizes for Atlantic salmon smolts and American shad exposed to treatment (turbine in) and control (turbine out) conditions. Dates and temperatures are presented as ranges, and velocity and depth are presented as mean and standard deviations. Flow velocity is taken 2.45 m upstream of the turbine and corresponds to the 'Upstream' panels of Figure 5. Flow depth measurements were taken 2.45 m upstream and 2.45 m downstream of the turbine hub.

						Flow Depth (m)	
Species	**Turbine**	**N**	**Date Range**	**Temp °C**	**Upstream Flow Velocity ($m\ s^{-1}$)**	**Upstream**	**Downstream**
Salmon smolts	In	117	May 13 - May 19	11.1 - 14.5	1.89 ± 0.13	2.17 ± 0.01	1.90 ± 0.02
	Out	56	May 13 - May 18	10.8 - 14.4	2.38 ± 0.07	1.99 ± 0.02	1.88 ± 0.02
Adult shad	In	134	May 26 -June 09	20.6 - 24.5	1.89 ± 0.02	2.17 ± 0.02	1.92 ± 0.02
	Out	74	May 26 -June 09	20.0 - 23.9	2.38 ± 0.17	2.01 ± 0.01	1.91 ± 0.01

Fortunately, however, the HTI system provided excellent data for many of the salmon smolts (N=85). Only a subset of all the introduced shad carried acoustic tags, and because of their larger size and multiple attempts analysis of those data is far more complex. This analysis is ongoing and will be provided along with a video analysis in a supplemental report once it is complete.

Movement behaviors and survival

Of the smolts that provided quality movement data, there was no evidence of avoidance of the turbine structure. With the turbine running, 43 smolts passed through, above, or beneath the swept area of the blades, and 17 passed around the outside of the blades. This is significantly greater than a 50:50 ratio, despite the fact that the swept area of the blades only occupied 50% of the flume width. This raises the possibility that smolts were actively entrained or attracted to the turbine. However an alternate explanation exists, which is that the smolts were simply avoiding the walls, or perhaps being drawn to the center of the flume by the greater velocities present there (Figure 5). This can be assessed by comparing treatment and control conditions, and under the control condition we also observed a tendency of smolts to gravitate toward the center of the flume, with 15 individuals passing in the turbine zone (with the turbine removed), and only 10 passing outside of that zone. Thus it is likely that the tendency to pass down the center of the flume reflects either volitional or passive avoidance of the walls and preference for the center of the flume (see also individual tracks, Appendix A, and discussion of video analysis below).

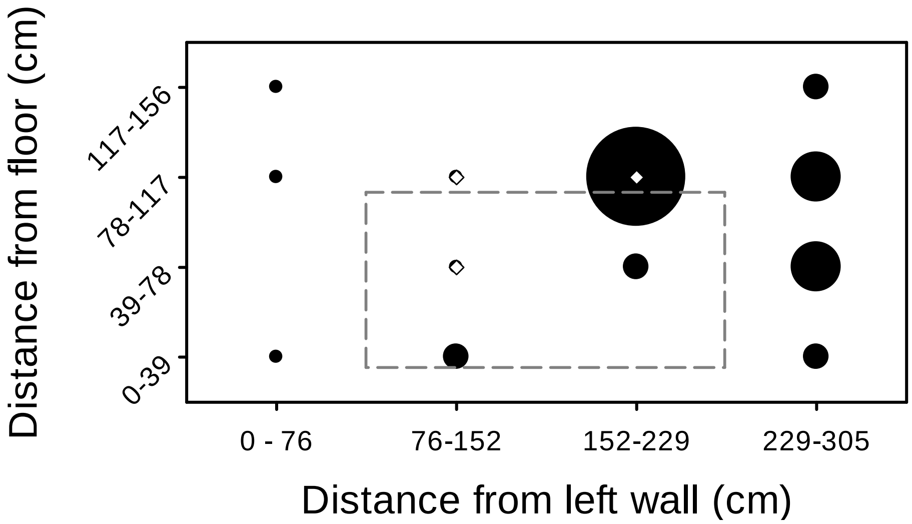

Figure 6. Distribution of passage locations for Atlantic salmon smolts passing downstream through turbine (viewed in downstream direction). Bubble size scales with number, with largest bubble indicating 8 individuals and smallest indicating single observations. White diamonds represent observations with the turbine removed, black circles represent observations with the turbine in place. The turbine spun in a counter-clockwise direction, viewed from above, i.e. the right side of the panel was associated with the downstream sweep of the turbine blades.

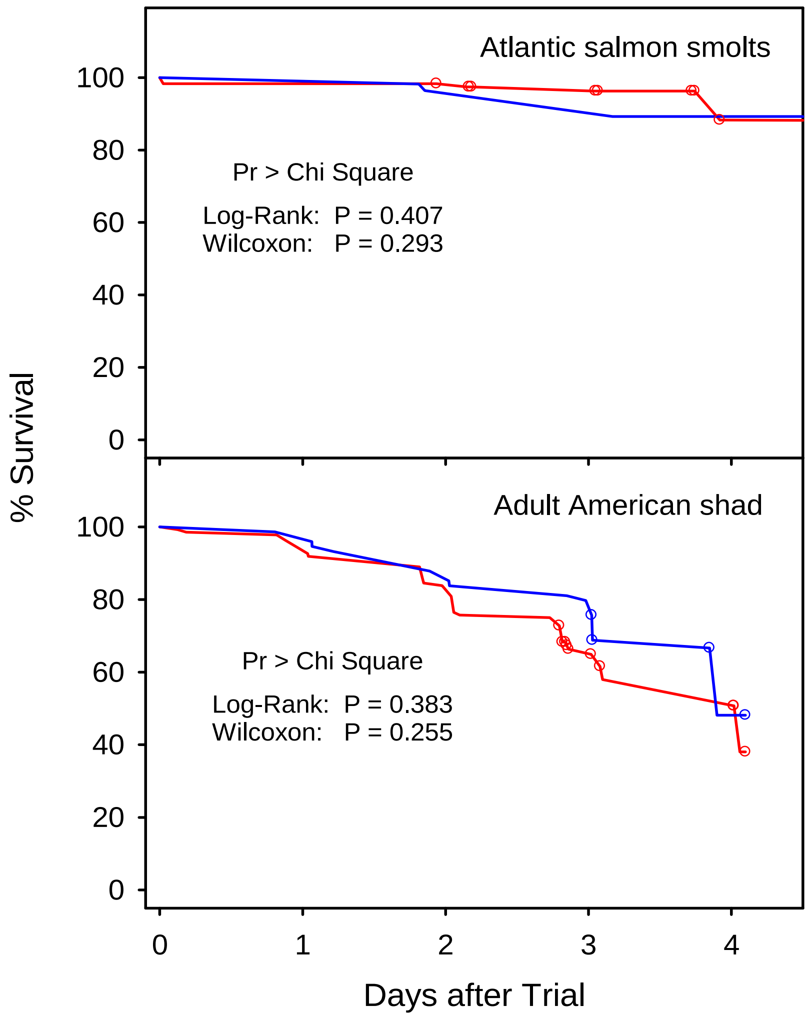

Figure 7. Survivorship curves for Atlantic salmon smolts and American shad exposed to turbine (red) and control (blue) conditions. Circles indicate censoring, when survivors were either sacrificed or returned to the river to continue their migration.

Despite the high incidence of turbine passage, we observed no injuries to individual smolts following trials. Also overall survival was high, with 48 hour survival of 98.3% (95% confidence interval from the binomial distribution (CI) = 95.4-99.7%) for treatment smolts and 96.4% (CI = 90.5-99.5%) for controls (Figure 7). This difference was non-significant (Log-rank P = 0.41; Wilcoxon P = 0.29).

It is important to recognize, however, that this study was designed to identify strong effects. Given the observed mortality among controls, the power provided by these sample sizes to detect 5% or 10% increases in mortality at a 0.05 significance level was 0.225 and 0.517, respectively. This means that negative results should be interpreted with caution. Analysis of the confidence intervals from the treatment and control groups suggest, however, that the maximum magnitude of the effect was unlikely to exceed 5%. This value can appropriately be applied as a precautionary interpretation of these data (Hoenig and Heisey 2001).

The low mortality rate may be attributable in part to the route through which most smolts passed the turbine. Video analysis suggests that smolts disproportionately passed over the top and around the side of the downstream-sweeping side of the turbine blade when the turbine was present (Figure 6; Chi Square P=0.05). Orientation of smolts to the current was variable, and about equally distributed among upstream-oriented, downstream-oriented, or sideways as they passed the cameras. Also, the observed pattern is reminiscent of the velocity profile (Figures 4 and 6)—it is possible that this pattern is affected by flow, but given the distribution it is likely that volitional response to the turbine has some effect on passage route.

Assessment of the speed at which smolts moved relative to the flow suggests that there was some ability to orient to and resist the current (Figure 8). There was noticeable hesitation in the Upstream zone for both treatment and control fish. This probably represents a response to the elevated floor and associated flow acceleration. In the presence of the turbine smolts were slightly slower in the approach zone than when it was removed, and slightly faster downstream as they exited the flume. These differences were non-significant, but are evocative of slight hesitation upstream of the turbine by some individuals, and perhaps escape behavior following passage. Several tracks appeared to indicate disorientation immediately following passage (Appendix A), which accounts for the slight drop in groundspeed in the Departure zone (Figure 8). It is important to recognize that, given the variability in behavior, it is possible that the observed patterns may have arisen by chance. There does appear to be a tendency toward more rapid downstream movement as the smolts passed downstream. This may represent the associated increase in flow velocity, or it may simply reflect the onset of fatigue as smolts swam against the very rapid flow.

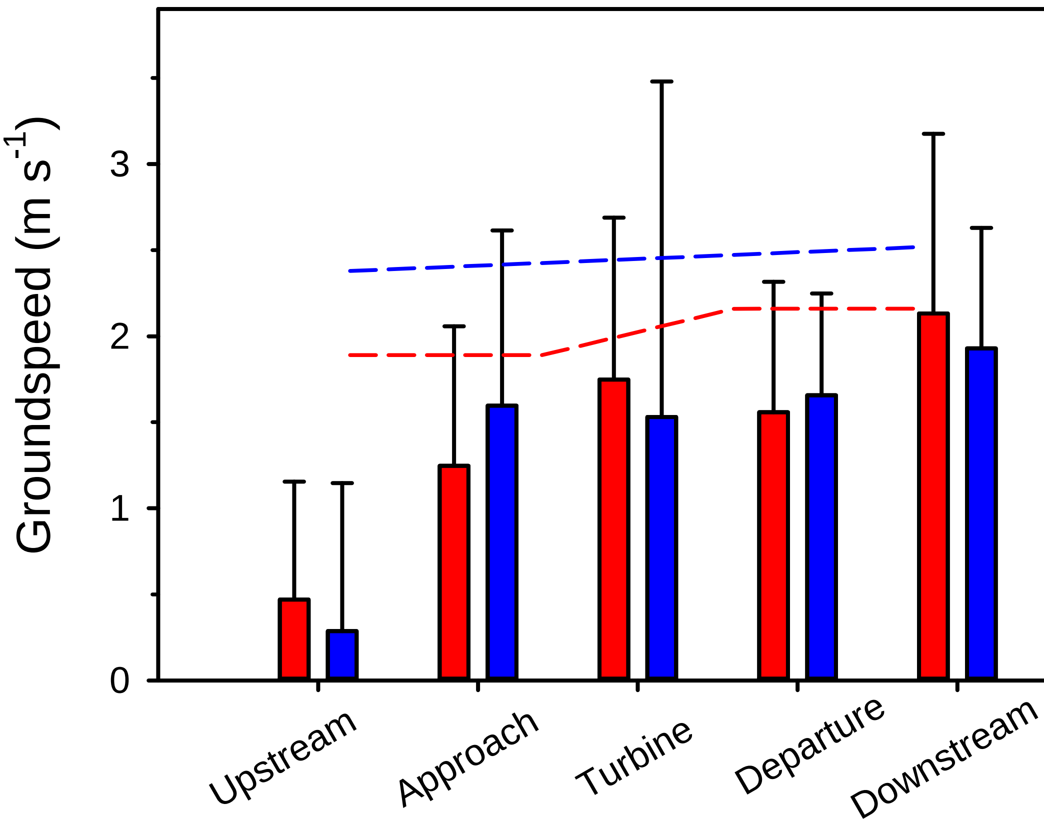

Figure 8. Groundspeed of Atlantic salmon smolts as they passed downstream through the flume under treatment (red) and control conditions (blue). This figure partitions the flume into 'Upstream' (> 4 m upstream of the turbine hub), 'Approach' (1-4 m upstream of the turbine hub), 'Turbine' (1 m upstream to 1 m downstream of the hub), 'Departure' (1 -4 m downstream of the turbine hub) and 'Downstream' (> 4m downstream of the turbine hub). Columns are means and error bars are standard deviations of groundspeed. This entire range is above the horizontal portion of the elevated floor, and so the reduced groundspeed upstream suggests either some response to the floor or pre-fatigue efforts to hold station in the rapid flow. The dashed lines show flow velocity under each condition (calculated from Table 1). Differences between groundspeeds for treatment and control conditions were nonsignificant for all zones, owing at least in part to strong variability in groundspeed. Mean groundspeeds were consistently less than flow velocity, however, indicating that smolts were resisting the current, backing downstream as they passed the turbine zone.

As mentioned above, fewer HTI tracks were recorded for American shad. Because of the much longer durations and exposure times of shad to the turbine and flume environment, analysis of the shad tracks is much more complicated and will be presented in a supplemental report.

Movement data are available, however, owing to the more complete PIT antenna array that was deployed for the shad trials. These data allow for evaluation of the effect of the turbine on movement up the flume, both in terms of distance of ascent and the willingness or ability of shad to enter the flume. The PIT system was configured to record transmissions at a rate of 14 Hz. As shad pass through individual antennas, multiple records are logged, typically with very short (< 0.25 s) lags between detections. Additional lags occur as shad move between antennas, as they hold station within the flume, and when they exit the flume and subsequently re-enter from the staging area. By plotting lags between detections, and comparing these with detection locations, it is possible to identify changes in slope associated with different behaviors (Figure 9; Castro-Santos and Perry *In Press*). In this case, PIT detections separated by < 150 seconds were predominantly associated with shad that were holding station within the flume, either between antennas or upstream of the raised floor. Lags > 150 s were typically associated with the downstream antenna and so can be assumed to represent discrete attempts. Using this approach, it becomes possible to quantify the number of entries for each shad that attempts to ascend the flume, and the maximum distance of ascent achieved on each attempt.

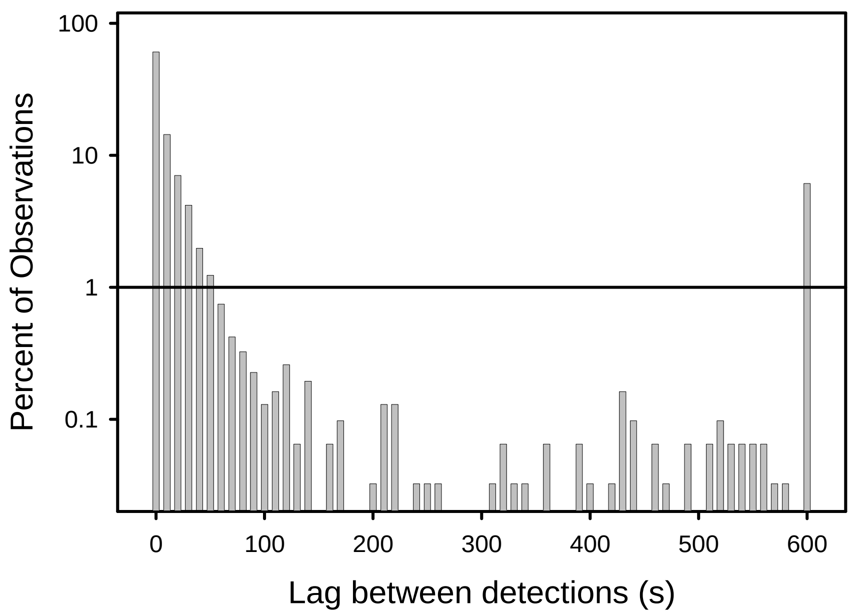

Figure 9. Intervals (Lag) between PIT detections of American shad attempting to ascend the test flume. Note the change in slope at about 150 s; this threshold was used to differentiate among successive ascent attempts by individuals.

Using this method there was some evidence that shad staged more attempts when the turbine was removed (mean ± SD number of attempts= 1.13 ± 2.1 with turbine in, and 1.80 ± 2.8 with turbine out). The data were strongly skewed, and a Kolmogorov-Smirnov test indicated that although the two distributions were not significantly different (P = 0.125), significance was approached, and there is weak evidence that shad were less attracted to the flume under the turbine-in condition.

For those shad that did enter the flume, there was a clear effect of the turbine on distance of ascent, with more shad passing the turbine location with the turbine removed than when it was in and running (Figure 10; Wilcoxon P=0.004; LogRank P=0.734). Both video and PIT analysis showed that shad actively avoided the turbine, being more likely to arrive at Antenna 4 once they passed the structure. This may reflect avoidance of the turbine once upstream of it, or improved swimming ability in the relatively lower flow velocities present upstream of the turbine when it was running.

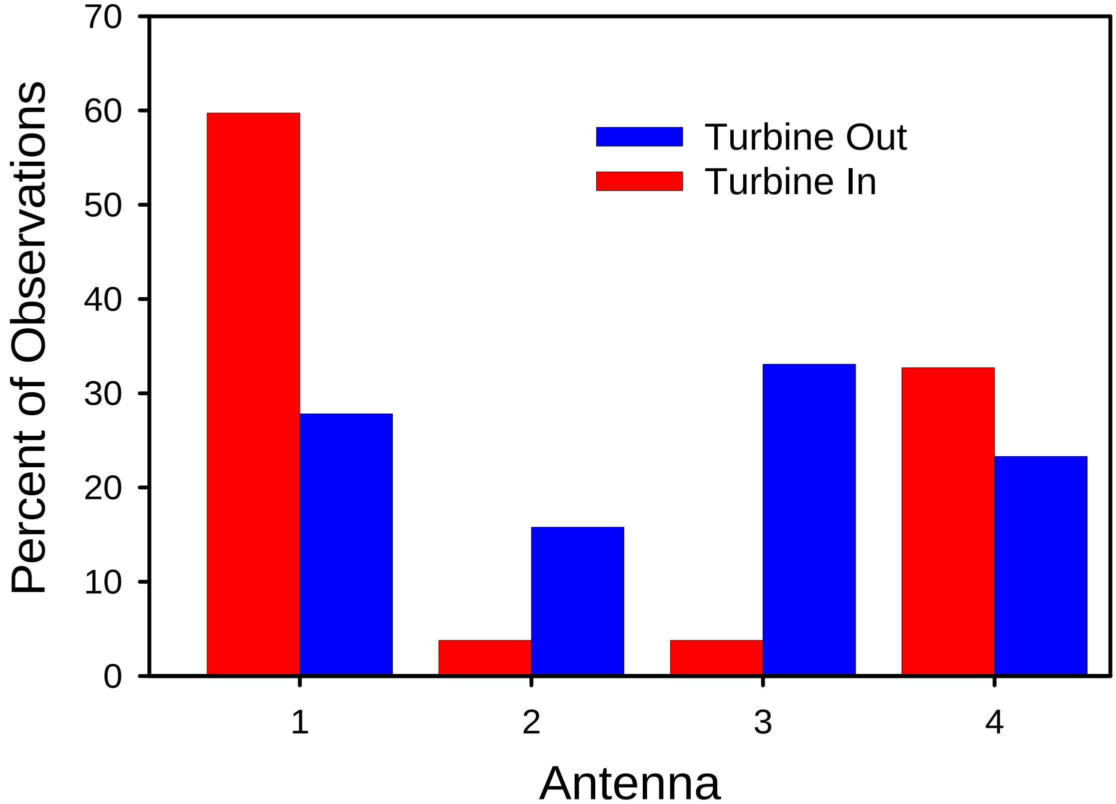

Figure 9. Maximum distance of ascent as measured by PIT antenna number (see Figure 1b). Antennas are numbered moving from downstream to upstream, i.e. flow moves from right to left, and turbine is located between Antennas 2 and 3.

Although HTI data are not available as of this writing to enable us to quantify how many shad passed through the turbine, anecdotal evidence from video observations indicates that many shad actively avoided the turbines, either by swimming around it or, for those individuals that passed successfully, holding station just upstream of the unit. Note that this, coupled with the distance of ascent data (Figure 10) suggests that under our test conditions shad were reluctant to pass this device in either direction.

As with the salmon data, post-test assessment of shad yielded no evidence of strike injuries, and survival of treatment and control groups was comparable (Figure 7; Wilcoxon P = 0.126; LogRank P = 0.413). Both groups of shad suffered greater mortality than did the salmon, especially after 2 days of post-trial observation (note that shad are sensitive to confinement, and these animals had been held for a total of >3 days). The observed mortality rates are consistent with those observed among shad held in these same facilities without any handling after being transported (Sullivan 2004). Given the observed mortality among controls, the power to detect a 10% increase in mortality after 48 h was 0.59 with this sample size, but after 96 h decreased to 0.29. The 48 h figure is probably the more reliable of the two, given the increased mortality among both treatment and control shad after this point. Nevertheless, the power of this test indicates that the nonsignificance of any effect should be viewed with caution, particularly since the Wilcoxon test, which is more sensitive to early mortality, approached significance.

DISCUSSION

The most striking result of this study is the apparent lack of any injury or mortality incurred as a result of passing through the turbine for either species. Even conservative estimates of turbine-induced mortality indicate values <5%. This is comparable with expected survival through the most fish-friendly turbine designs currently in use, such as some Kaplan turbines, and is also comparable to experimental units under development with the specific objective of reducing harm to fish (Odeh 1999; Electric Power Research Institute 2011).

In order to definitively show lower mortality rates, studies with much larger sample sizes would have to be conducted. The power of tests on turbine mortality studies is important because it informs us of the scale of likely effects. In this case, mortality rates of <5% may be acceptable for a small number of turbines deployed on a large river system where individual risk of exposure was low. For resident species, large arrays of units, or systems in which individuals may be exposed many times to similar devices (e.g. tidal situations), even lower rates would likely be a cause for concern.. In order to get confidence intervals small enough to ensure safety in the context of multiple exposures, much larger sample sizes will be required.

This is particularly true for species like American shad, which are sensitive to handling and holding. As mortality rate of controls increases, the relative sample size needed to detect effects also increases. This need for large sample sizes and controlled follow-up is one great advantage of laboratory studies over field studies—handling effects and losses to follow-up can be minimized, meaning that laboratory studies can be far more efficient at detecting survival effects than field studies.

A counterpoint to the above is that the smolts used in this study were of hatchery origin, and the flume environment is highly artificial. The turbine occupied a much larger proportion of the flume than would be expected in a field situation. Also, actual behaviors of wild smolts in a free-flowing river may differ from what was tested here. Because of this, any conclusions drawn from this and other laboratory work should be viewed as preliminary and subject to verification in the field.

Similar conclusions can be applied to the adult American shad. In this case the fish were wild, and their behaviors may be more representative of what one would expect in the field. Here again, though, the flume environment is highly artificial and movements were constrained. The observed reluctance to pass the turbine may be less of an issue if it were to be deployed in a larger river system, with more space above, below, and around the turbine through which fish could pass unimpeded.

Behavioral barriers are a concern because they create a situation in which fish may avoid passage, or reduce the rate of passage (i.e. increase the time required to pass). On the scale of an individual unit, such delays may be inconsequential, but at larger scales, with many turbines deployed throughout a river system, cumulative effects could lead to reduced spawning viability, reduced access to habitat, and possibly increased risk of predation, disease transmission, etc. (Castro-Santos and Haro 2010; Castro-Santos and Letcher 2010) American shad are notorious for being reluctant to pass structures of many designs, and these results demonstrate that these devices have the potential to obstruct movements of upstream adult migrant fishes. As with the salmon smolt data, any conclusions drawn from laboratory studies should be viewed as preliminary and subject to verification in field settings. Furthermore, likely effects of deployed turbines in the field will vary as a function of the number of units deployed and the scale and hydrography of the deployment location. It is likely, for example, that with sufficient space around the devices, the behavioral barriers may become negligible. More studies, in both field and laboratory situations, will be needed to determine the scale of this effect.

A final note of caution: these studies were performed on only two species, and were done under strong lighting conditions. Other species and life stages might have responded differently to this turbine, and more data on a greater diversity of species would help define the scale of likely effects. Also, many riverine and migratory species are most active at night. Although we saw evidence that fish passing through this turbine appeared not to suffer injury, it is an open question as to whether the same would be true under low-light conditions. Further work is needed to address this question. Lessons learned from this first year of study have shown the difficulty of using video to monitor movements, but also the benefits of advanced telemetry systems to offset this challenge. Alternative video and acoustic technology should be applied to see if they produce better imagery; infrared video might hold some promise as well. Regardless, additional study on other species, life stages, lighting, and hydraulic conditions would further advance the conclusions and broader relevance of this study.

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Appendix A. Smolt tracks from HTI data

The following figures show the HTI tracks of Atlantic salmon smolts as they moved downstream through the flume structure. Units are in meters, 'xpos' indicates meters from the upstream pair of hydrophones; 'ypos' indicates meters from the right wall (facing downstream), with the origin (i.e. the wall itself) located at ypos=0.5, and the left wall located at ypos=3.5. The turbine was located at xpos=5.9, ypos=2.0, and had a radius of 0.76 m. In some cases individual observations are placed outside the wall. This is the result of positioning error—when smolts were close to the walls this error tends to increase because the acoustic signal can echo off the wall creating a false position. Overall, precision of each estimate averaged ± 20 cm, so positions outside the walls should be interpreted as indicating that the fish were very close to the wall.

Smolt Tracks, Treatment = Turbine

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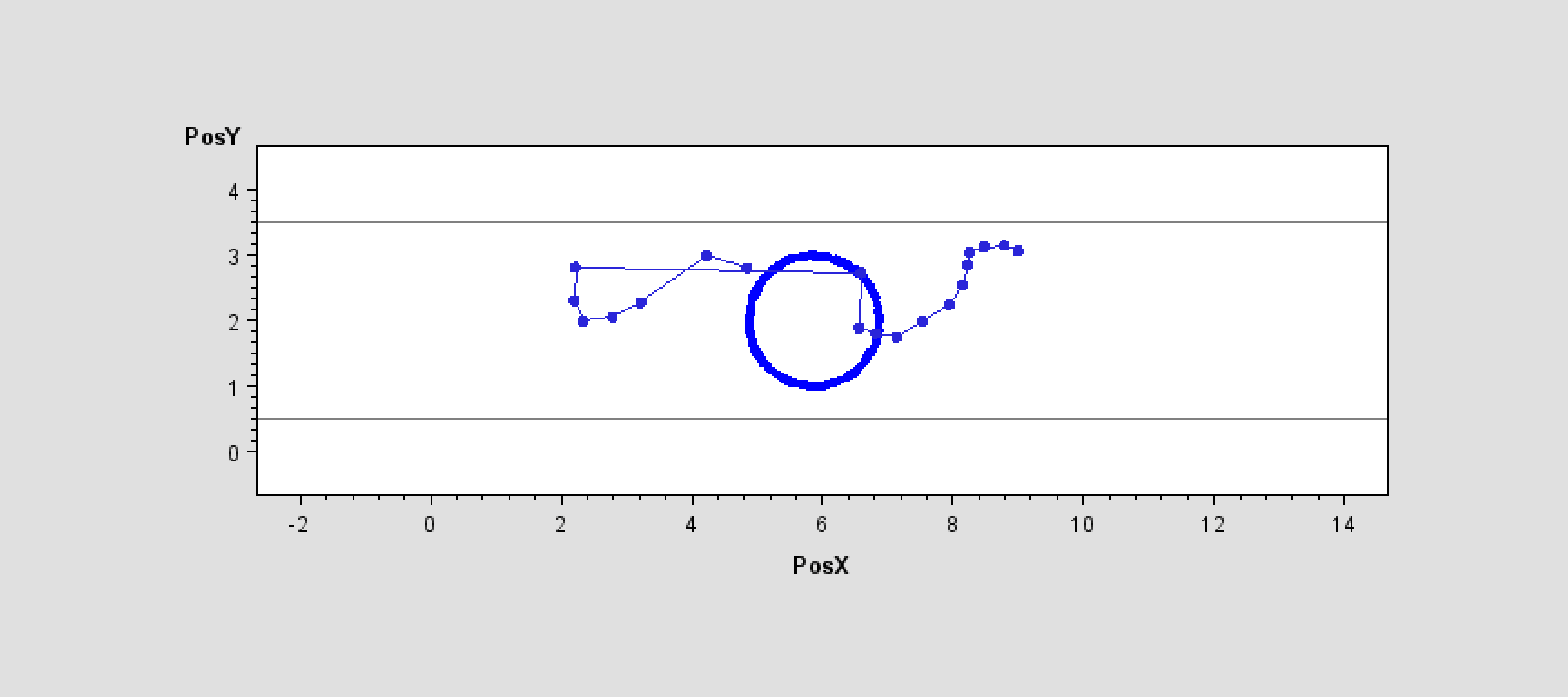

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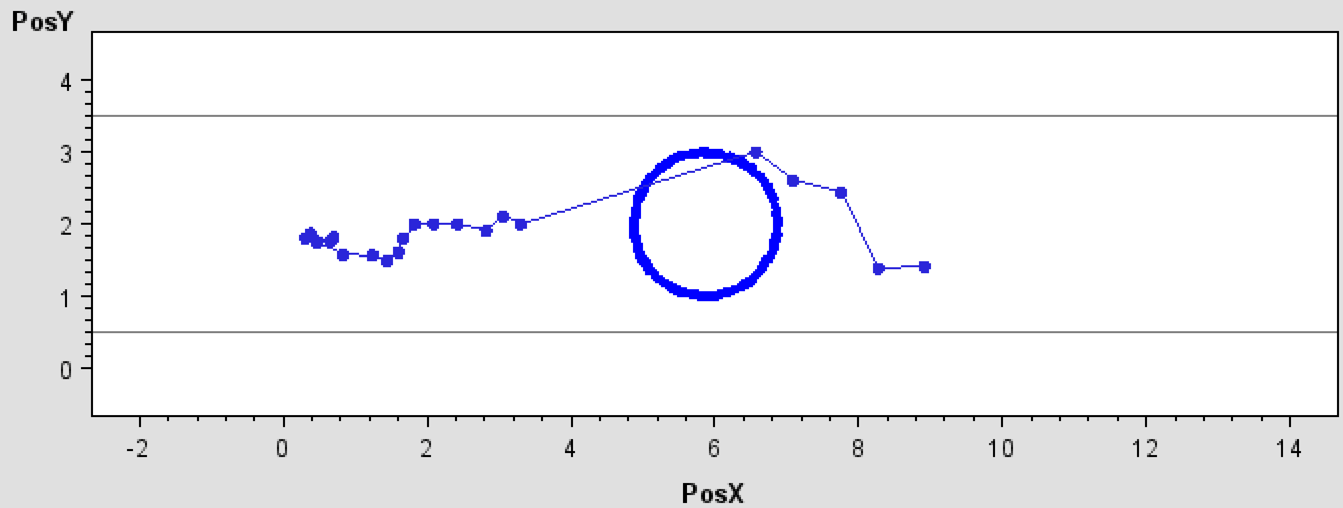

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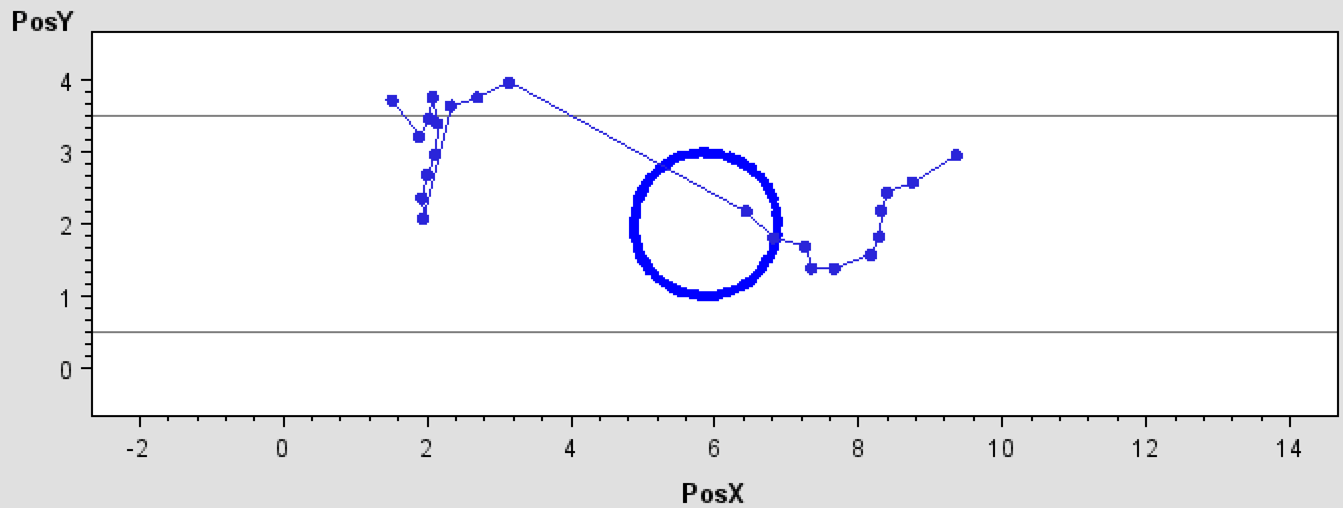

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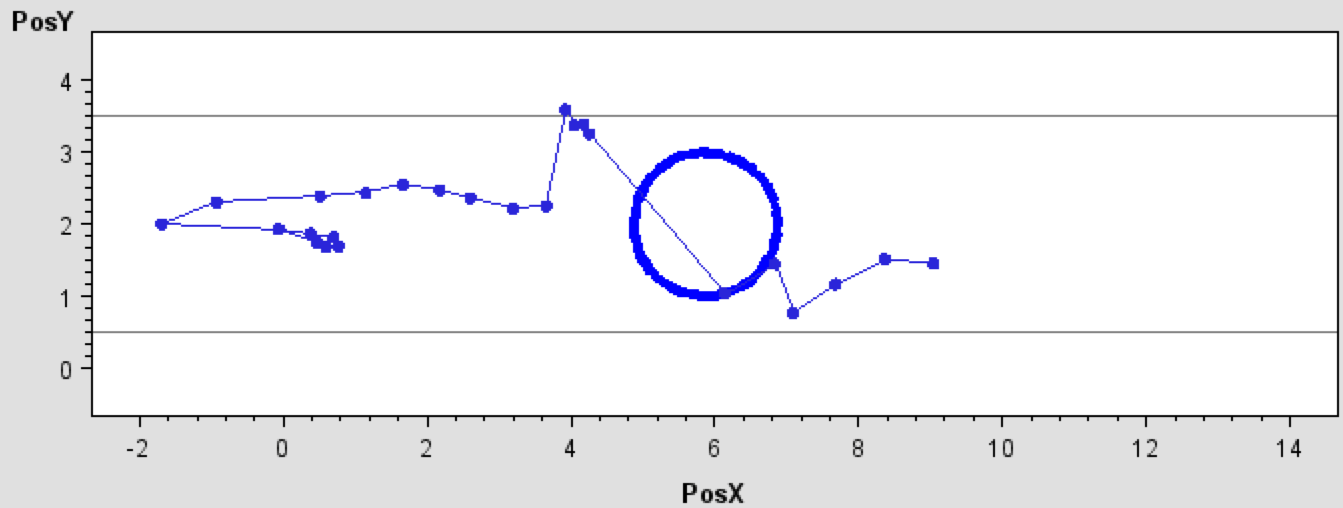

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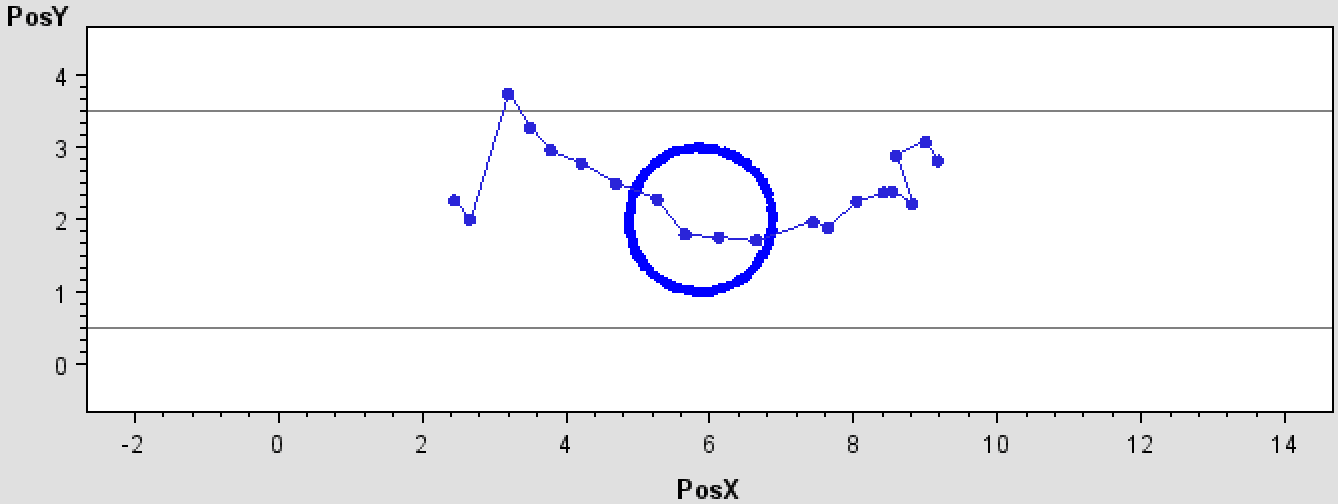

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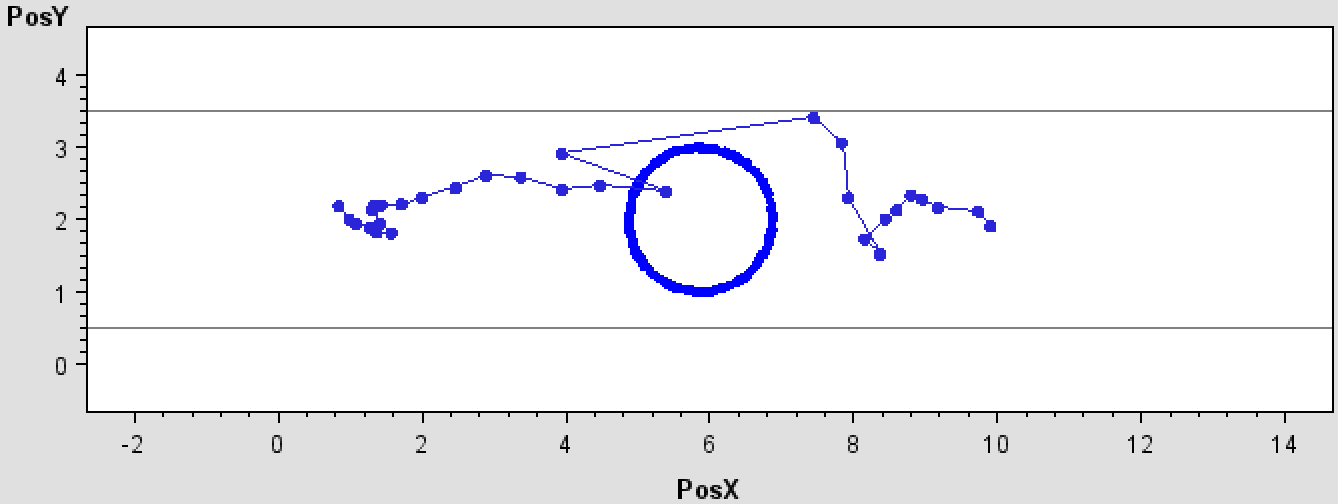

Smolt Tracks, Treatment = Turbine

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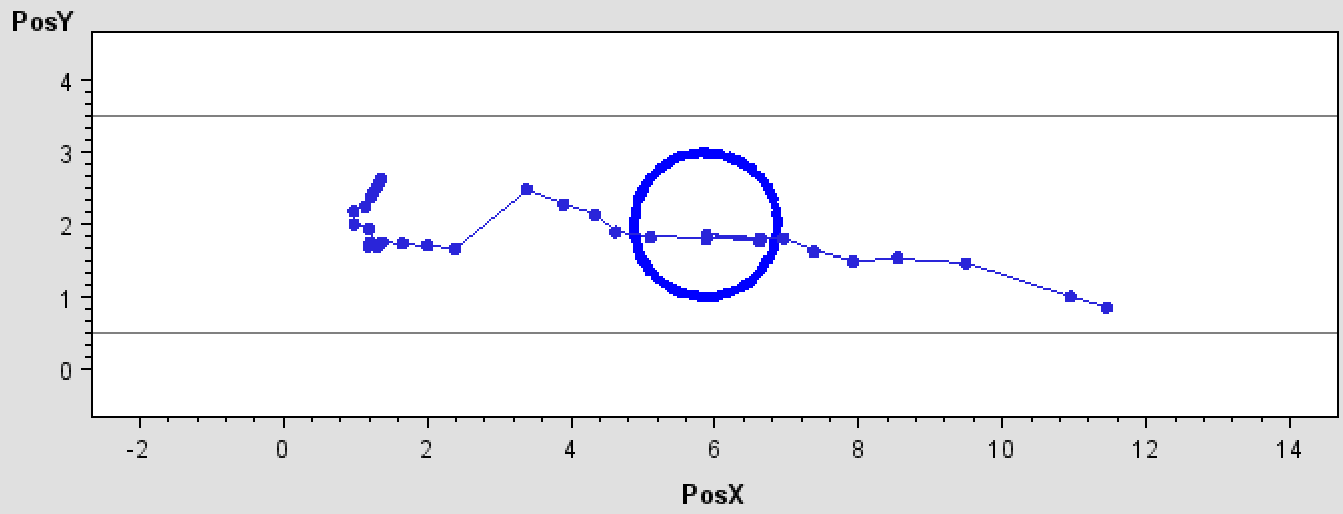

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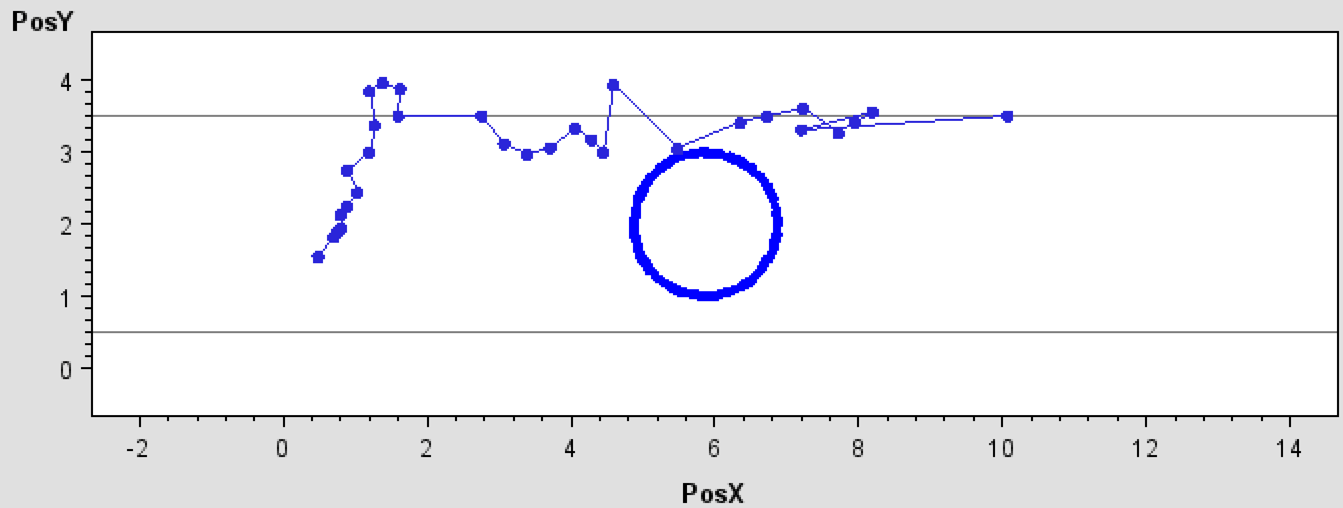

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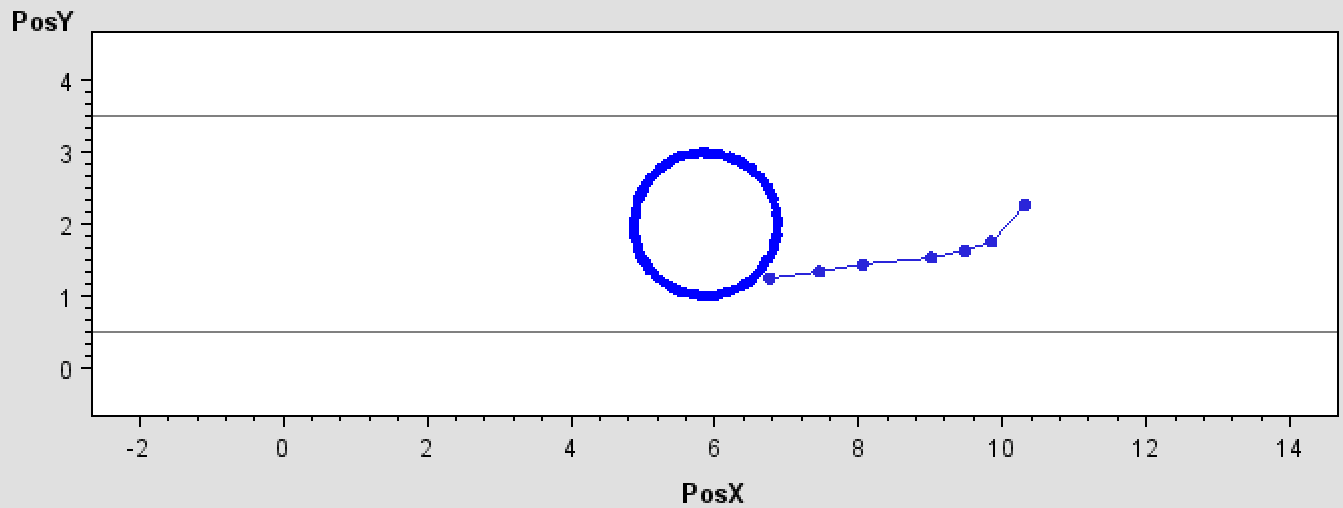

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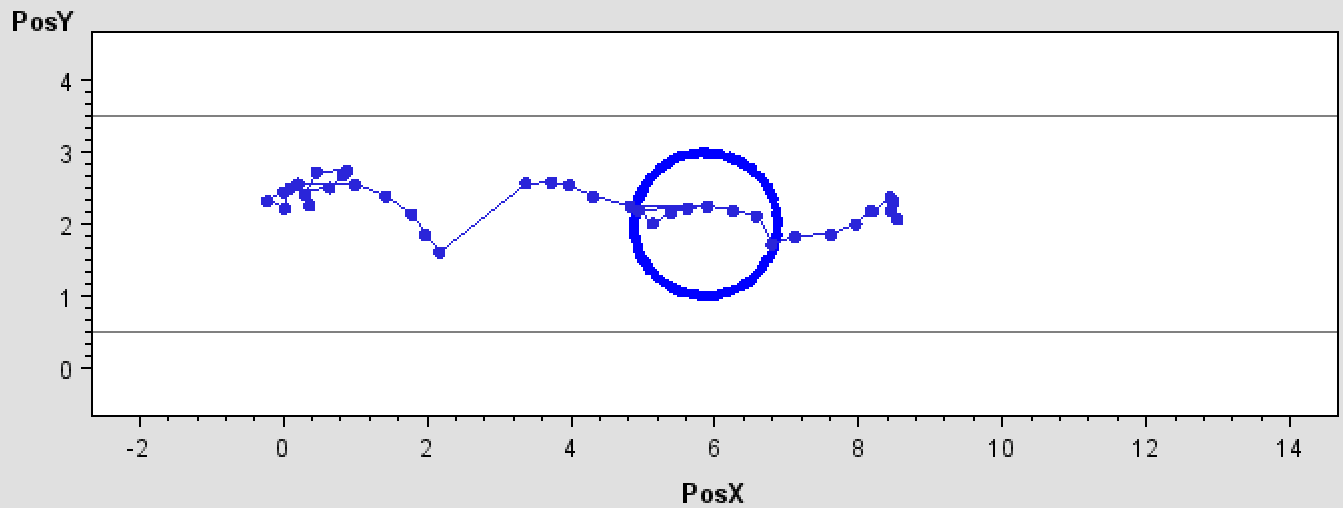

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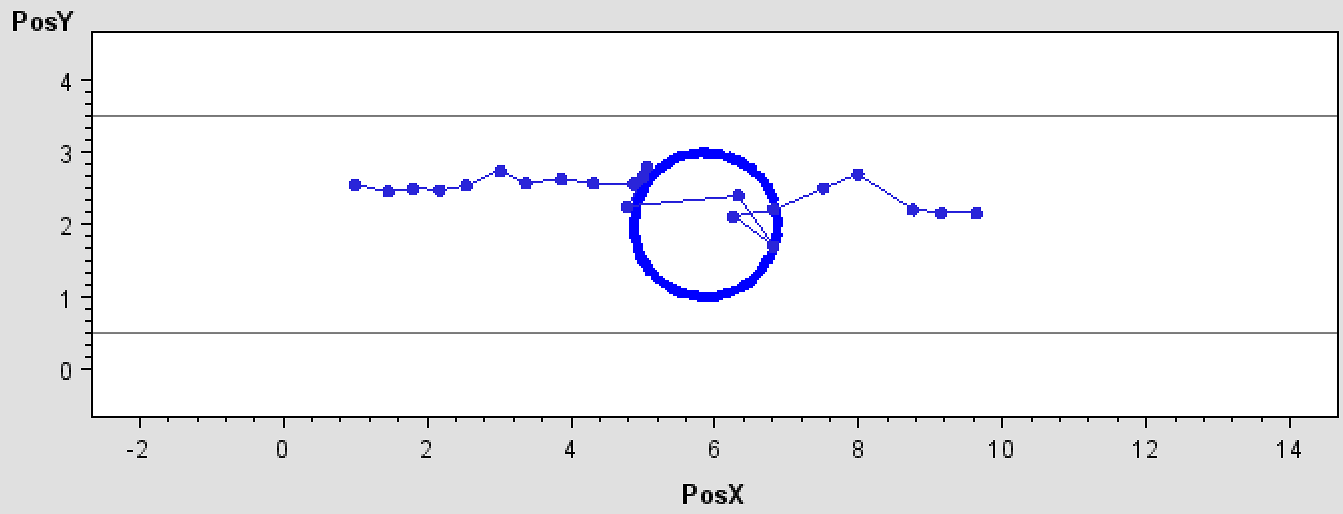

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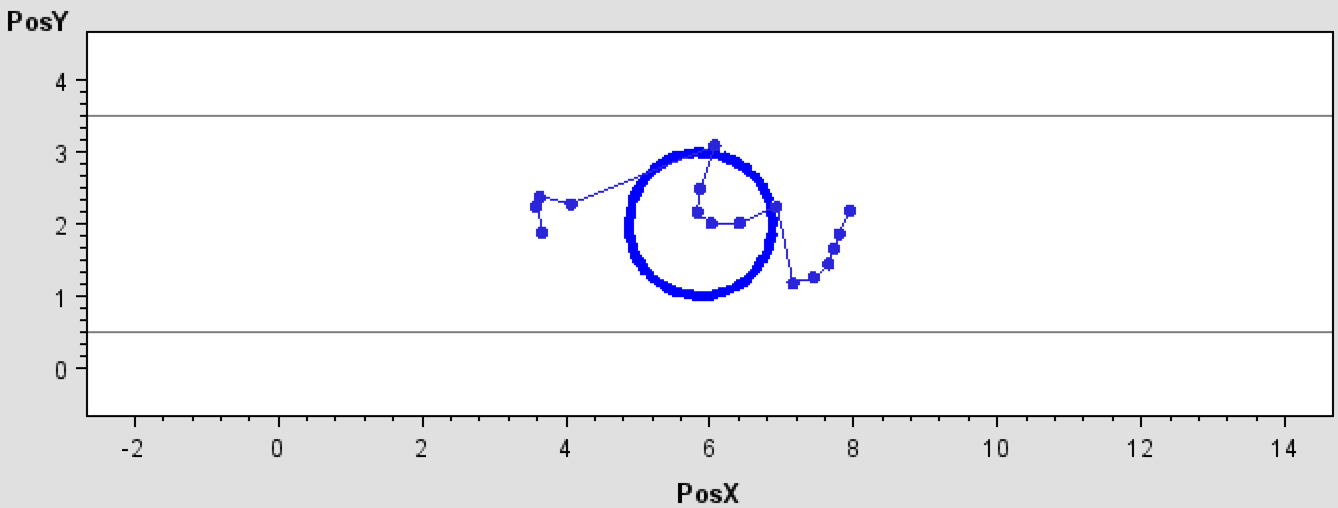

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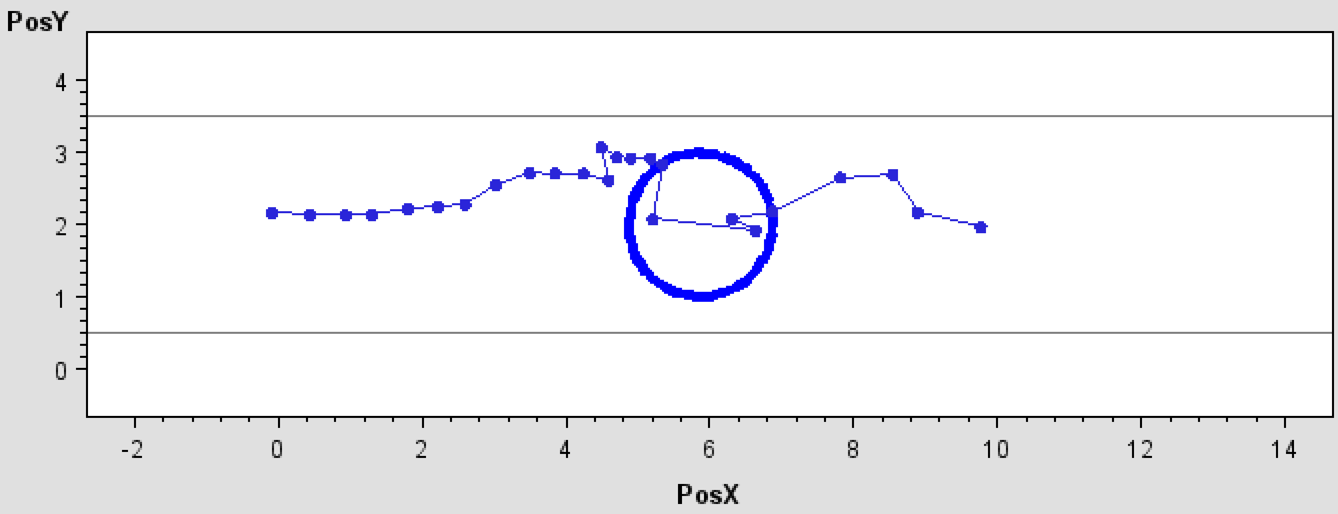

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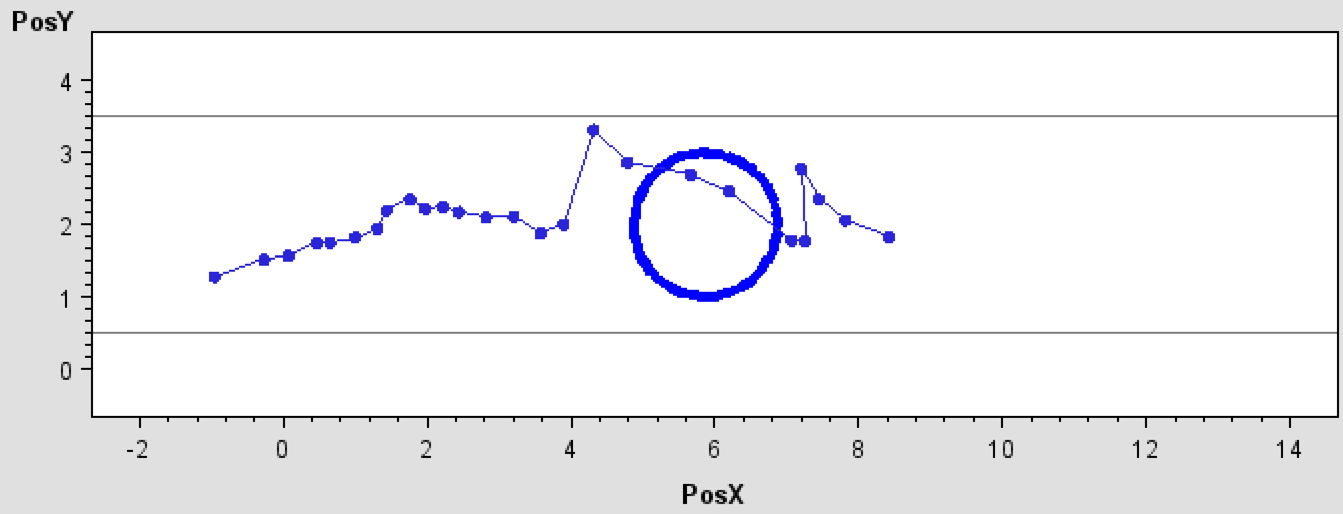

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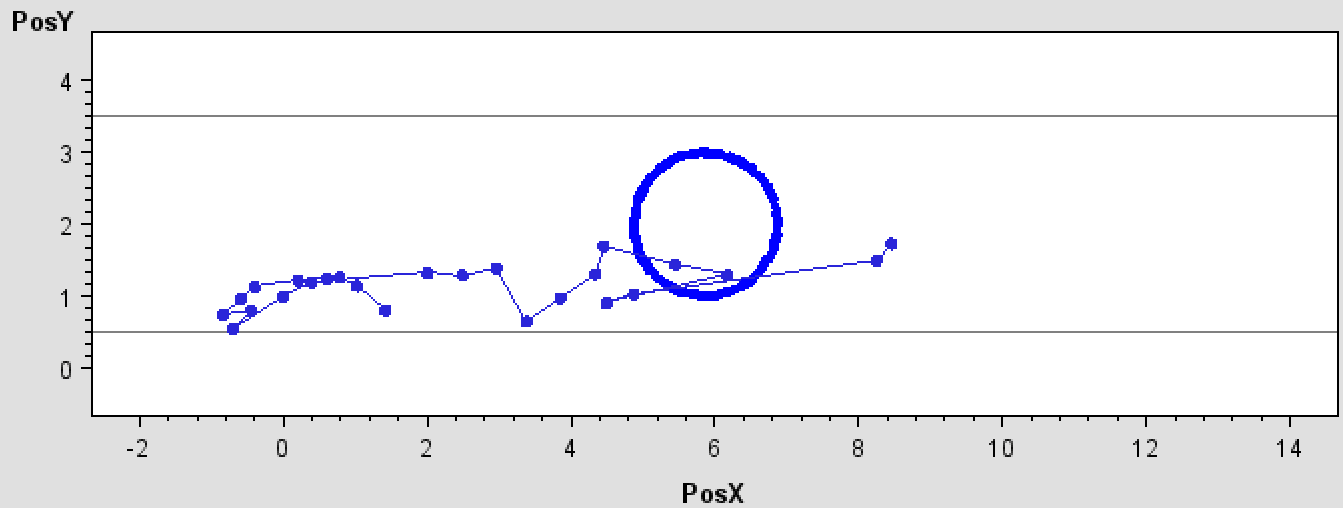

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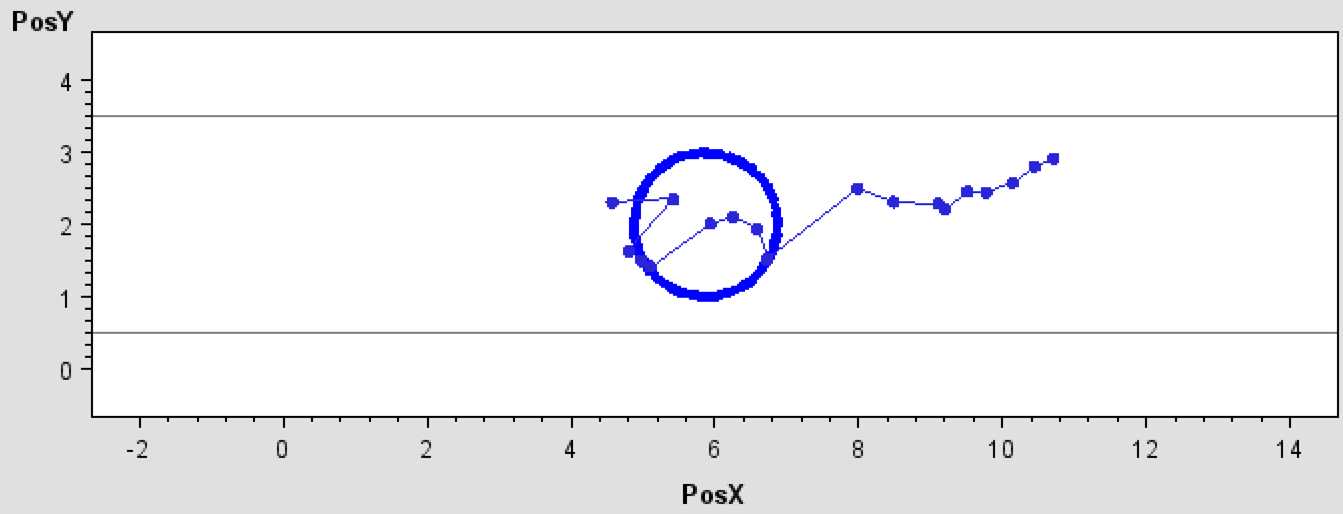

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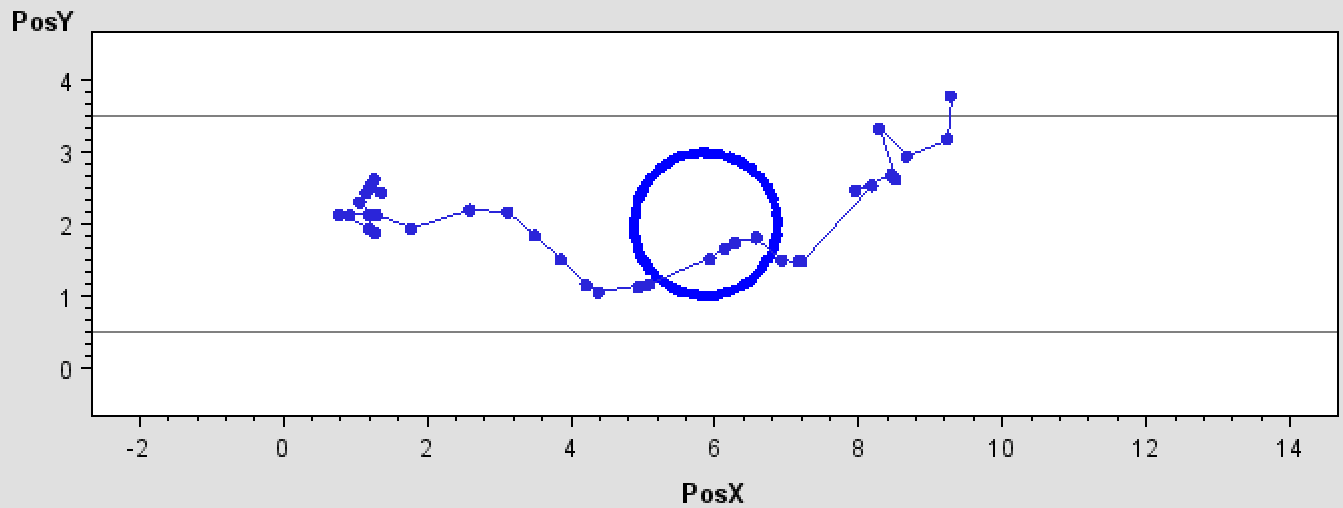

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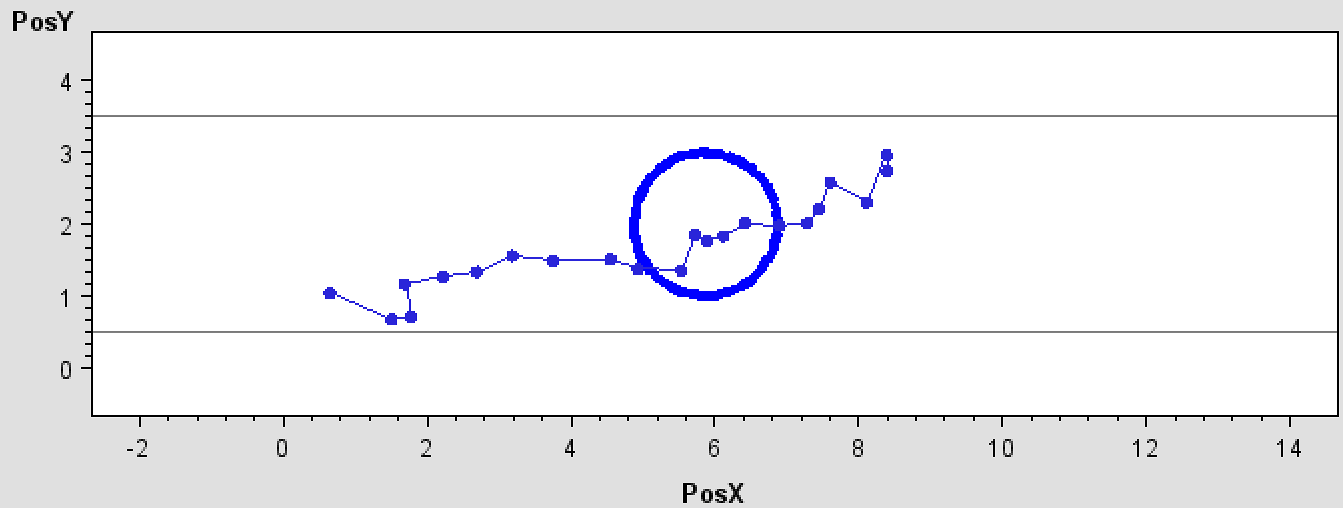

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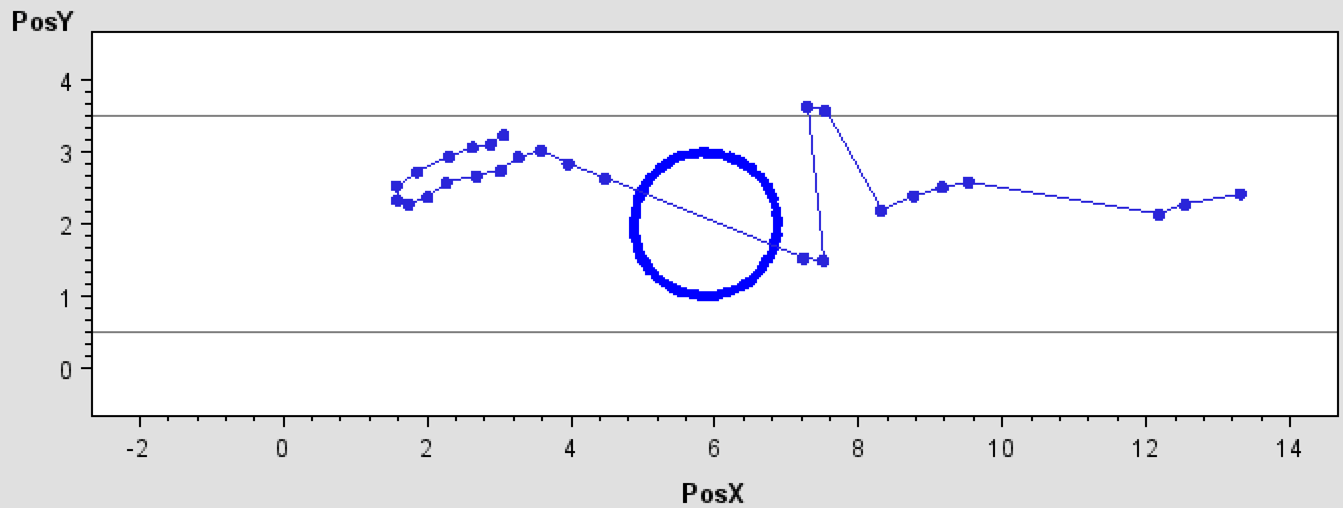

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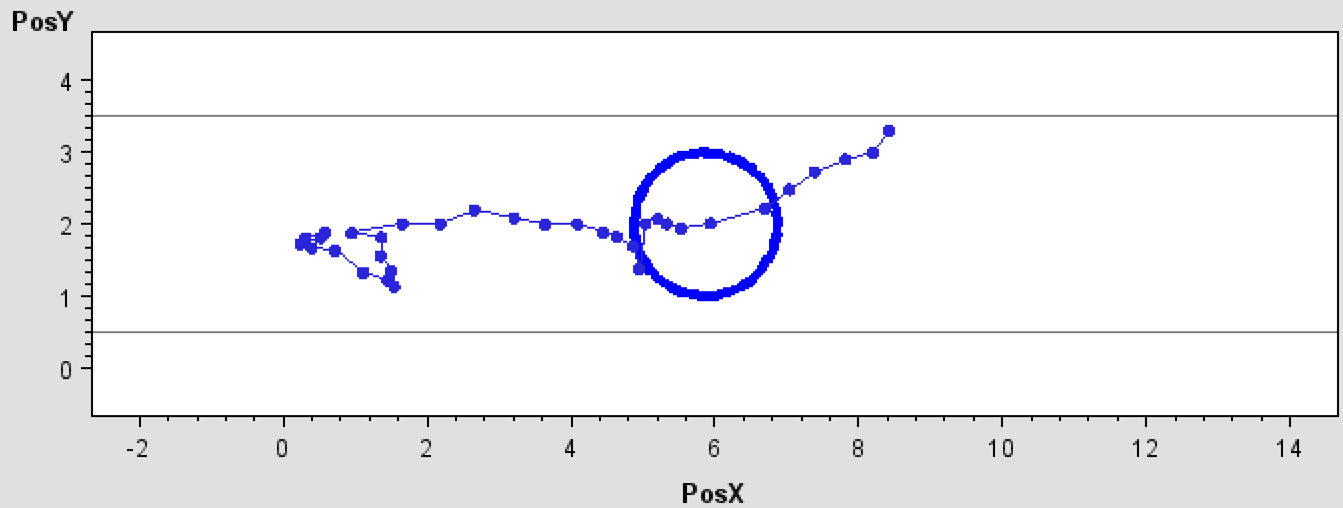

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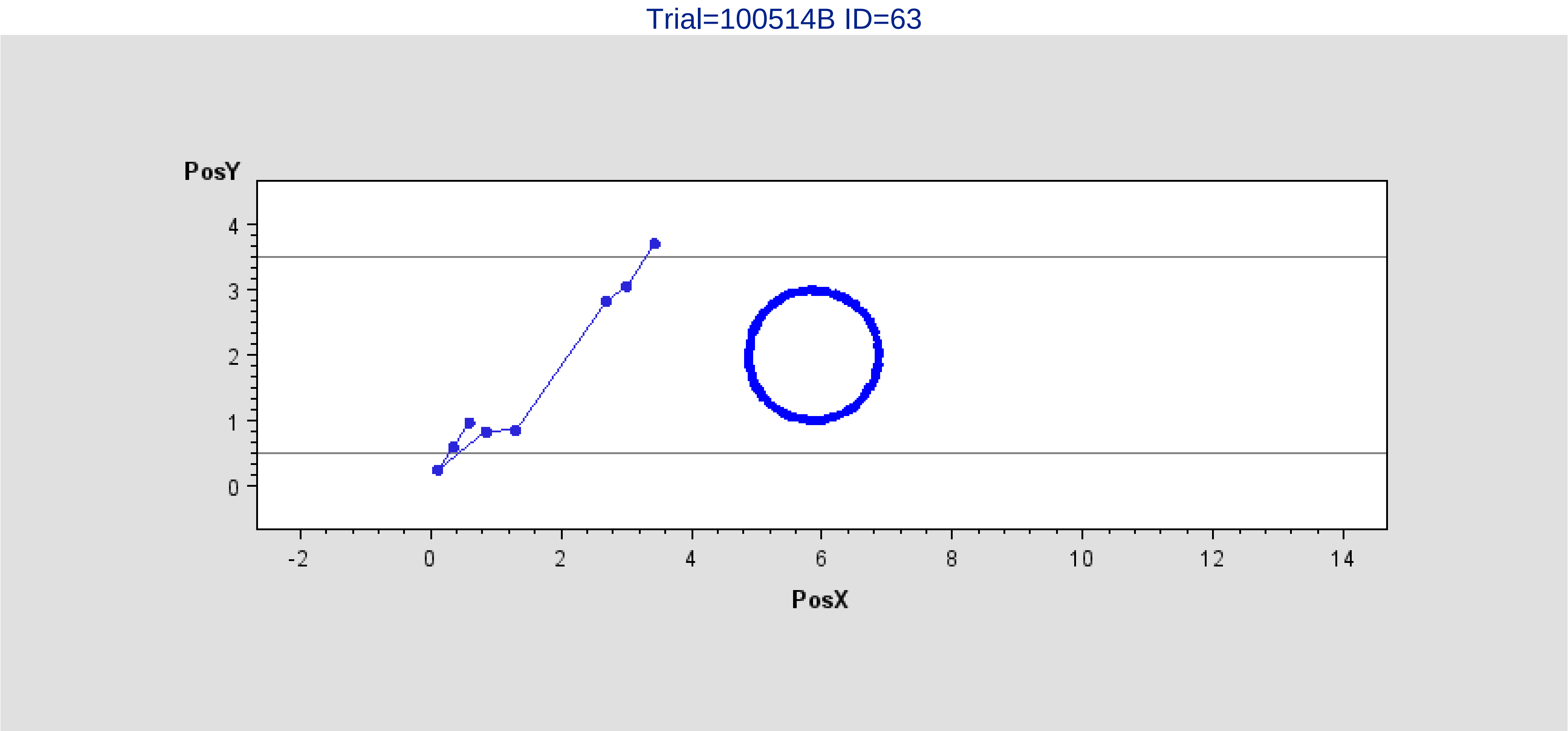

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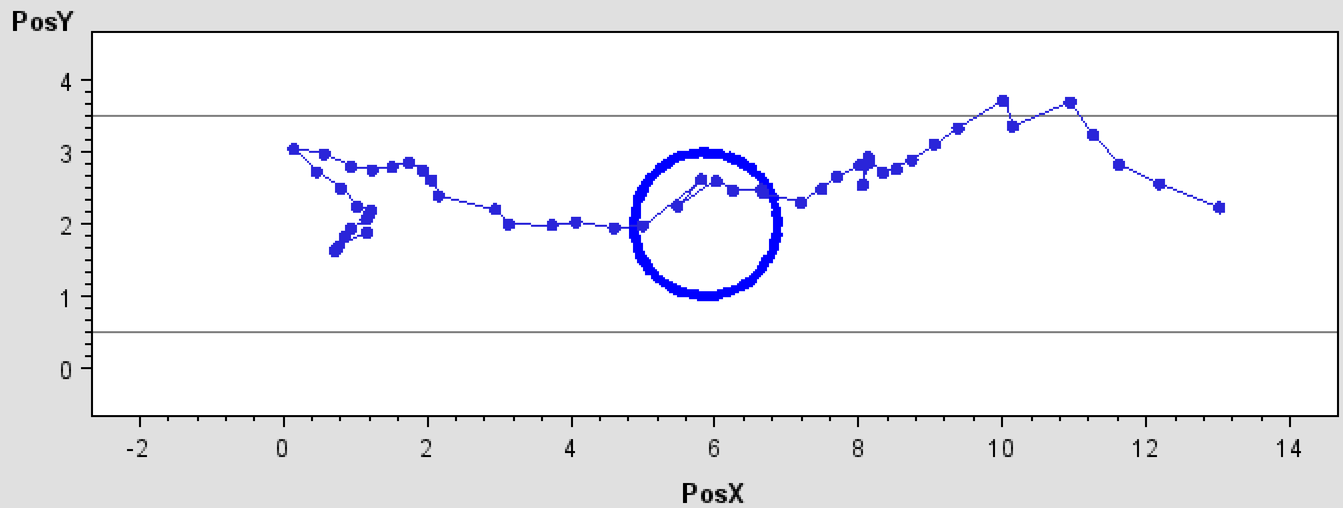

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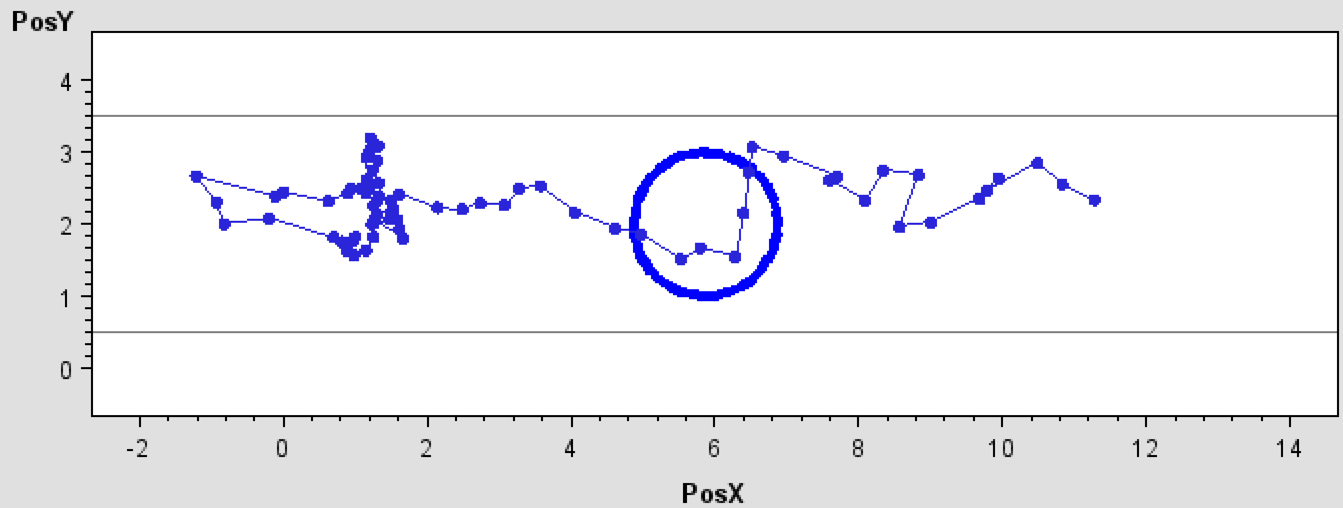

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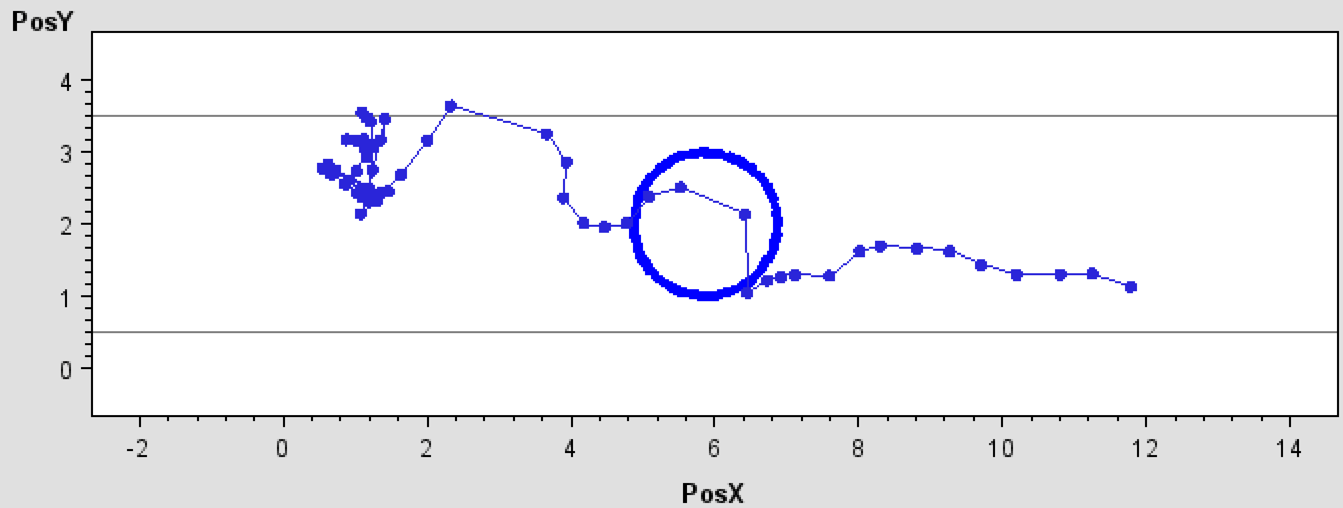

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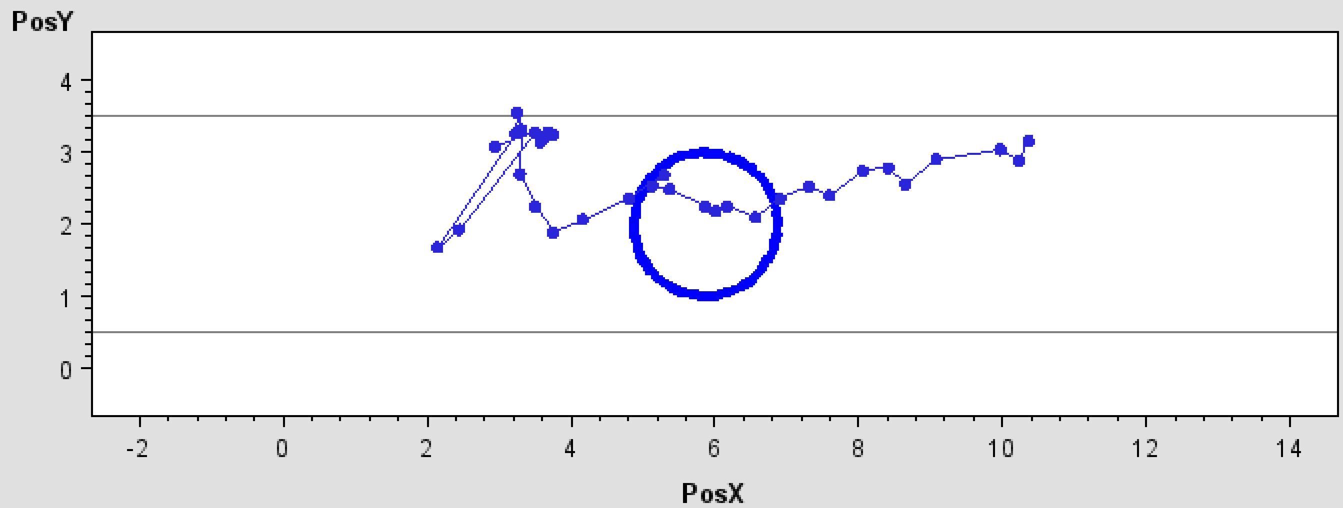

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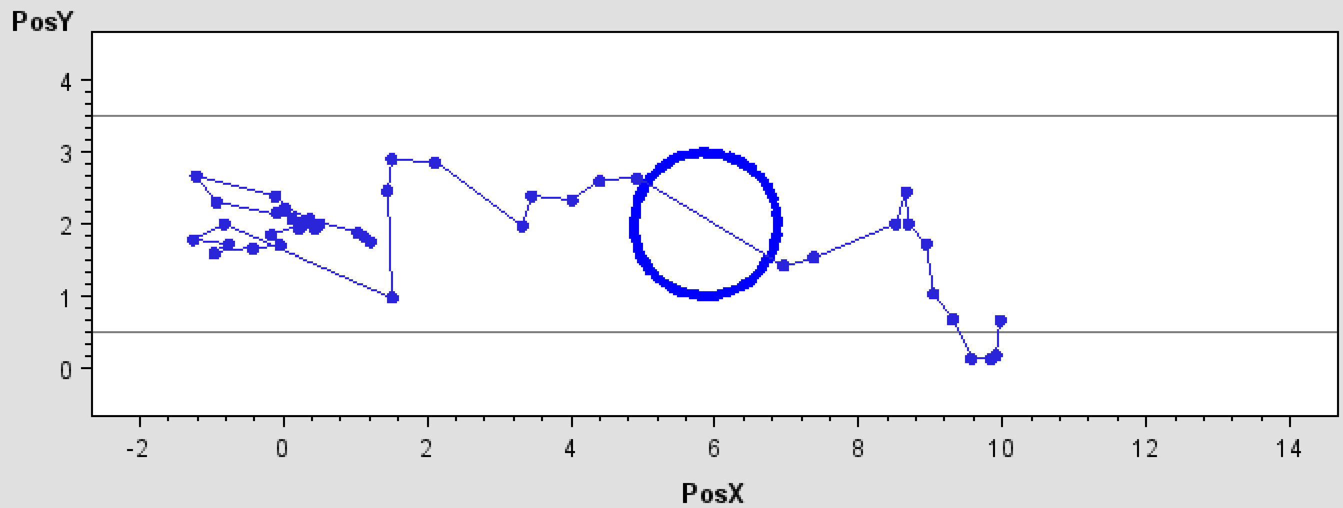

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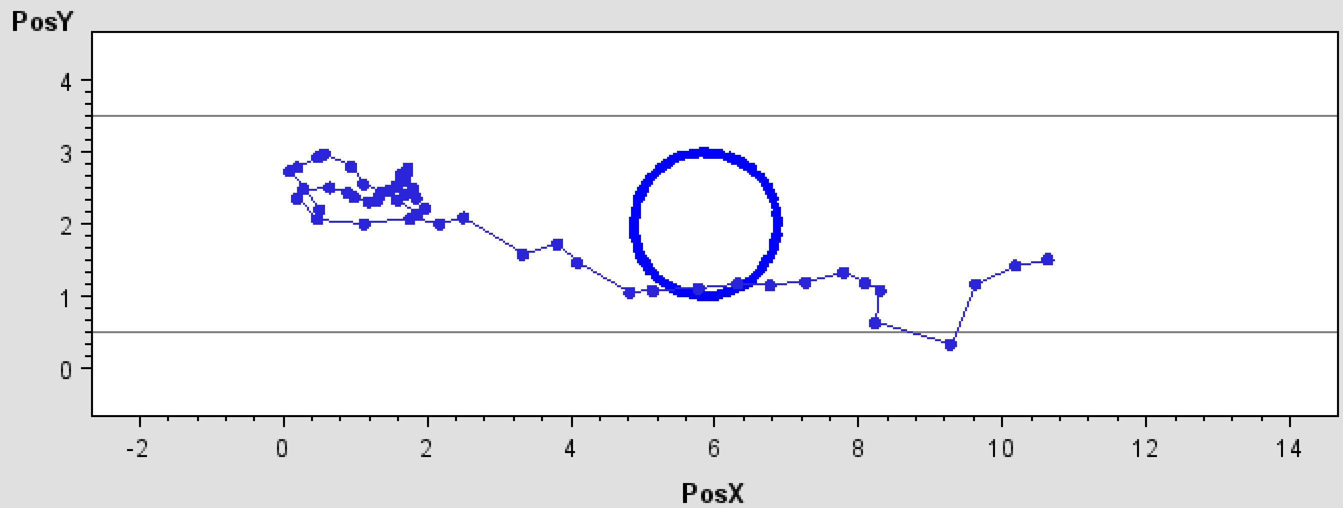

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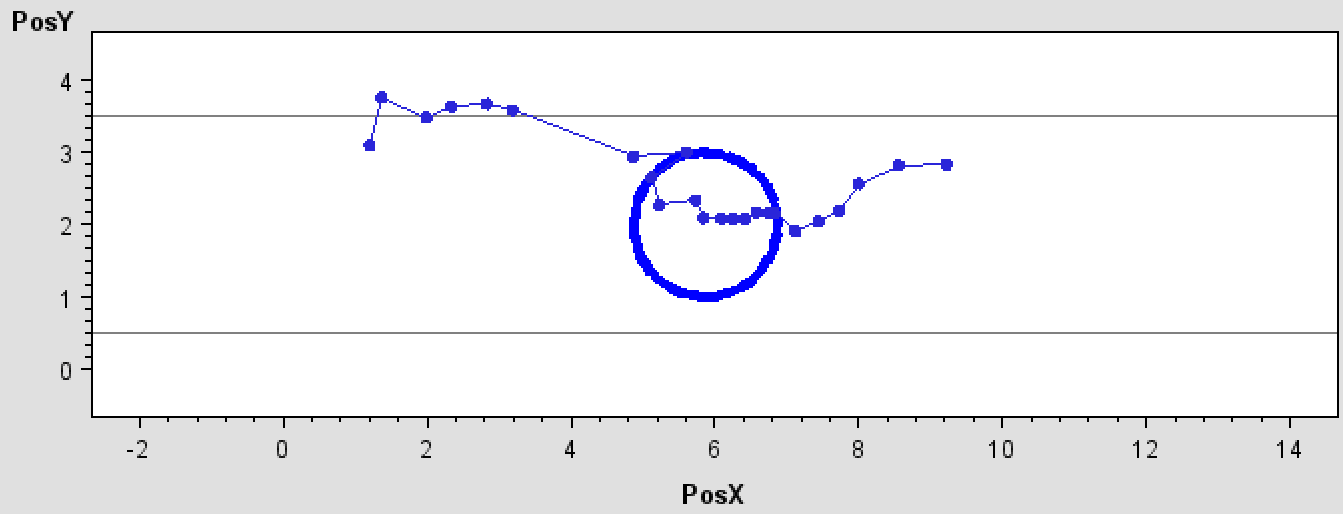

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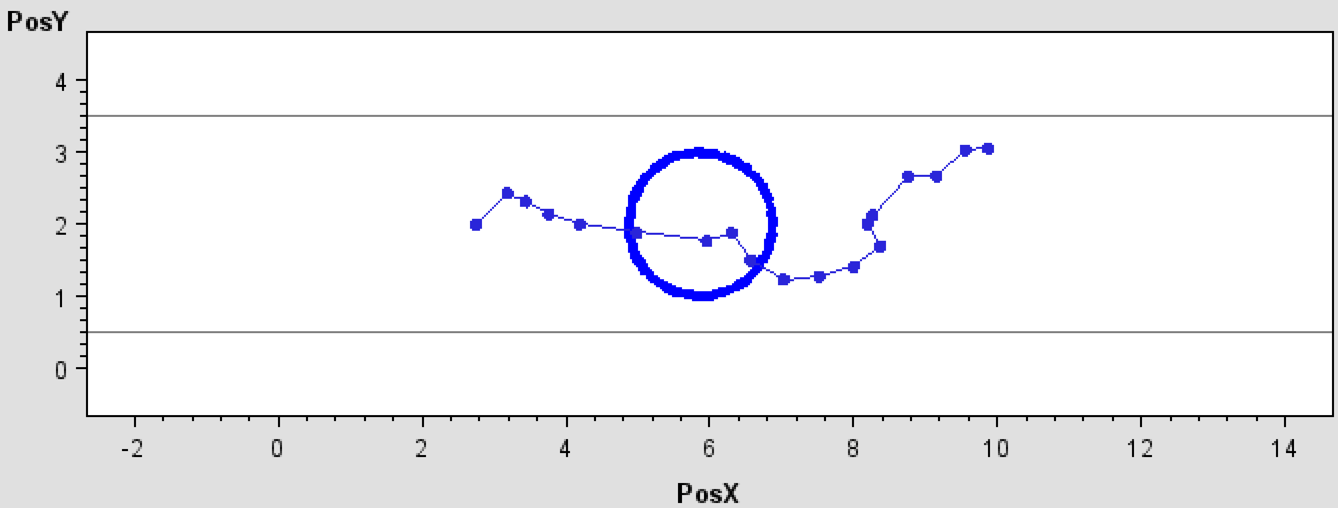

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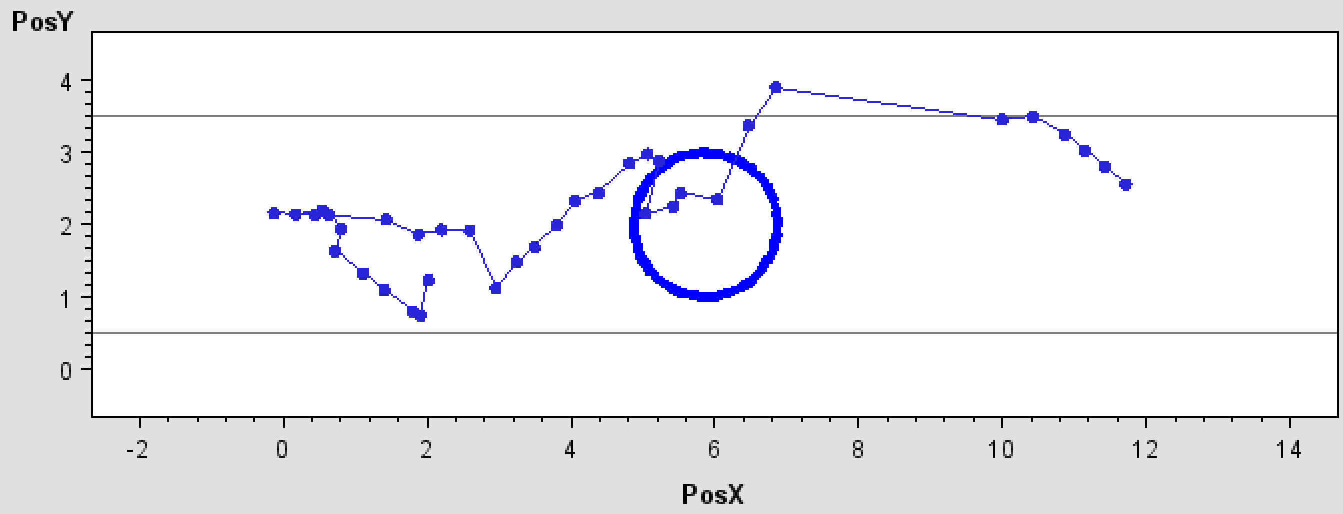

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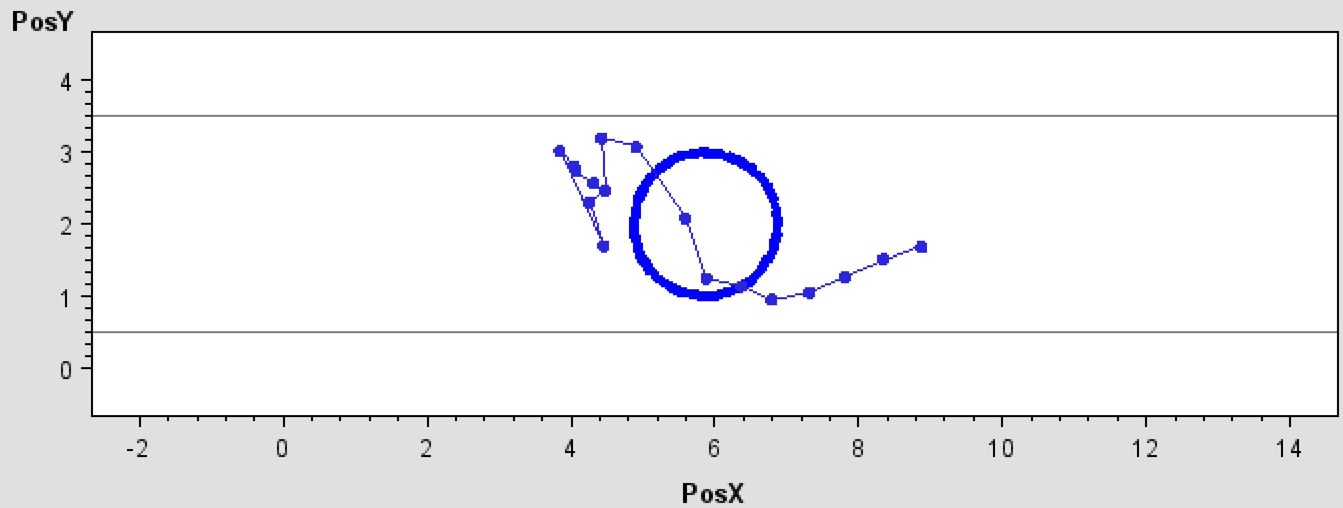

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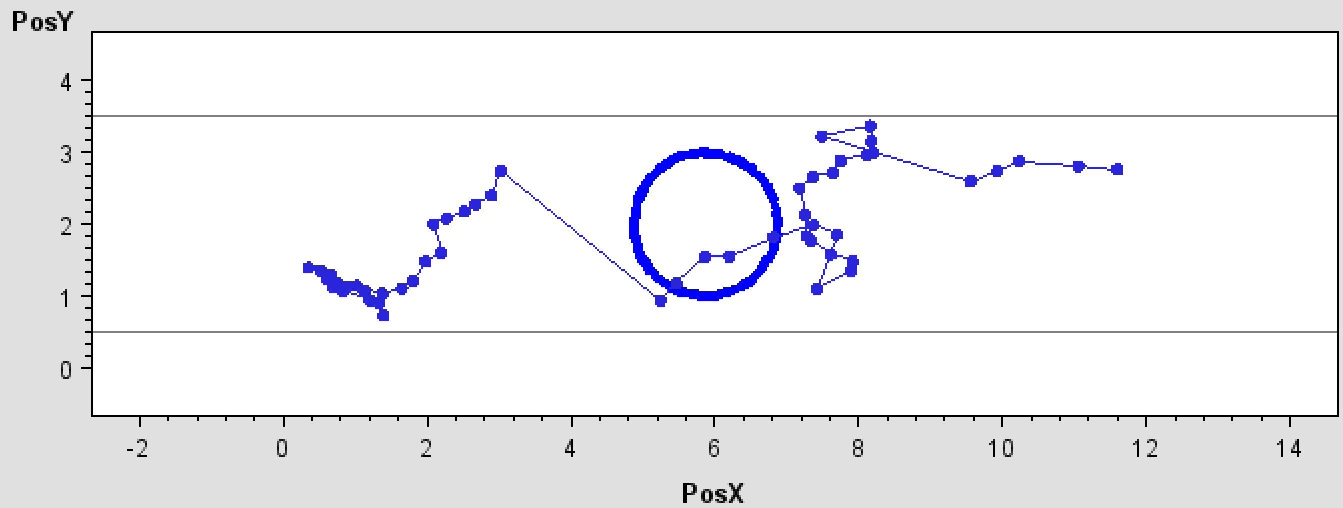

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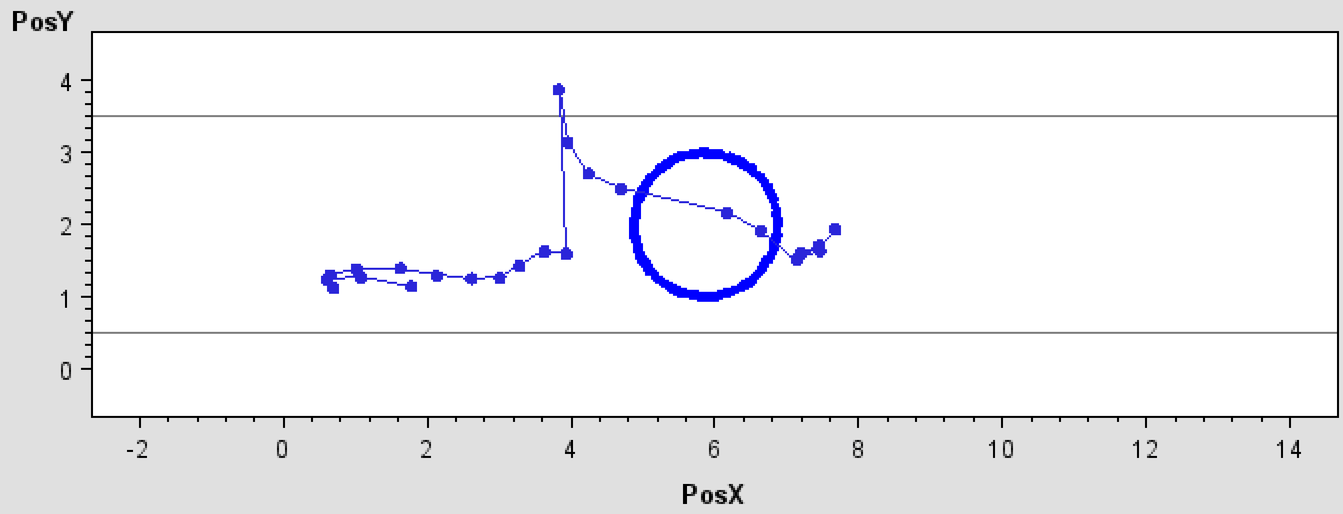

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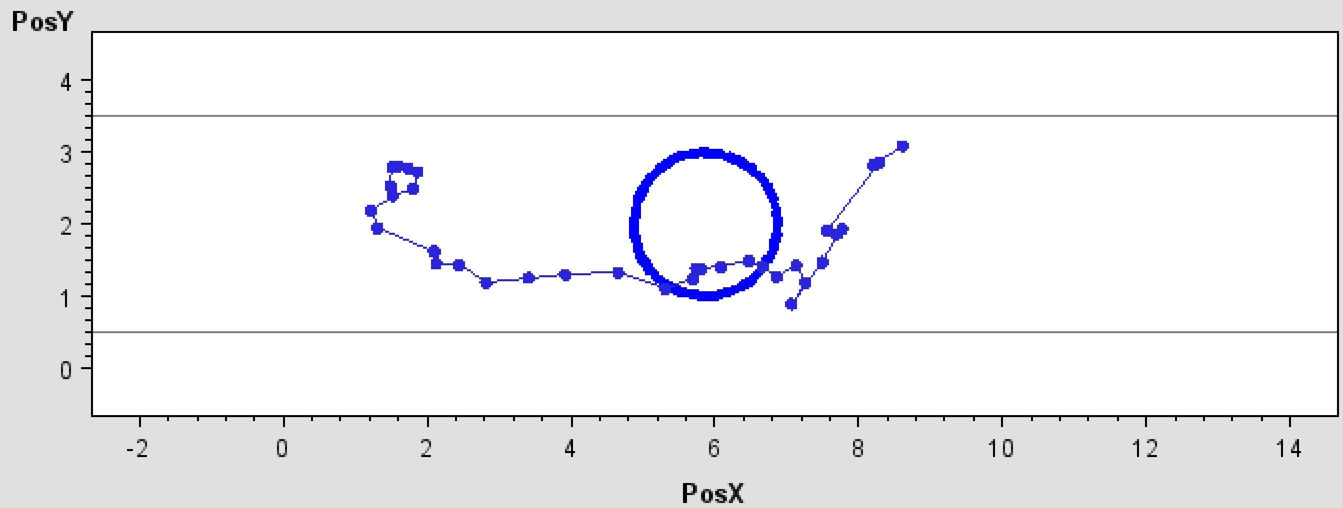

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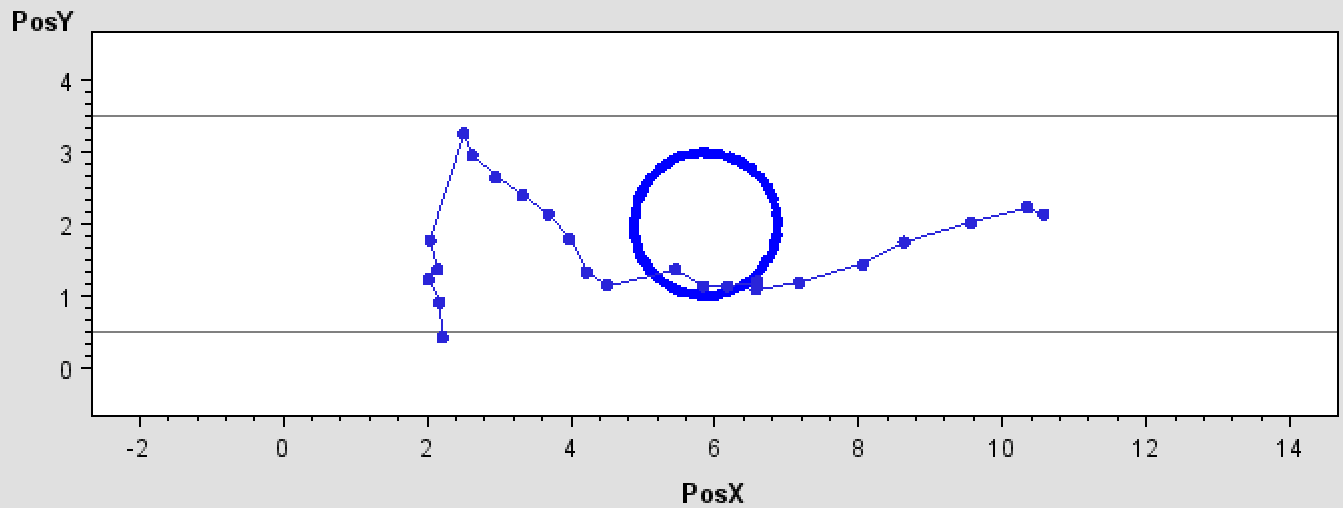

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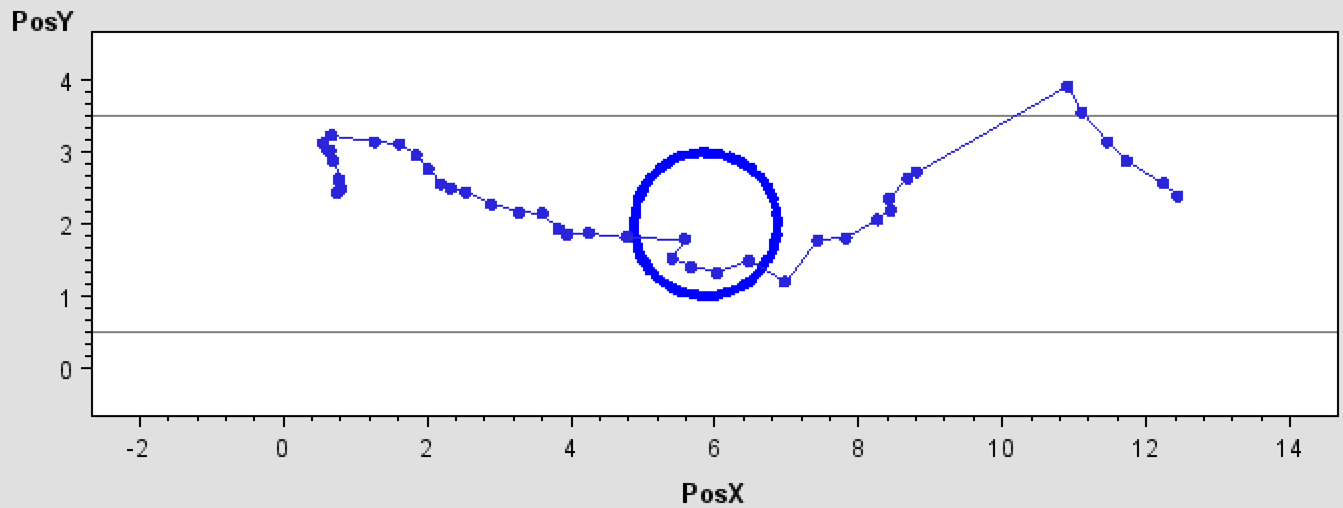

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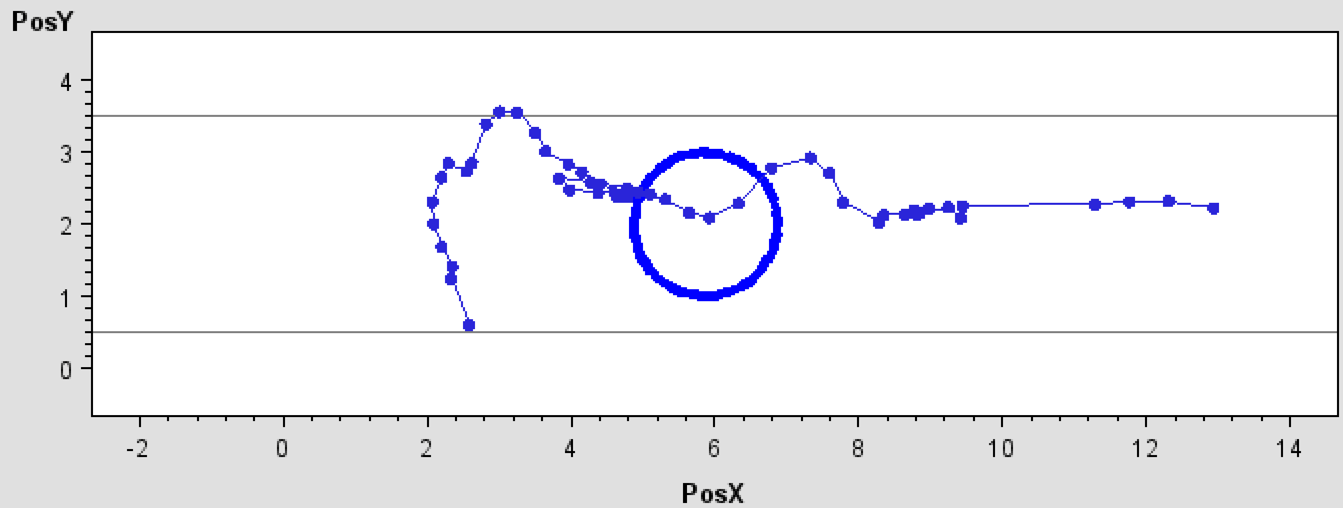
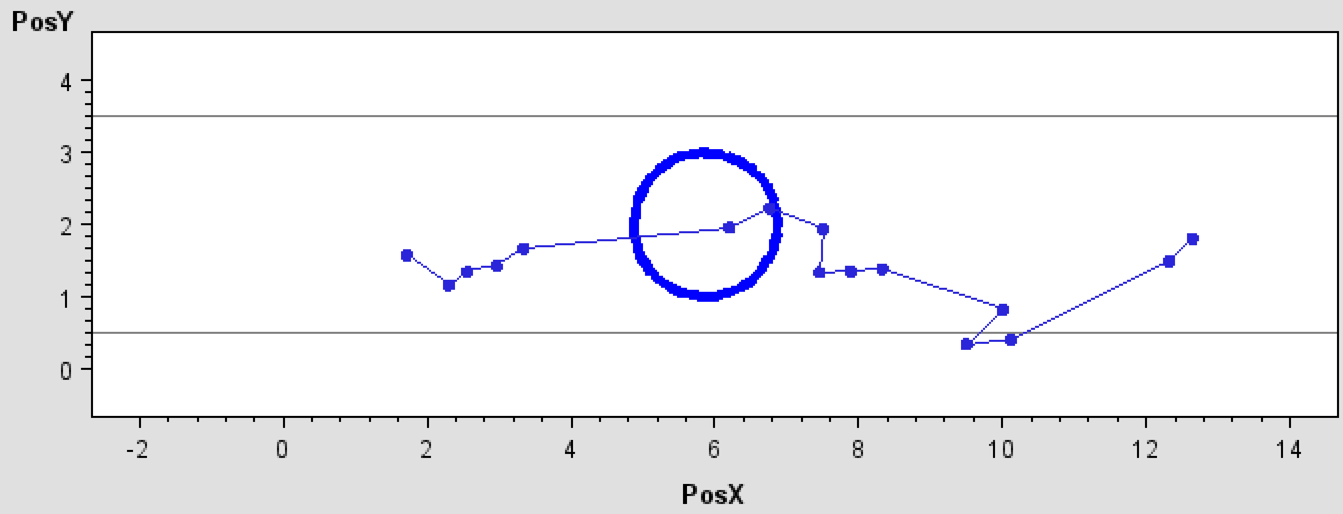


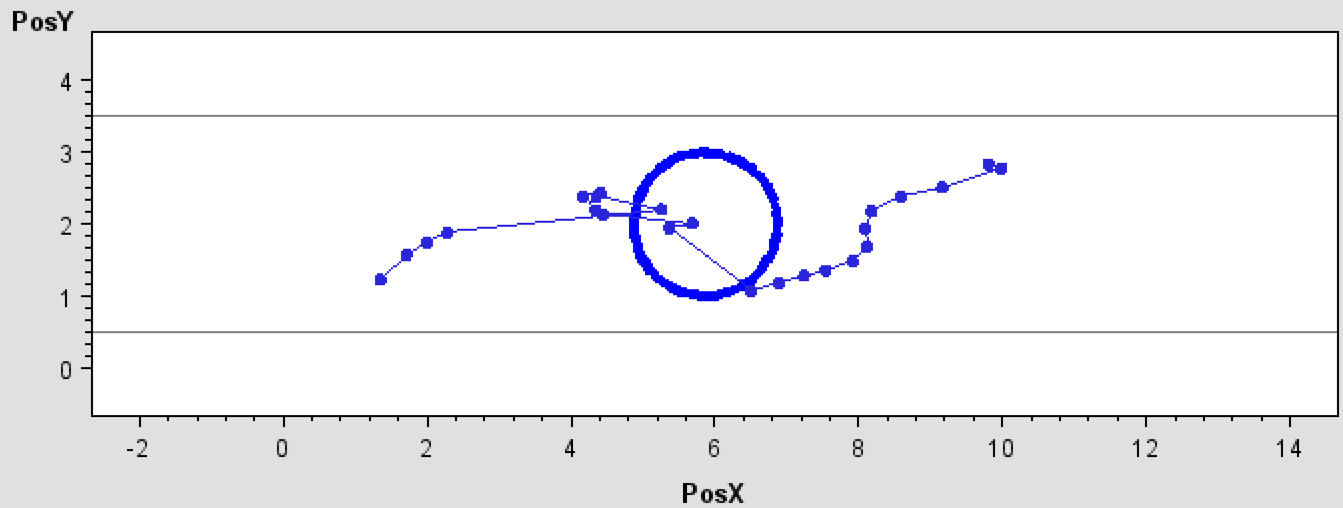
Smolt Tracks, Treatment = Turbine

Trial=100518B ID=157



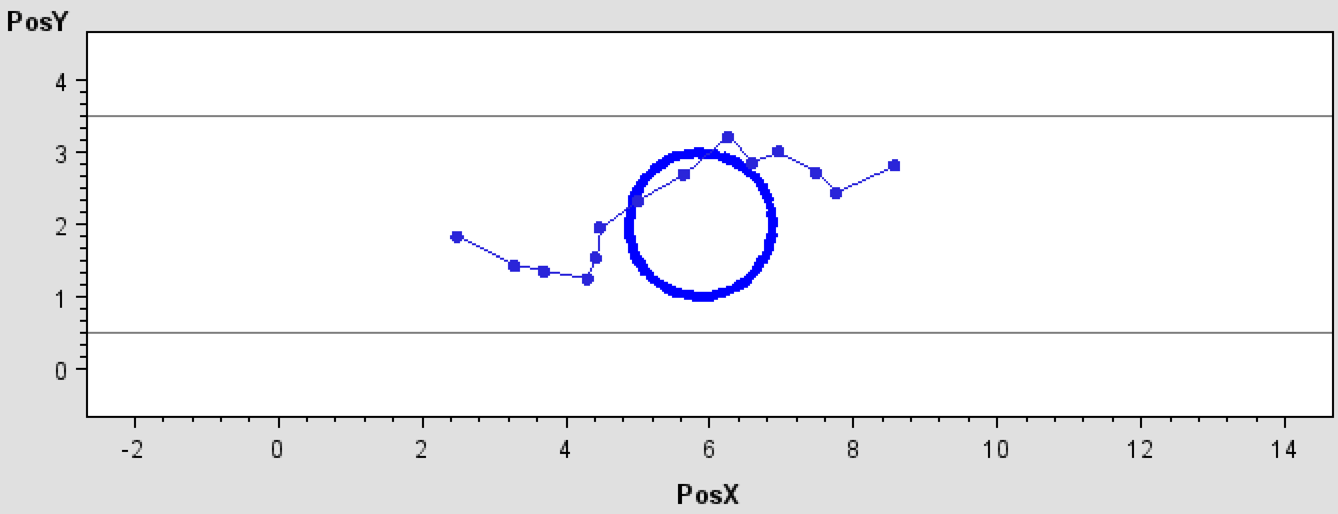
Smolt Tracks, Treatment = Turbine

Trial=100518B ID=175



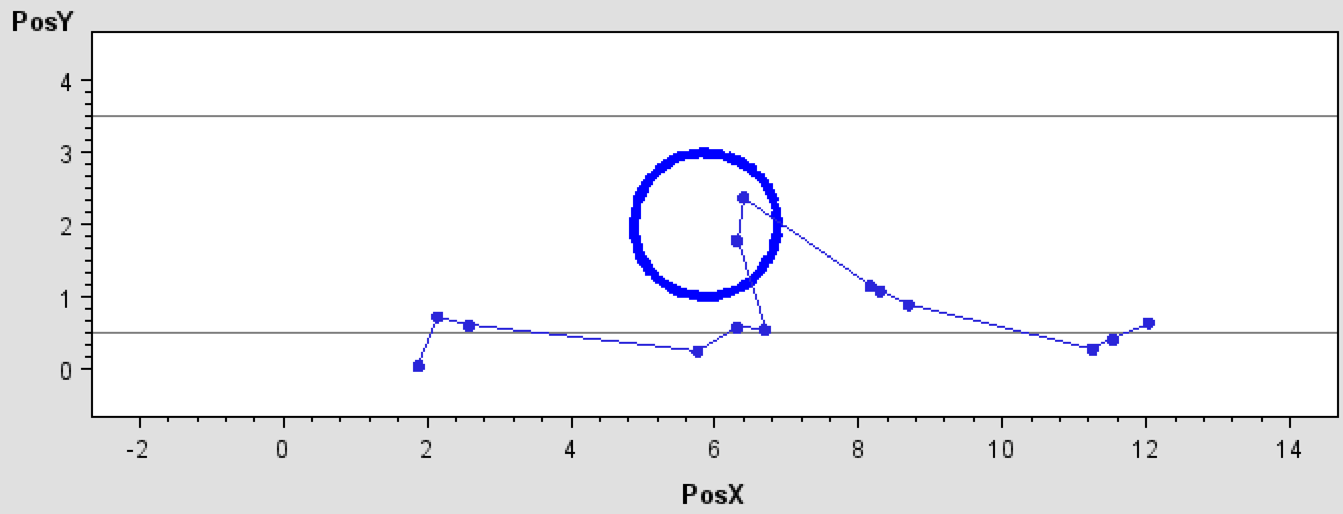
Smolt Tracks, Treatment = Turbine

Trial=100518B ID=180



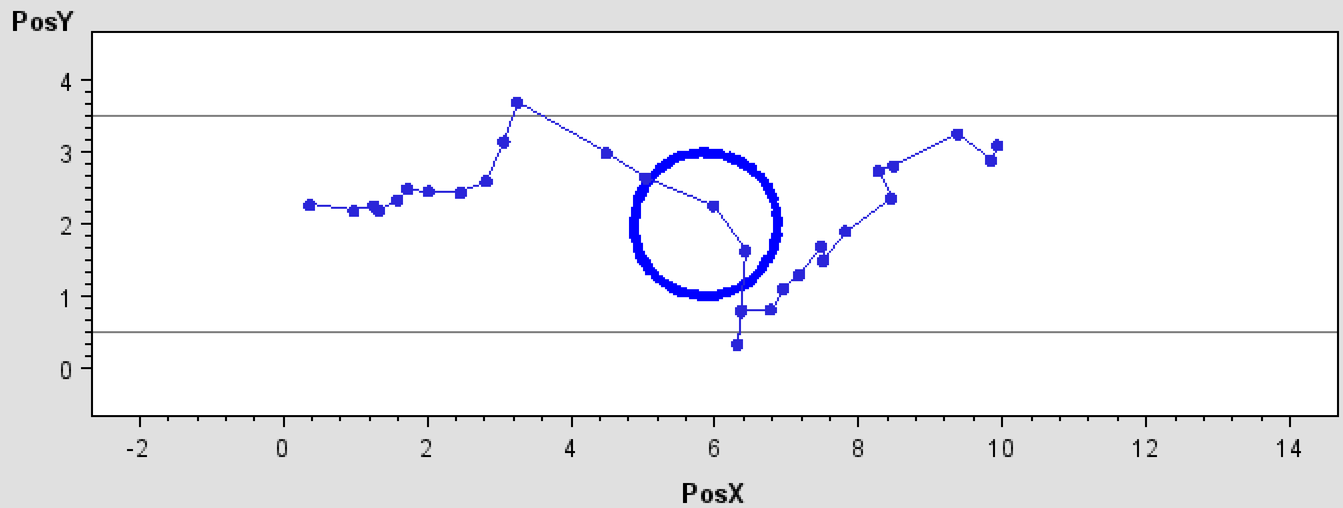
Smolt Tracks, Treatment = Turbine

Trial=100518B ID=191



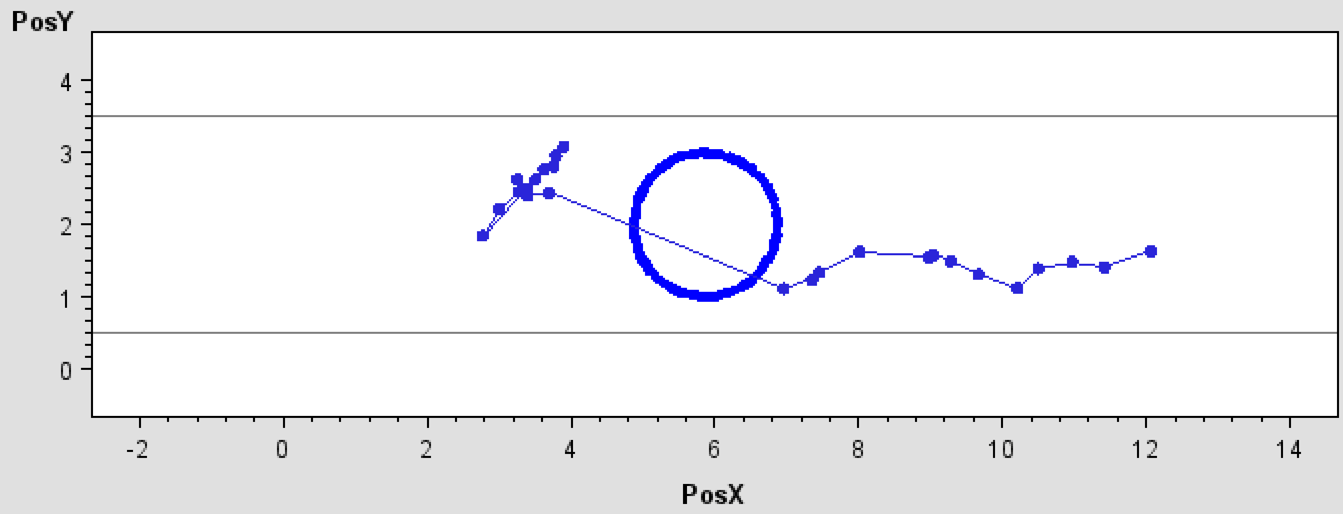
Smolt Tracks, Treatment = Turbine

Trial=100518B ID=197



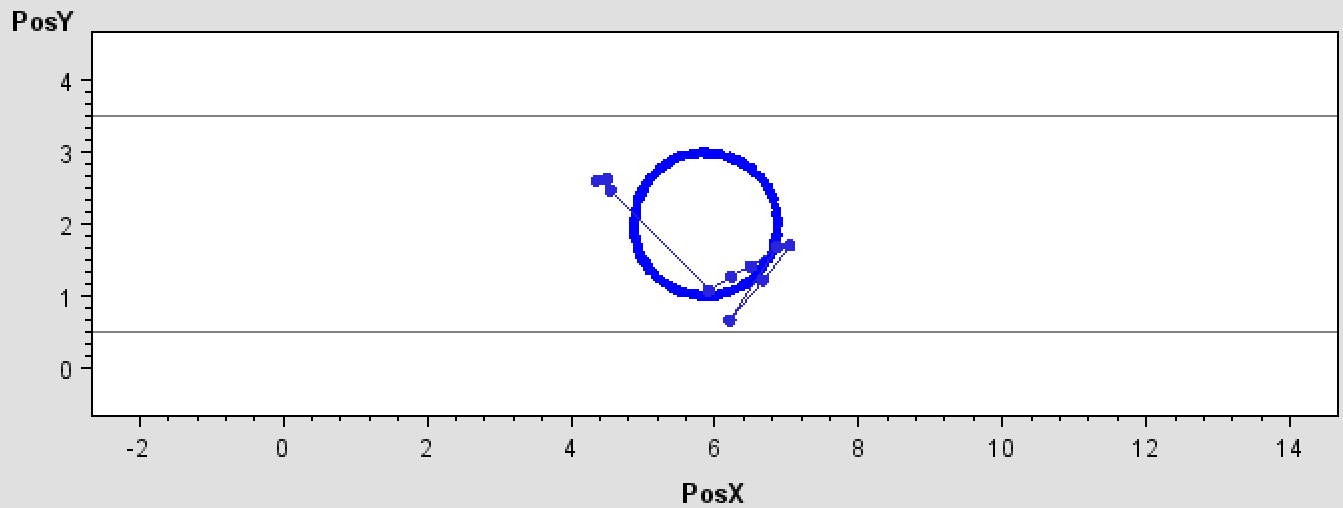
Smolt Tracks, Treatment = Turbine

Trial=100518B ID=202



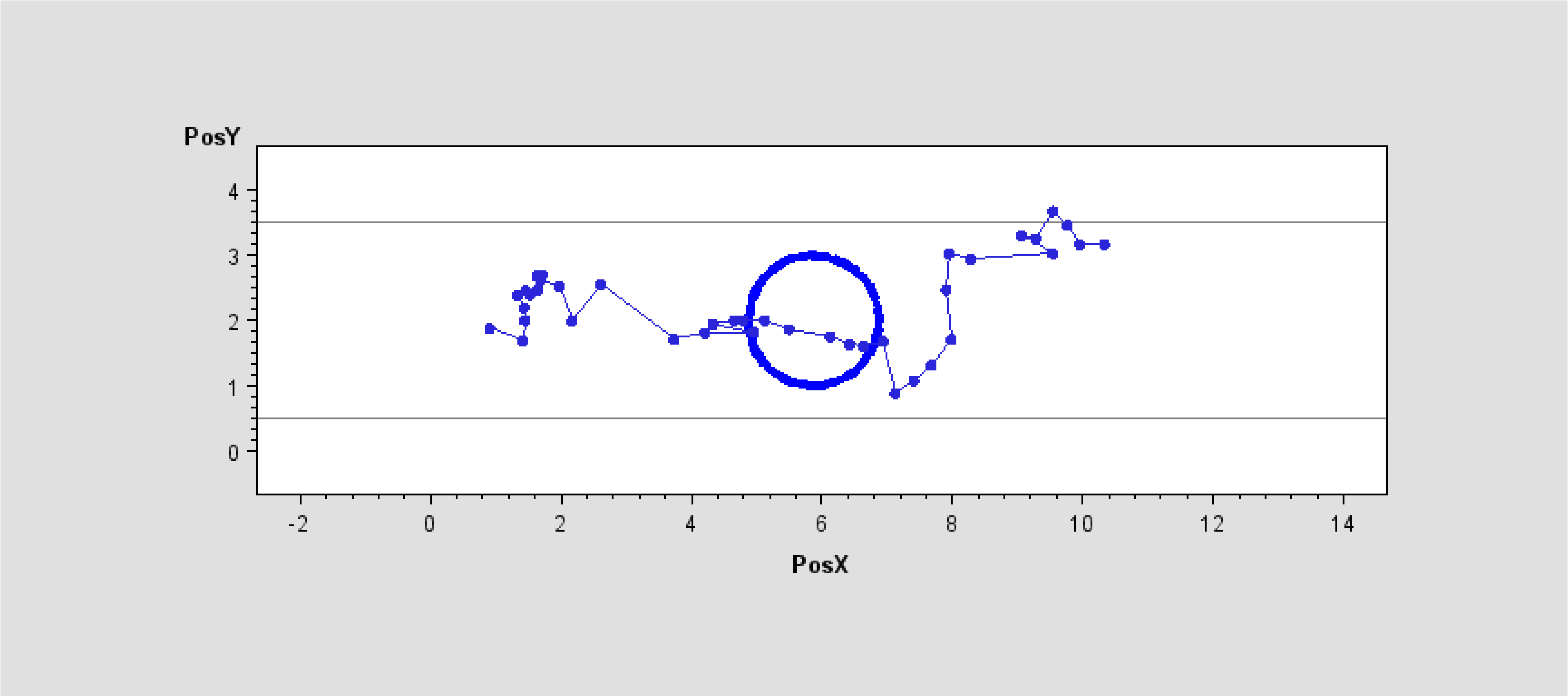
Smolt Tracks, Treatment = Turbine

Trial=100519A ID=16



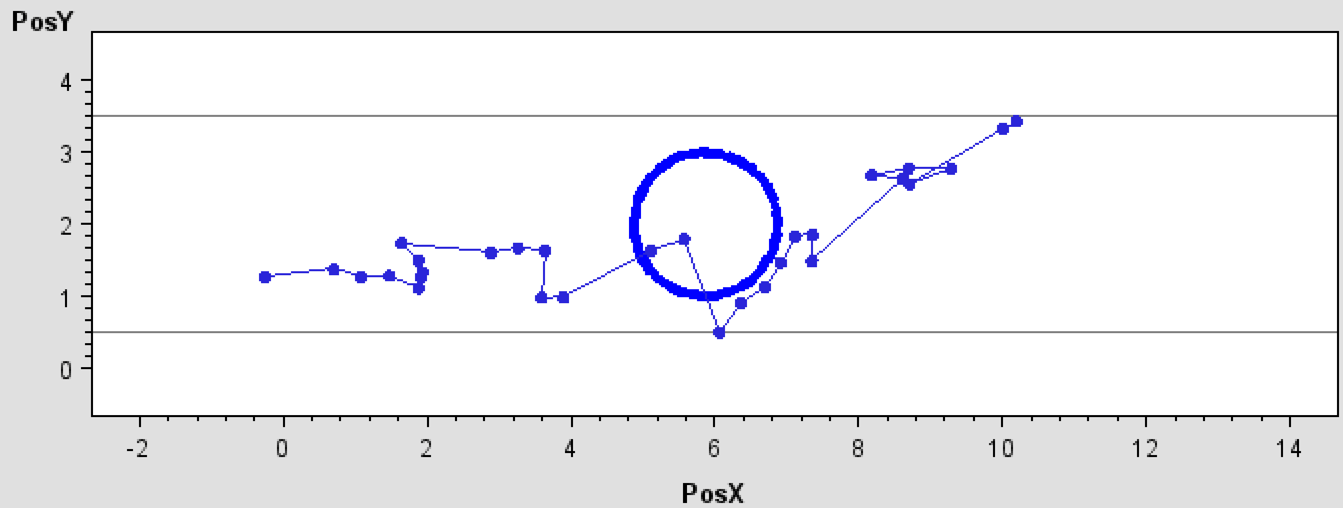
Smolt Tracks, Treatment = Turbine

Trial=100519A ID=40



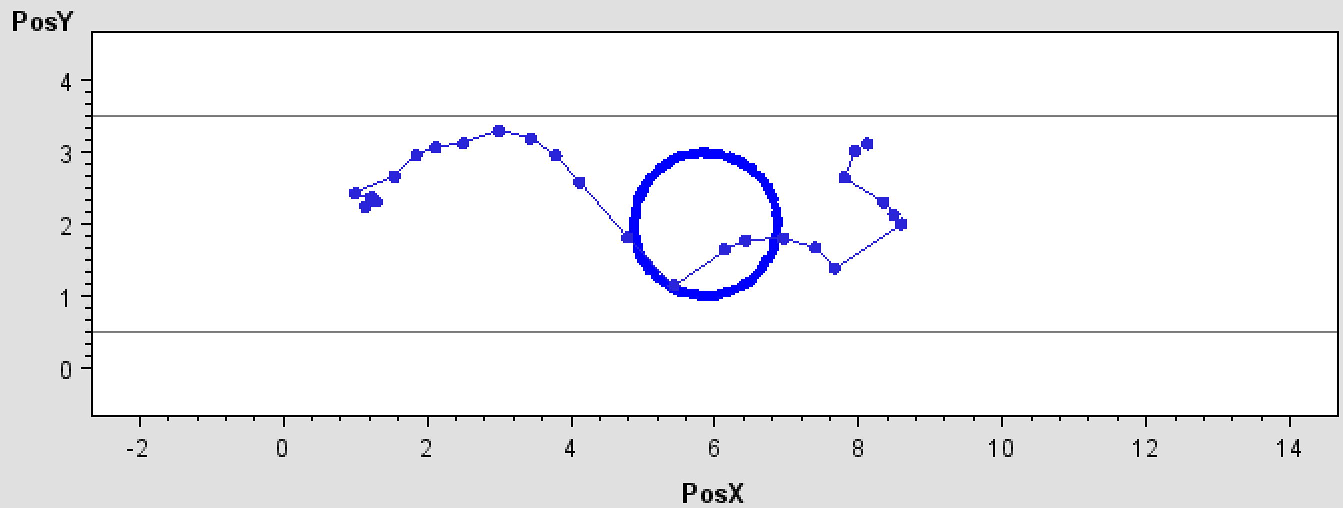
Smolt Tracks, Treatment = Turbine

Trial=100519A ID=85



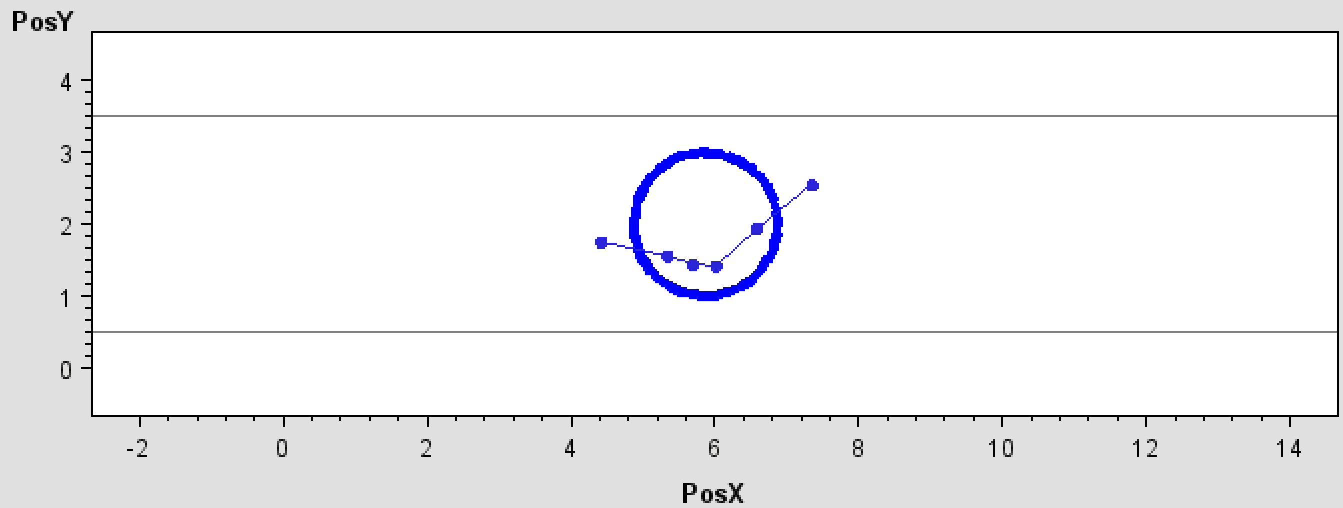
Smolt Tracks, Treatment = Turbine

Trial=100519A ID=106



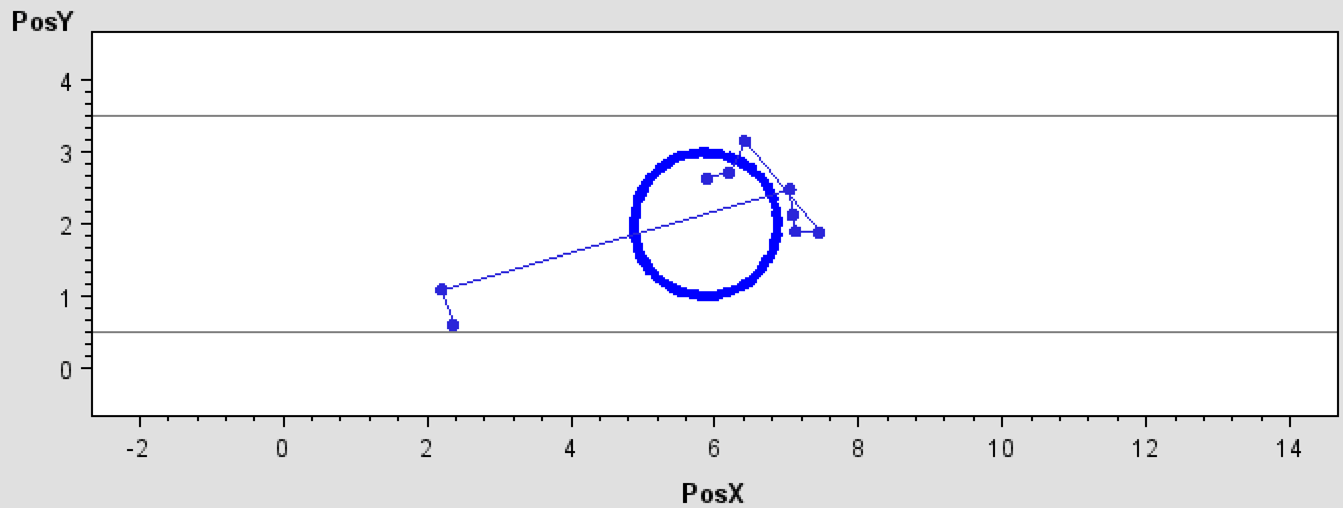
Smolt Tracks, Treatment = Turbine

Trial=100519A ID=108



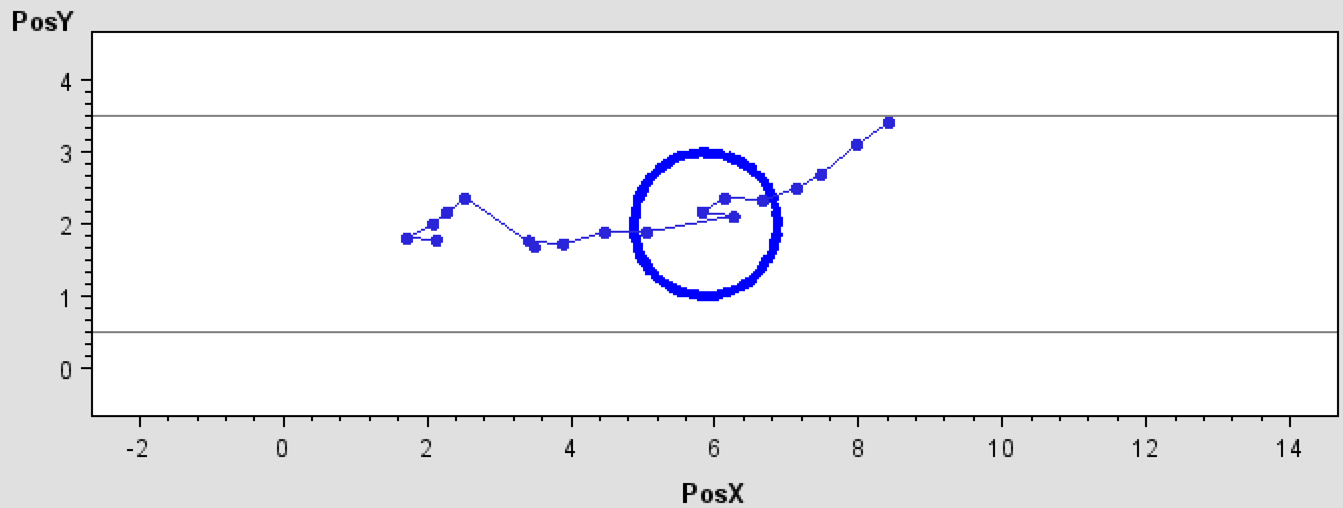
Smolt Tracks, Treatment = Turbine

Trial=100519A ID=125



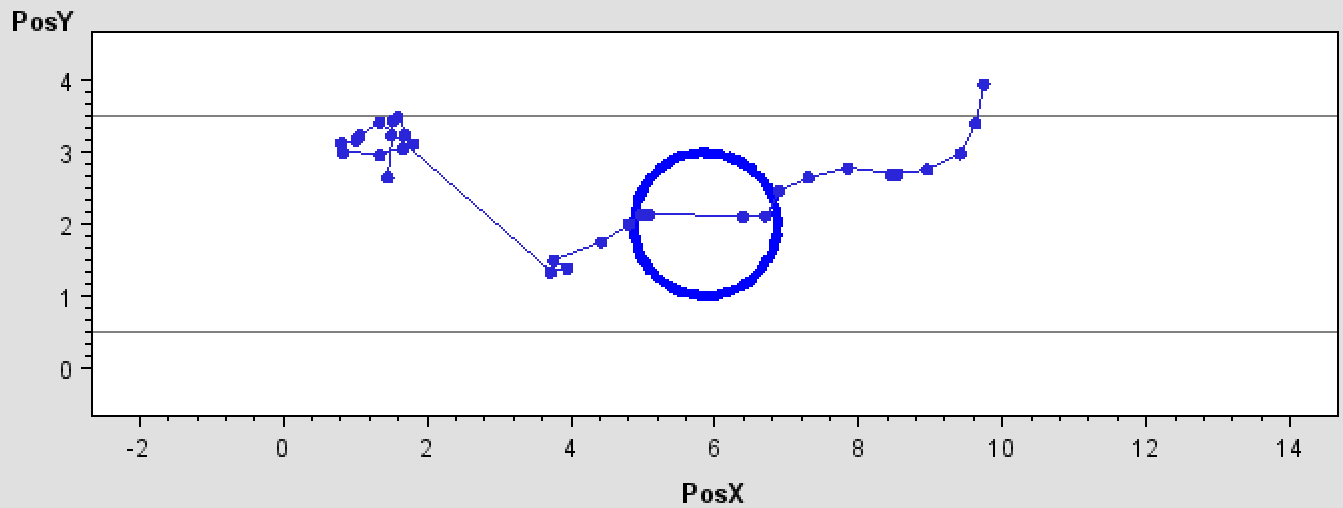
Smolt Tracks, Treatment = Turbine

Trial=100519A ID=127



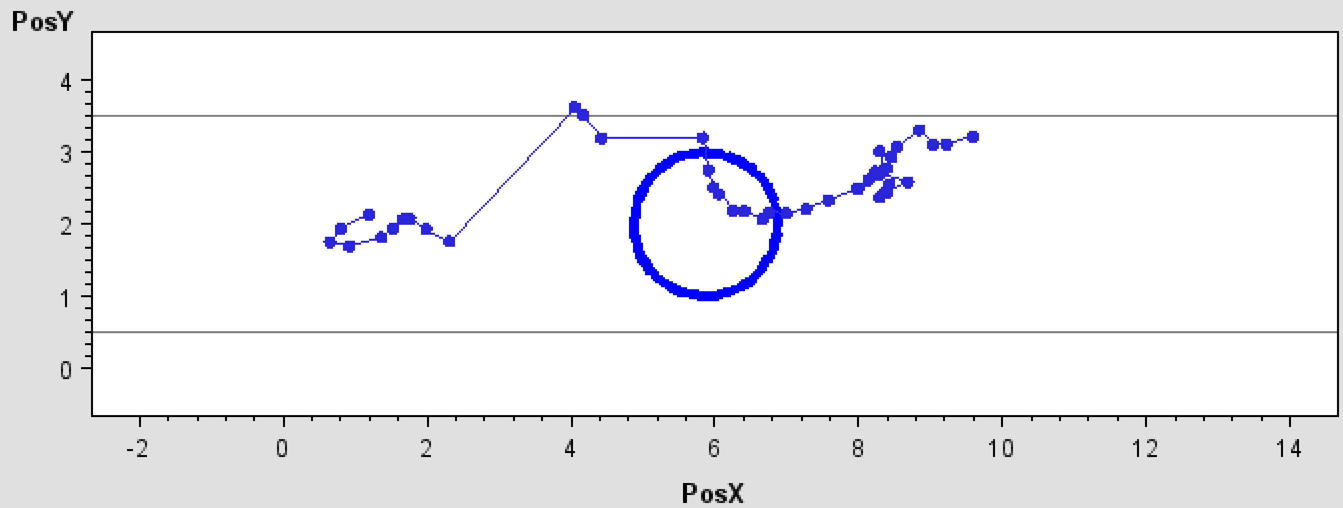
Smolt Tracks, Treatment = Turbine

Trial=100519A ID=129



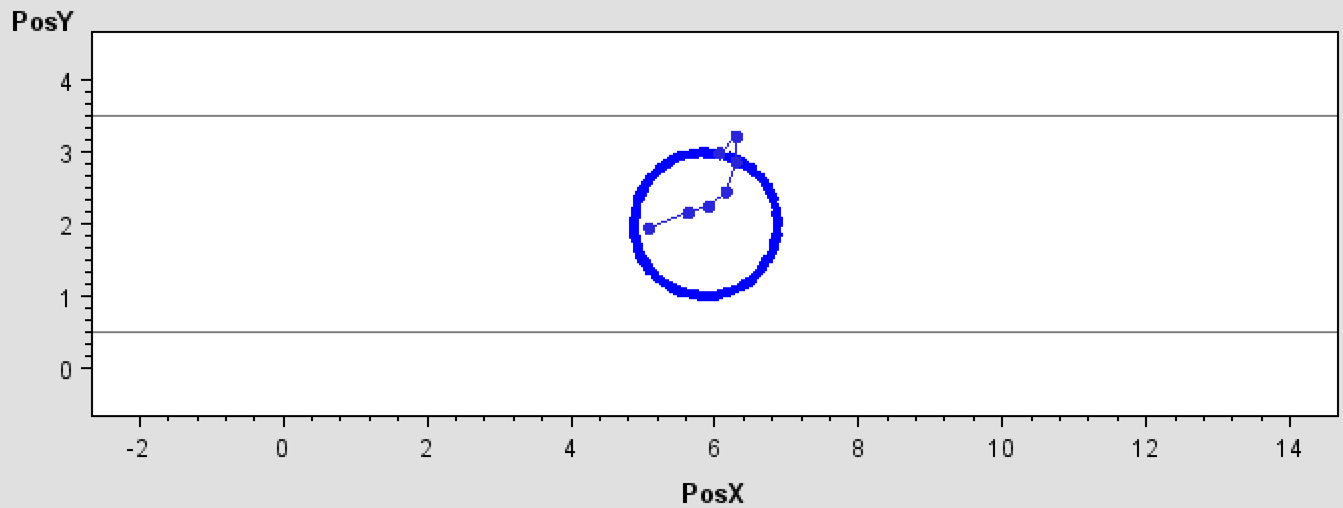
Smolt Tracks, Treatment = Turbine

Trial=100519A ID=134



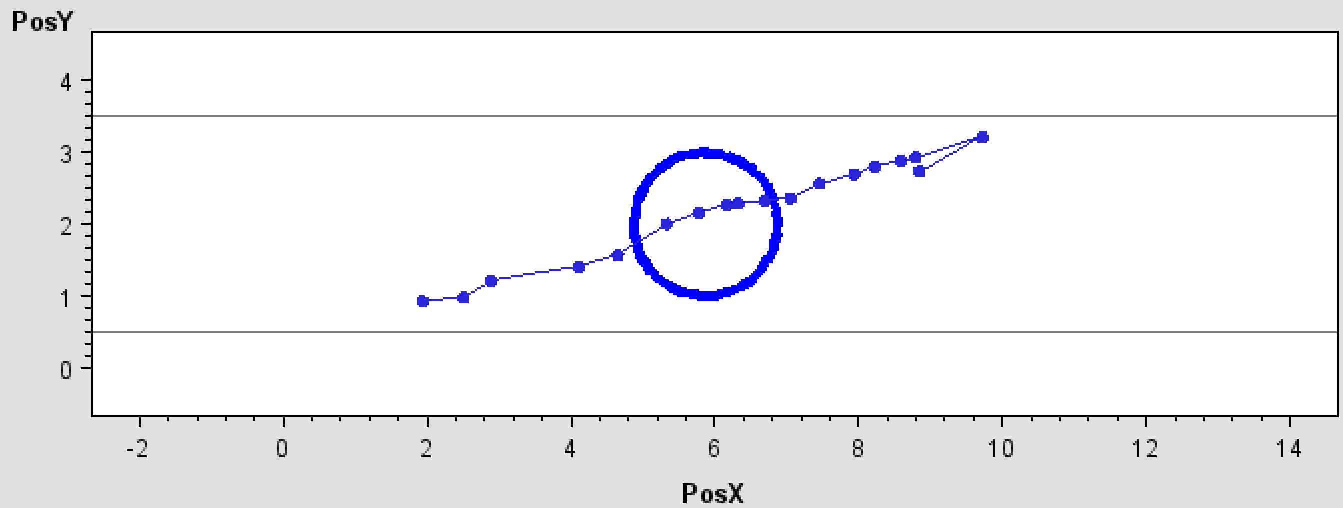
Smolt Tracks, Treatment = Turbine

Trial=100519A ID=135



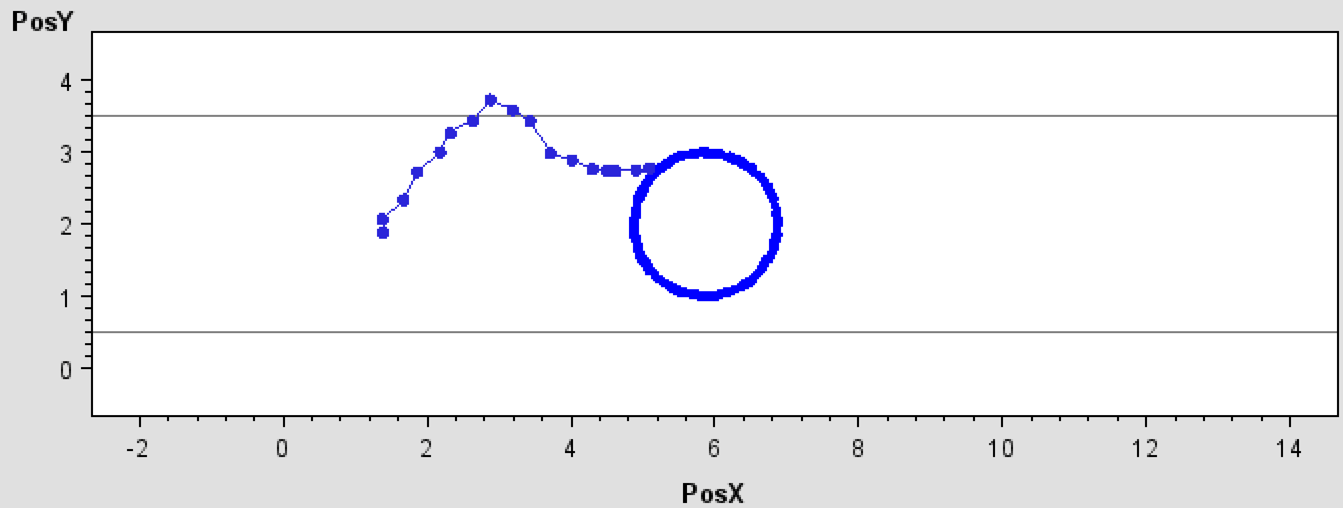
Smolt Tracks, Treatment = Turbine

Trial=100519A ID=140



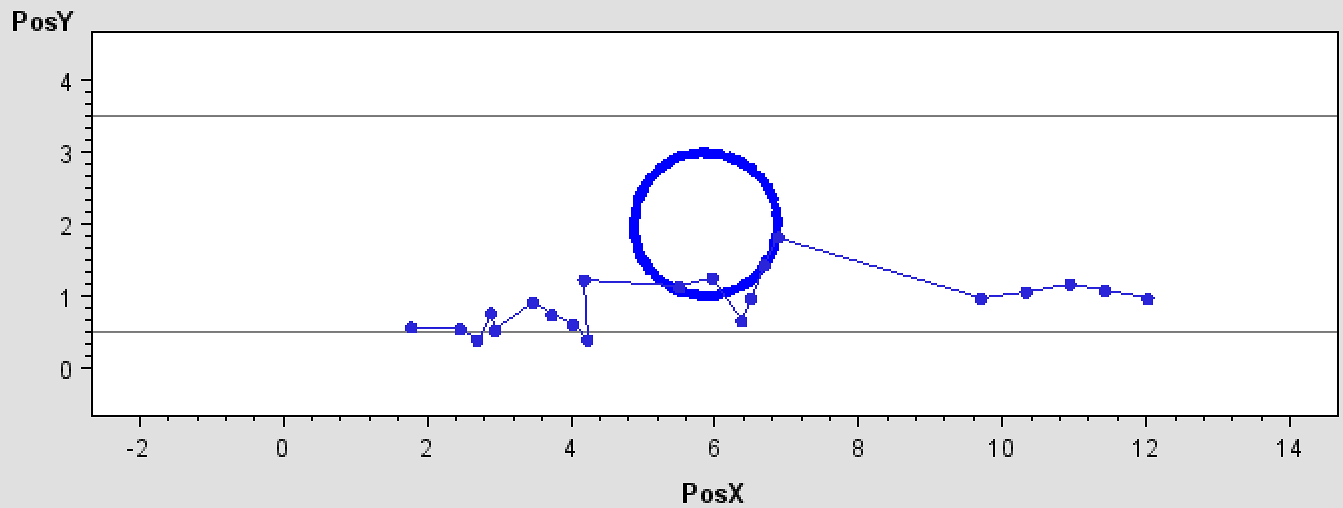
Smolt Tracks, Treatment = Turbine

Trial=100519A ID=149



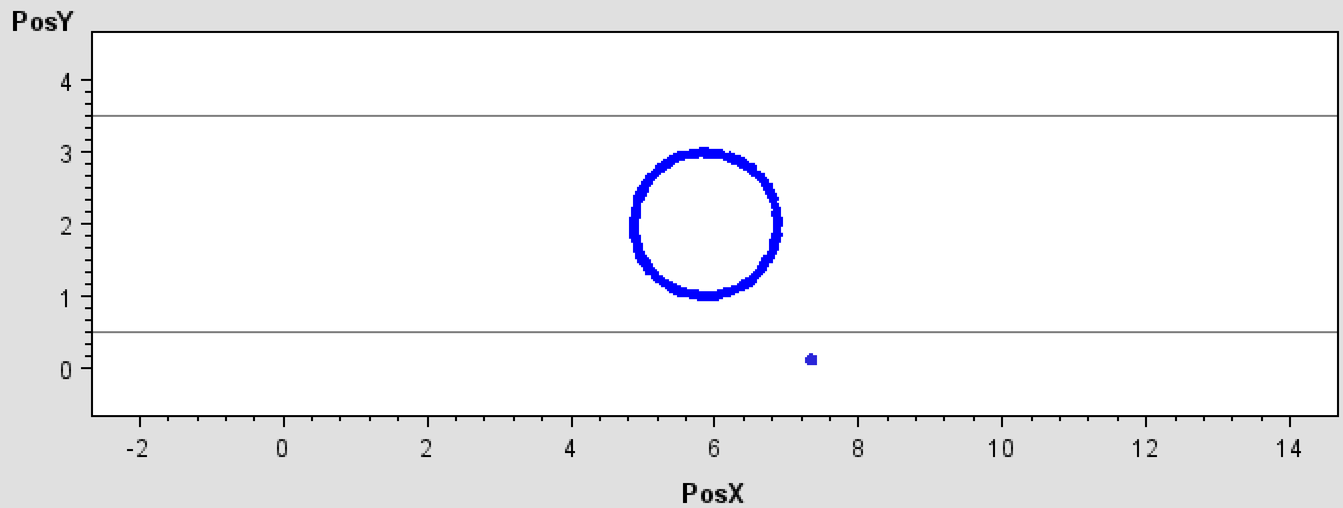
Smolt Tracks, Treatment = Turbine

Trial=100519A ID=154



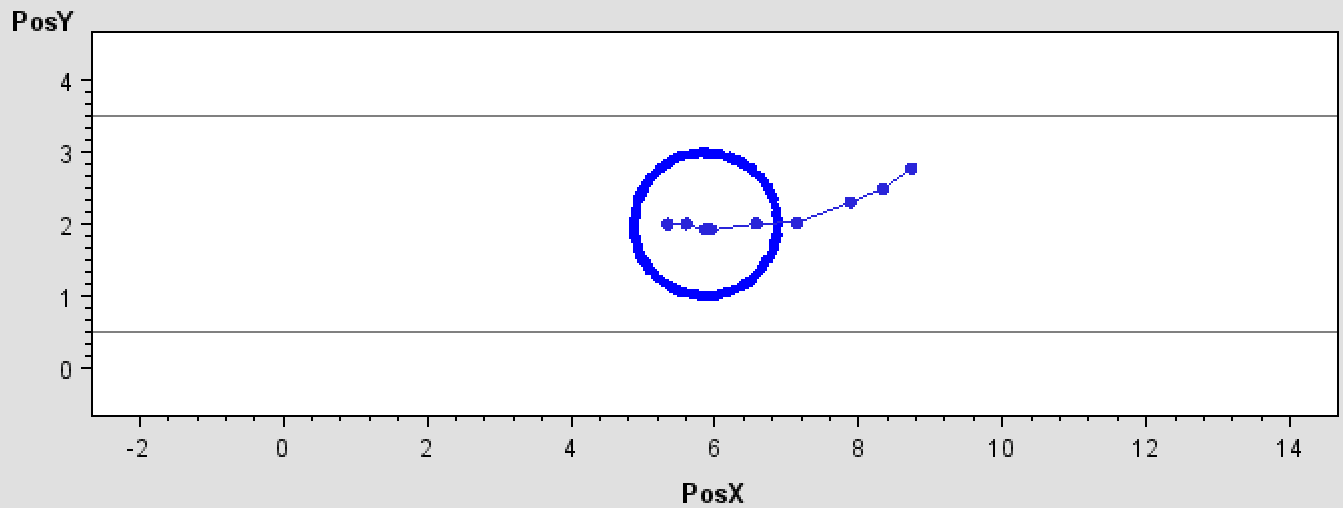
Smolt Tracks, Treatment = Turbine

Trial=100519A ID=159



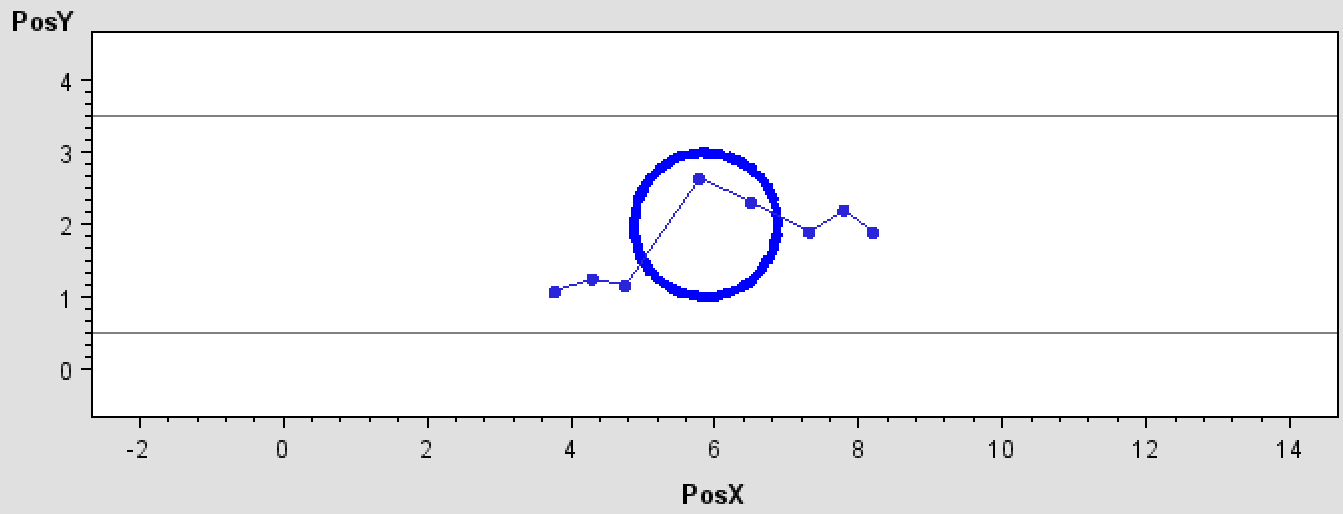
Smolt Tracks, Treatment = Turbine

Trial=100519A ID=165



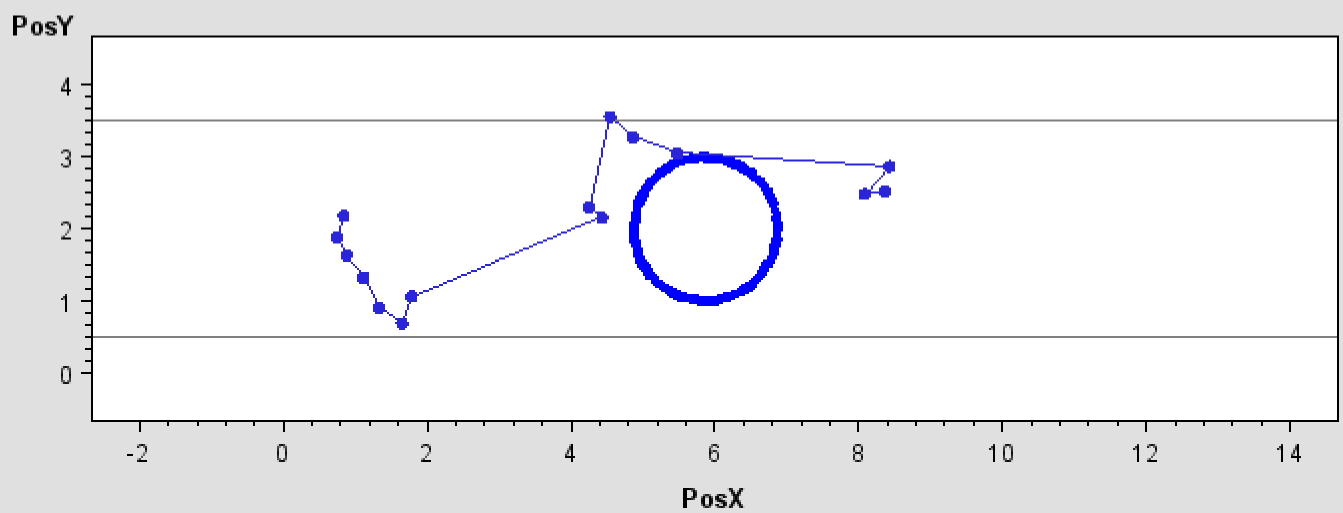
Smolt Tracks, Treatment = Turbine

Trial=100519A ID=169



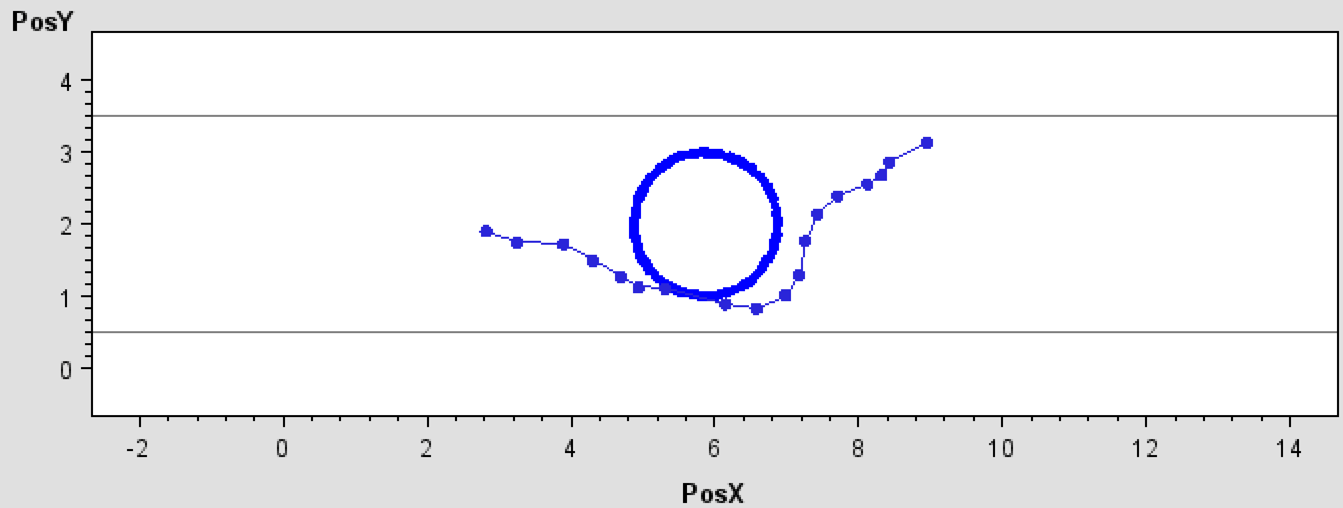
Smolt Tracks, Treatment = Turbine

Trial=100519A ID=177



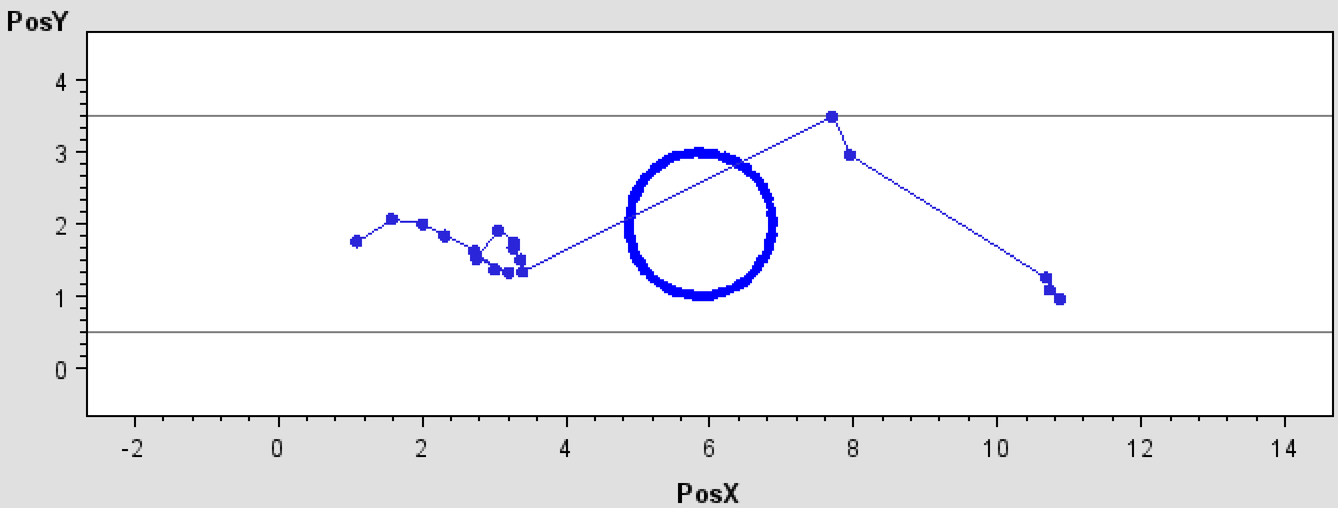
Smolt Tracks, Treatment = Turbine

Trial=100519A ID=182



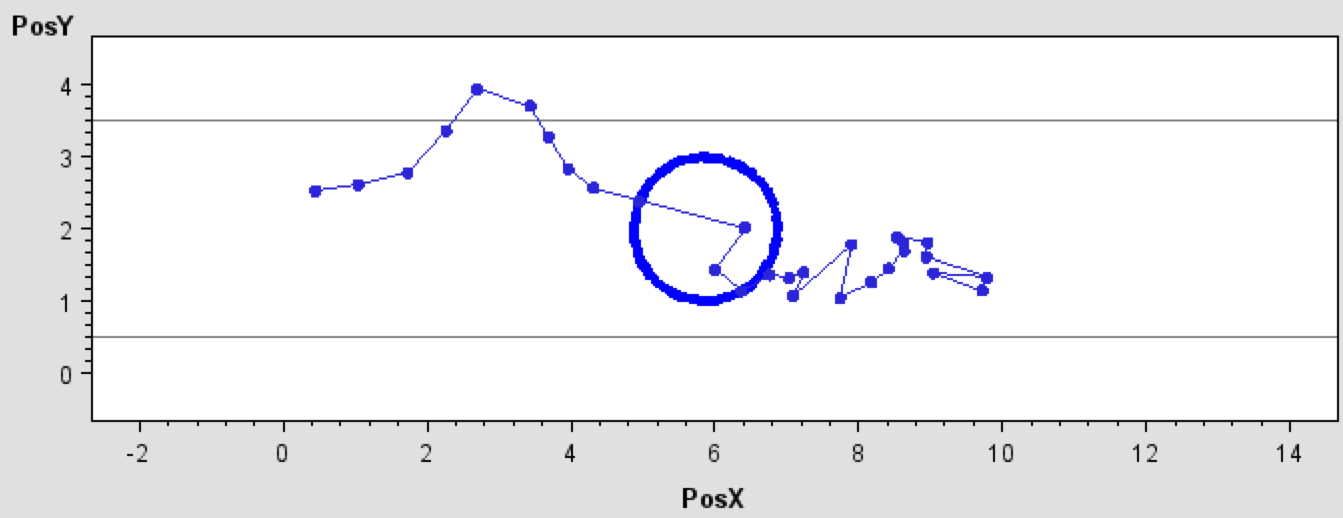
Smolt Tracks, Treatment = Turbine

Trial=100519A ID=187



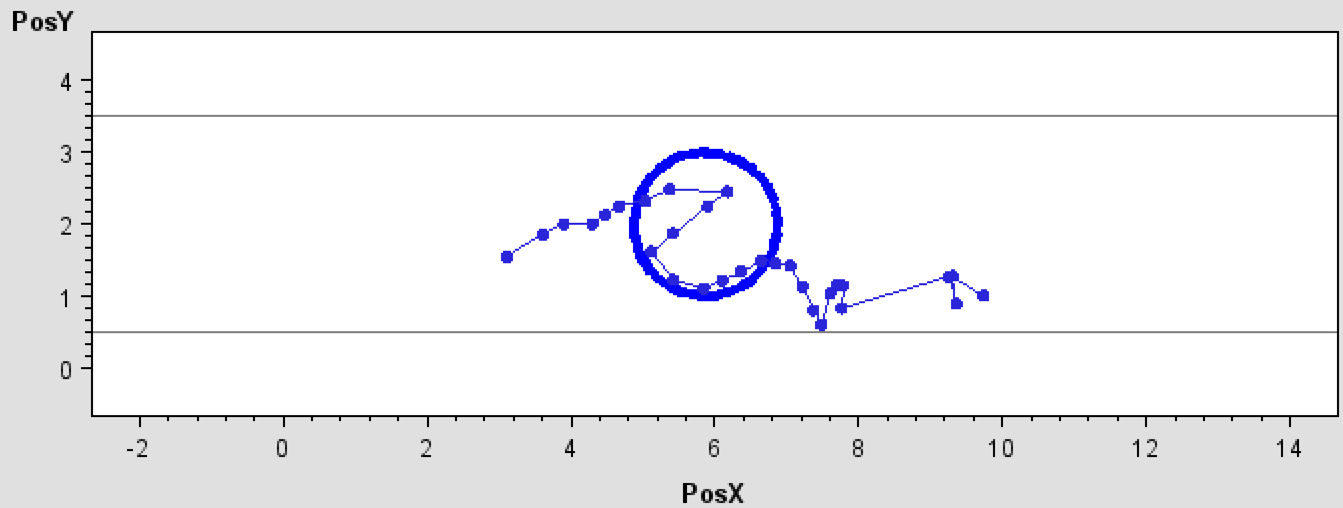
Smolt Tracks, Treatment = Turbine

Trial=100519A ID=198



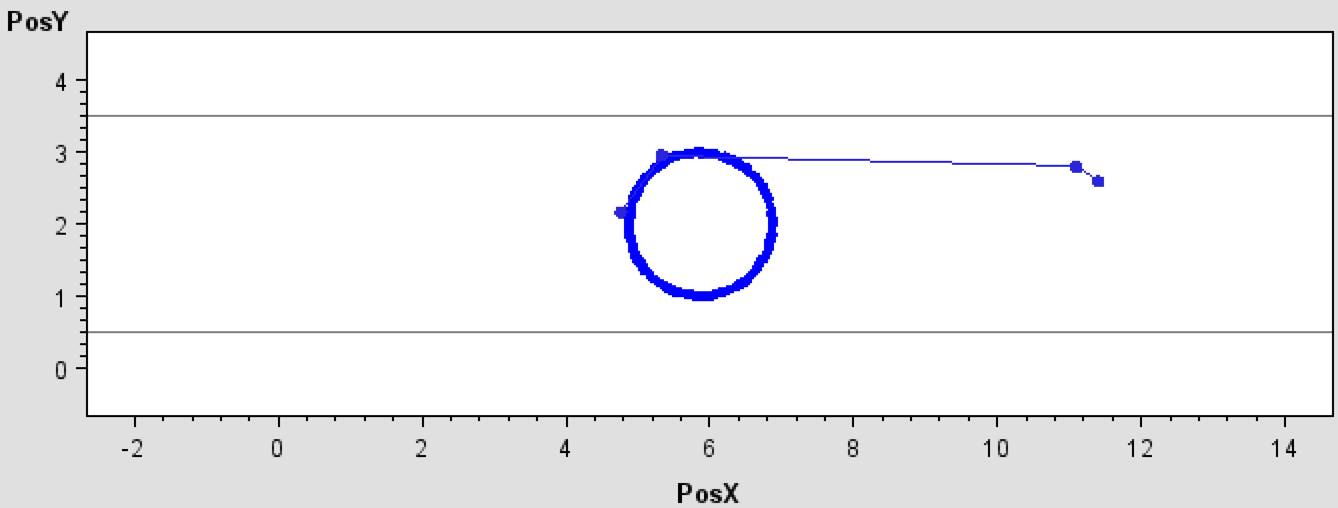
Smolt Tracks, Treatment = Turbine

Trial=100519A ID=199



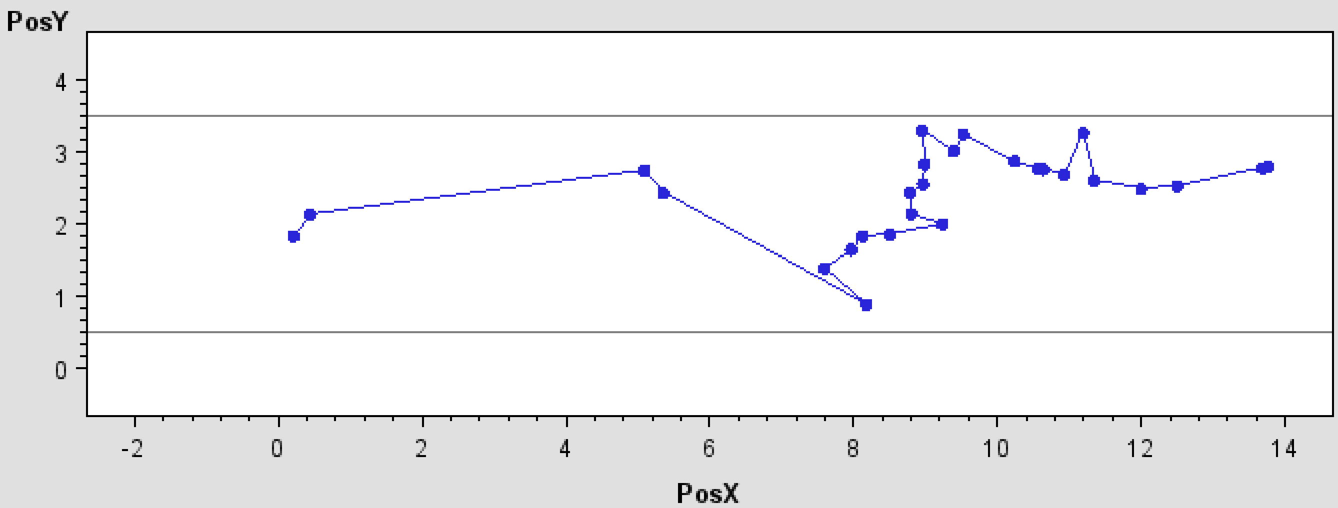
Smolt Tracks, Treatment = Turbine

Trial=100519A ID=204



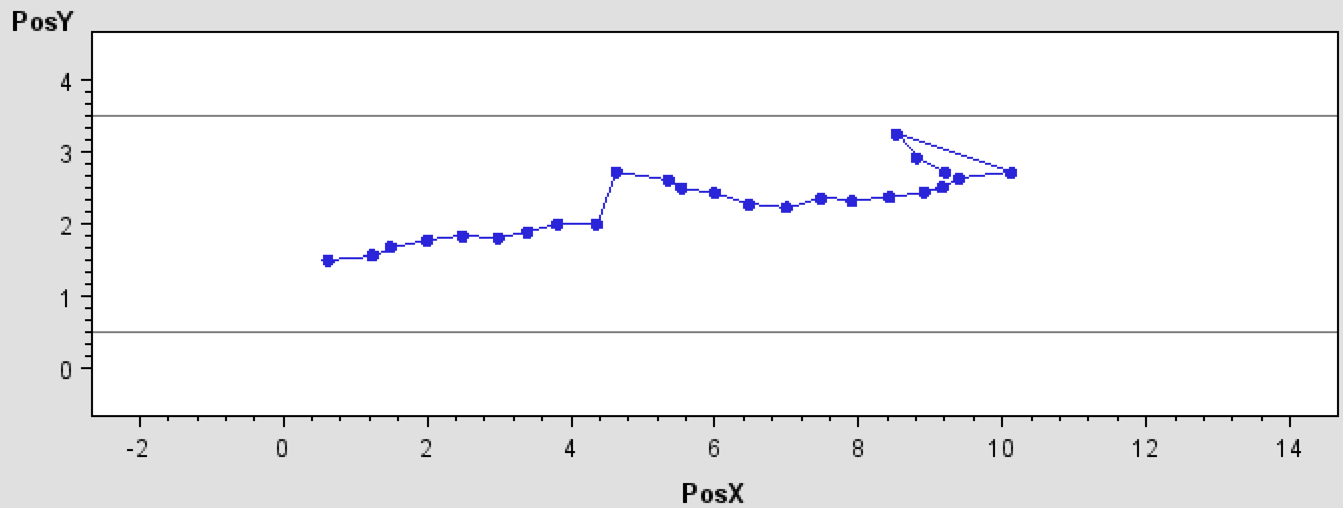
Smolt Tracks, Treatment = Control

Trial=100513A ID=20



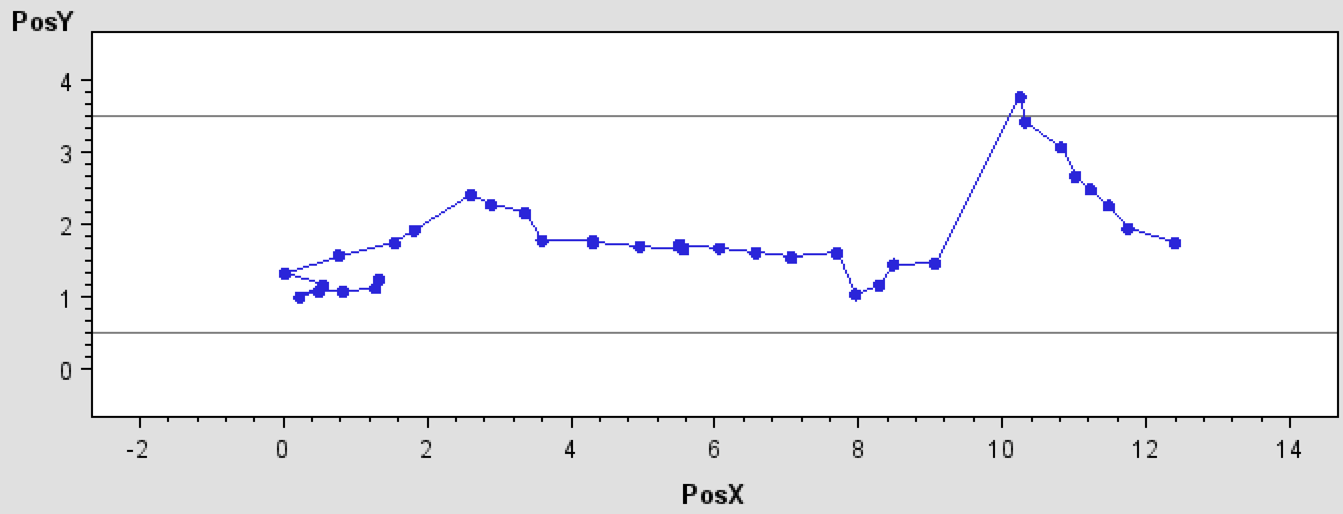
Smolt Tracks, Treatment = Control

Trial=100513A ID=34



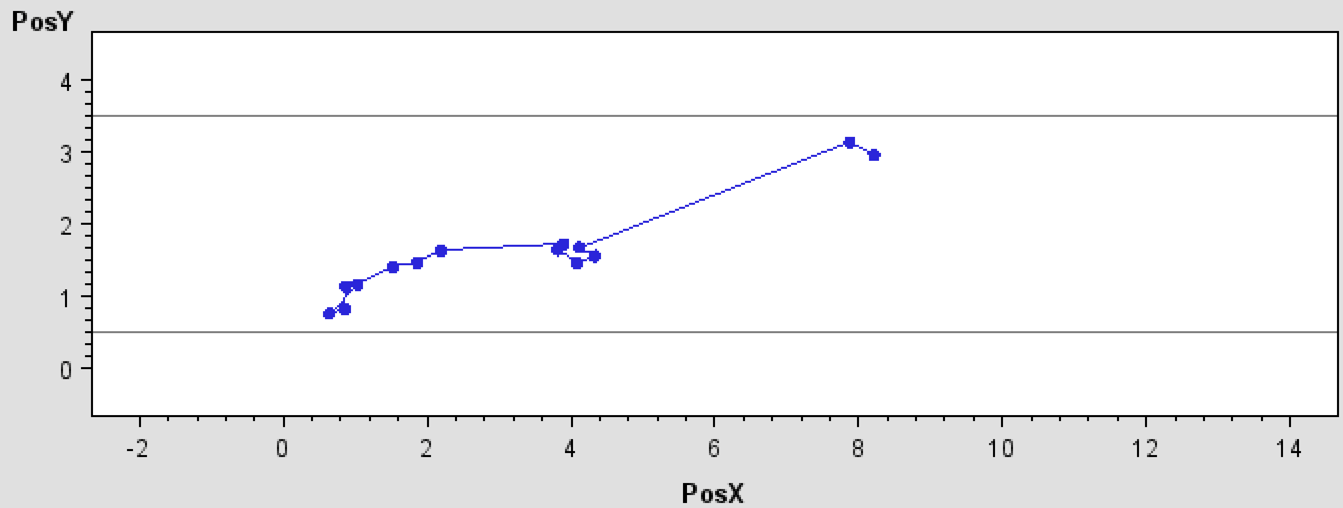
Smolt Tracks, Treatment = Control

Trial=100513A ID=48



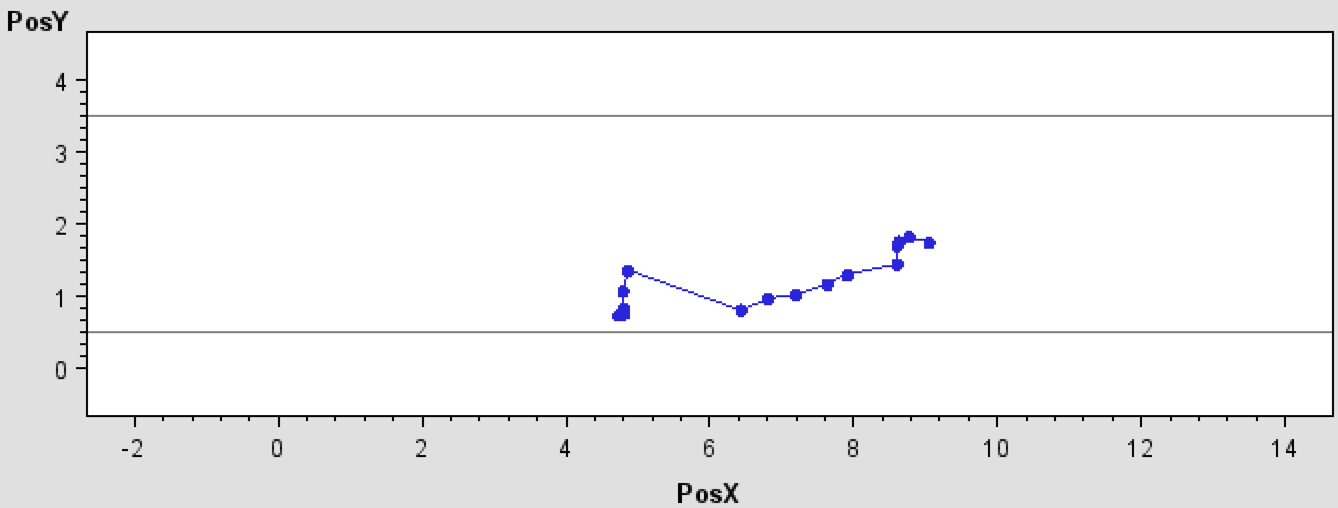
Smolt Tracks, Treatment = Control

Trial=100513A ID=81



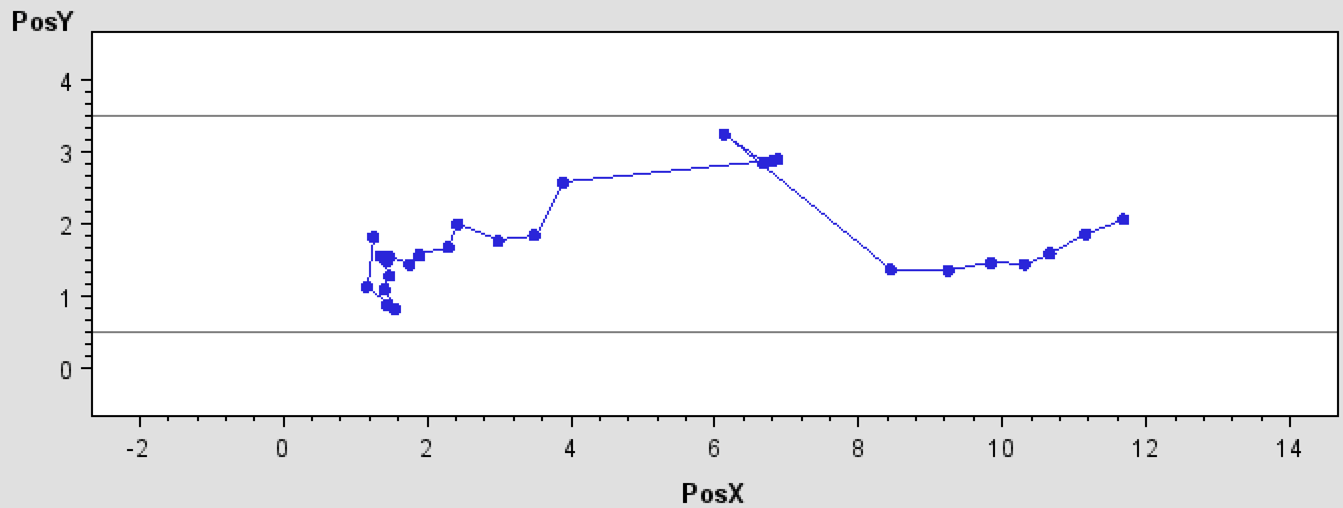
Smolt Tracks, Treatment = Control

Trial=100513A ID=83



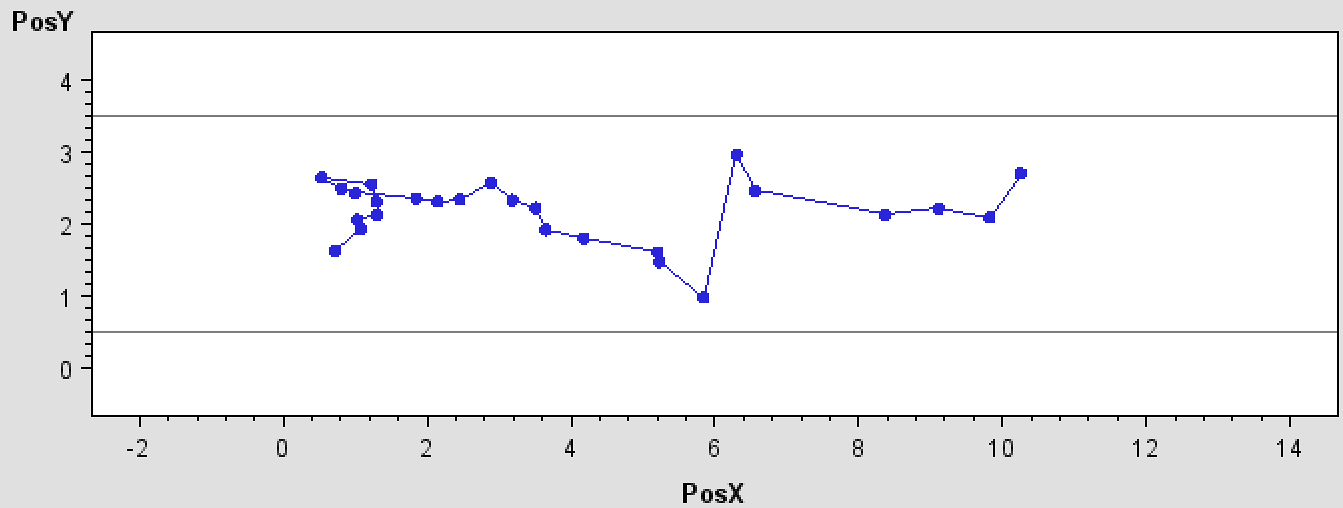
Smolt Tracks, Treatment = Control

Trial=100518A ID=51



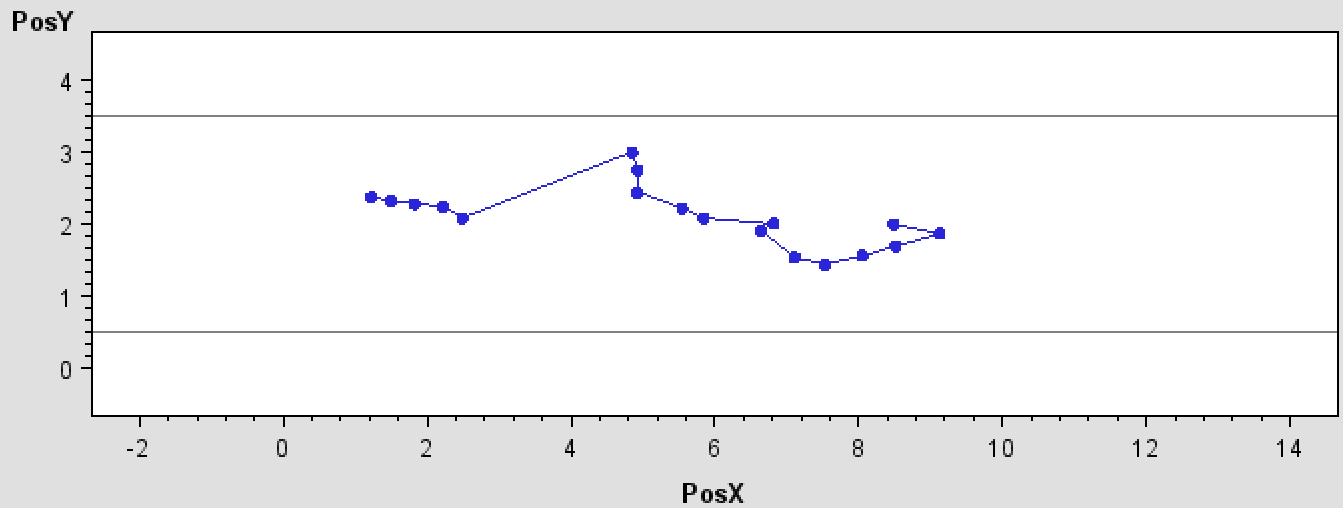
Smolt Tracks, Treatment = Control

Trial=100518A ID=87



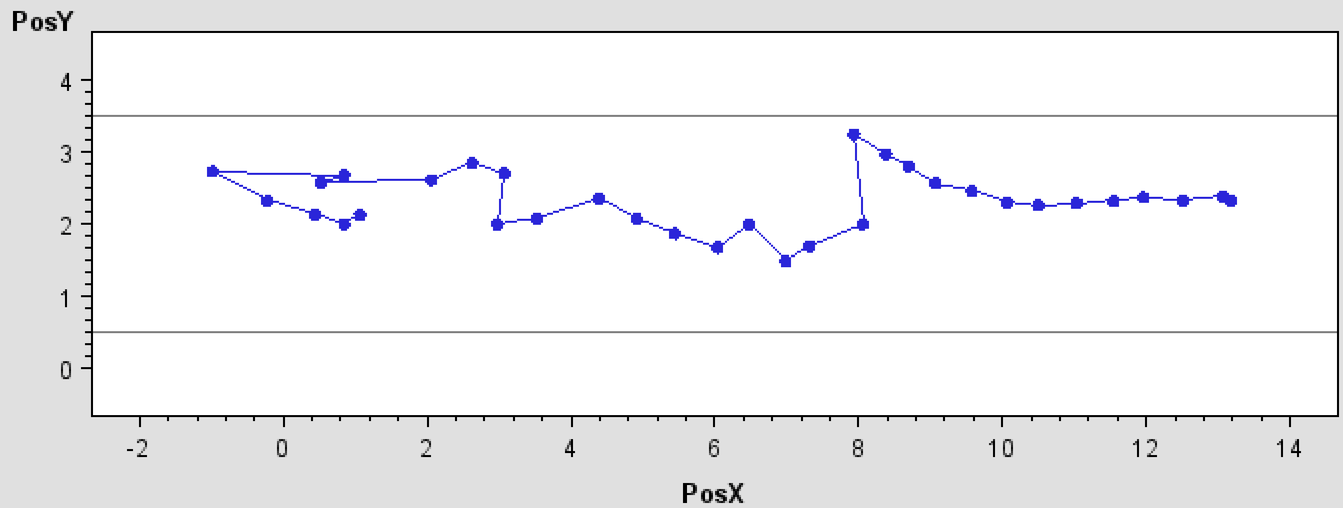
Smolt Tracks, Treatment = Control

Trial=100518A ID=103



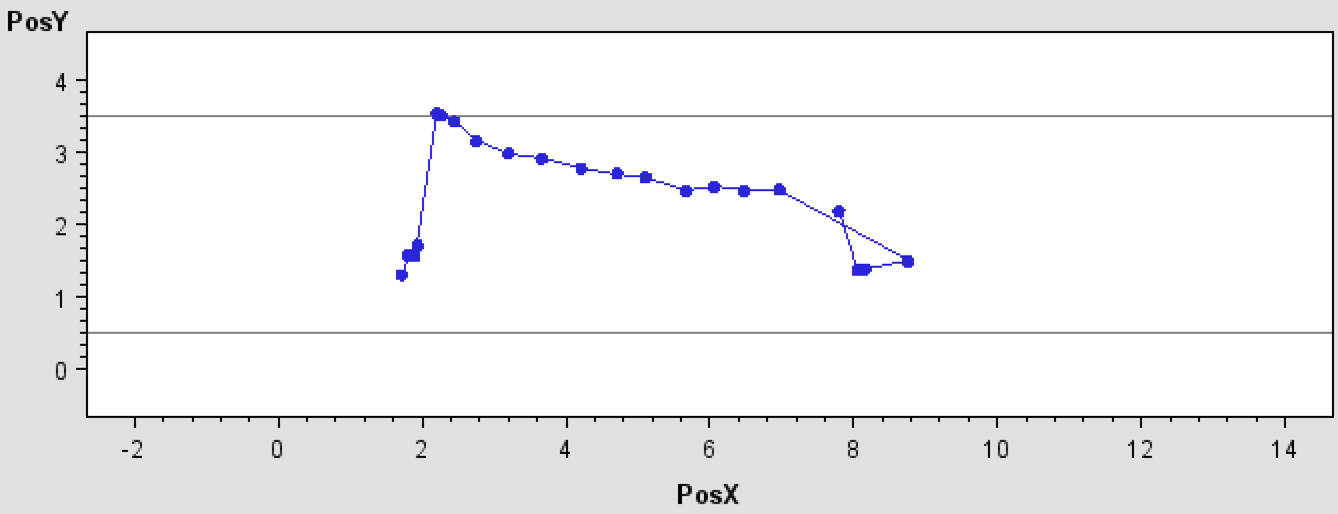
Smolt Tracks, Treatment = Control

Trial=100518A ID=110



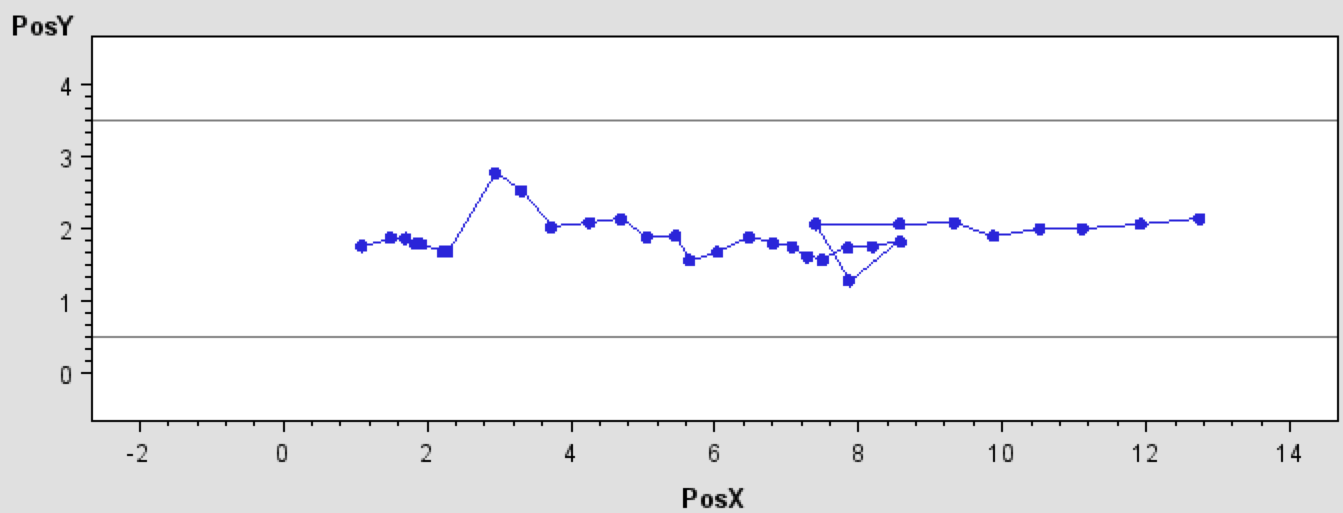
Smolt Tracks, Treatment = Control

Trial=100518A ID=114



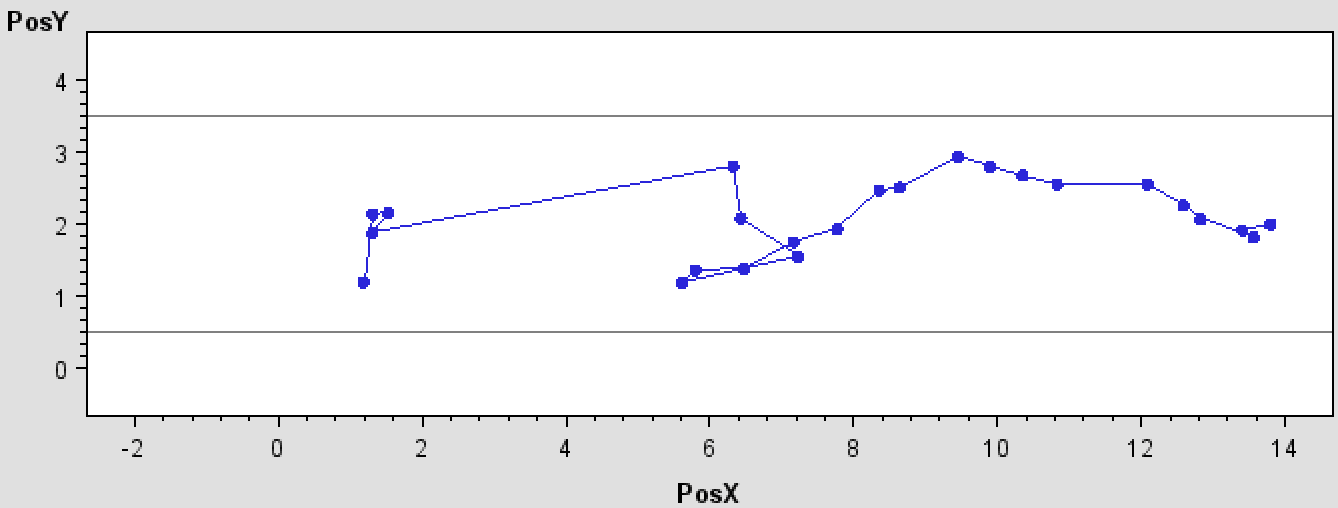
Smolt Tracks, Treatment = Control

Trial=100518A ID=115



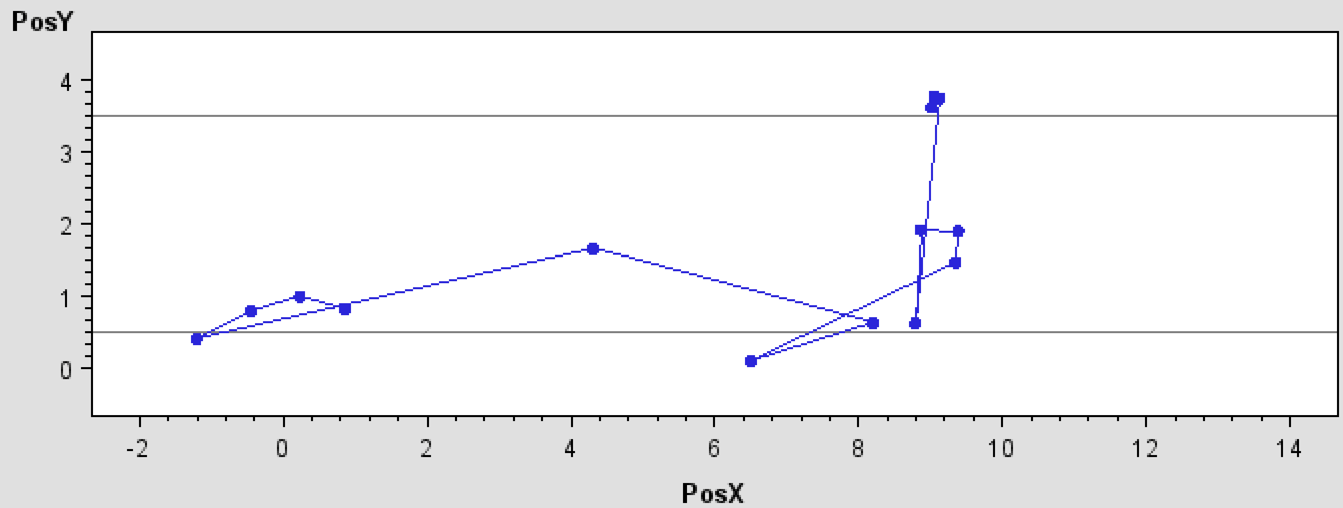
Smolt Tracks, Treatment = Control

Trial=100518A ID=117



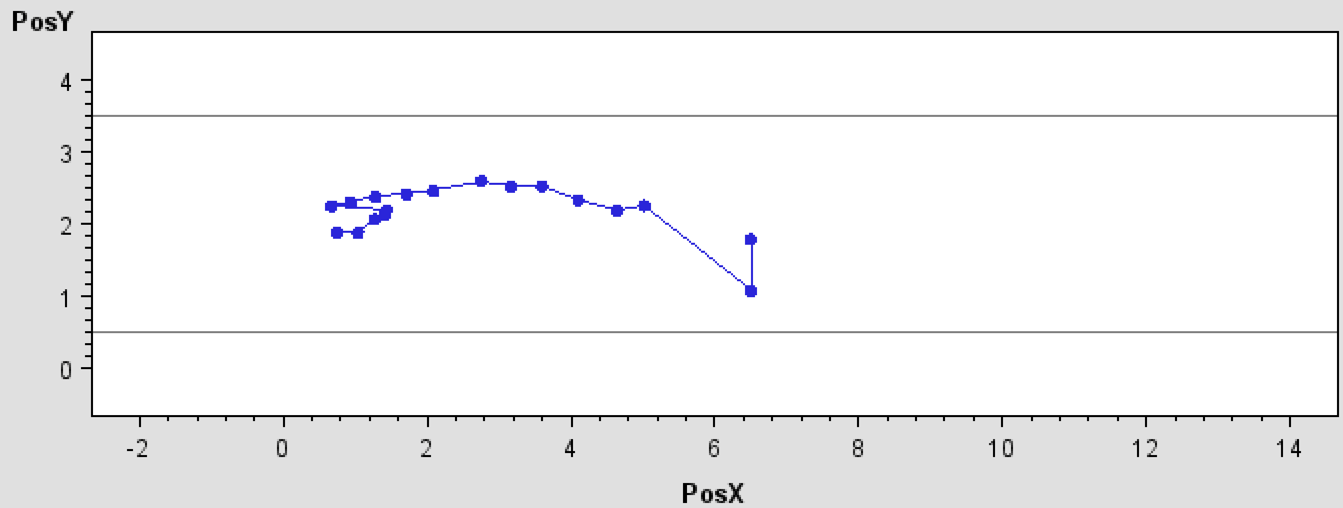
Smolt Tracks, Treatment = Control

Trial=100518A ID=130



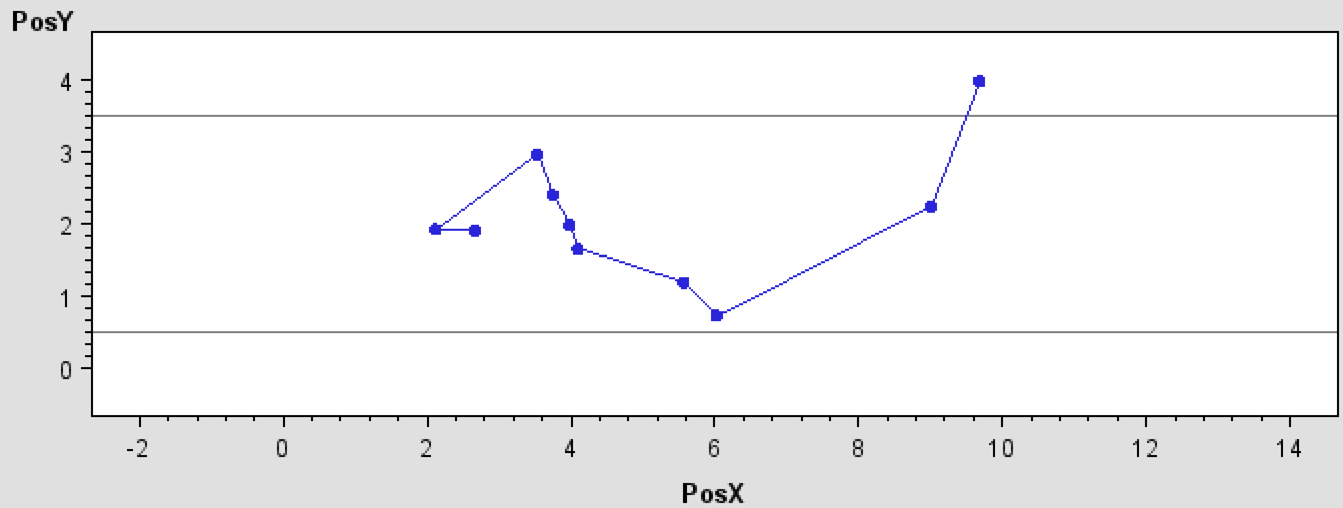
Smolt Tracks, Treatment = Control

Trial=100518A ID=131



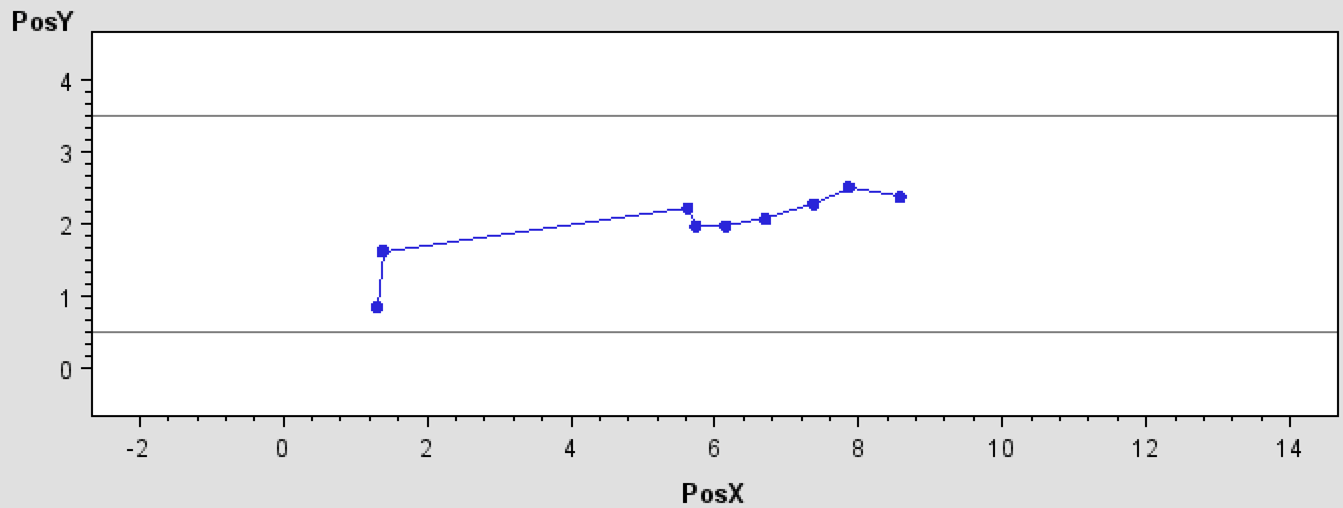
Smolt Tracks, Treatment = Control

Trial=100518A ID=151



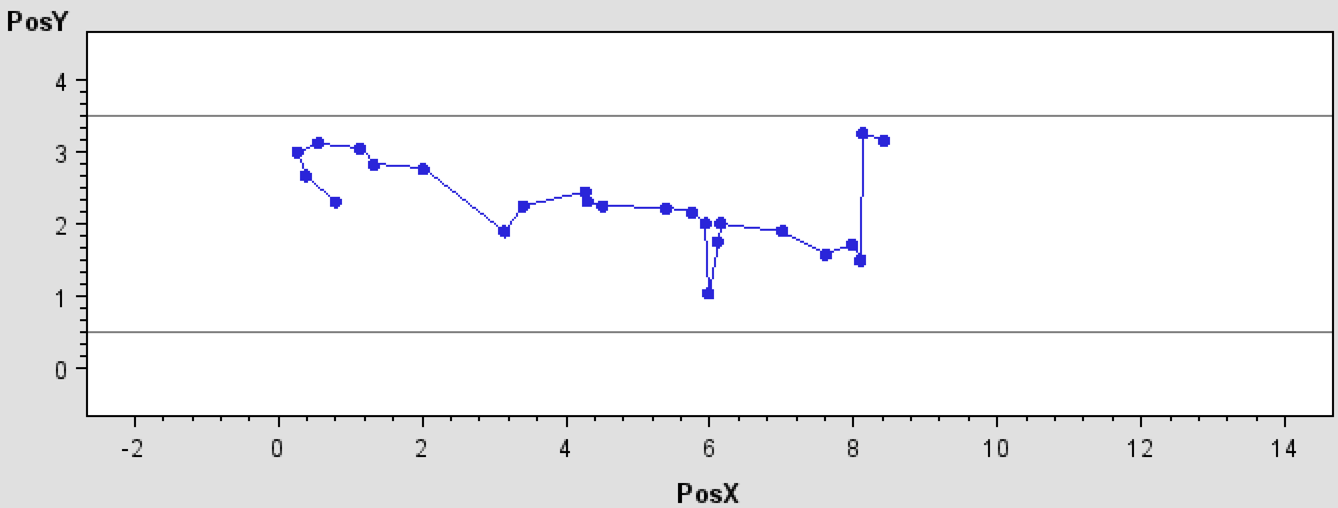
Smolt Tracks, Treatment = Control

Trial=100518A ID=153



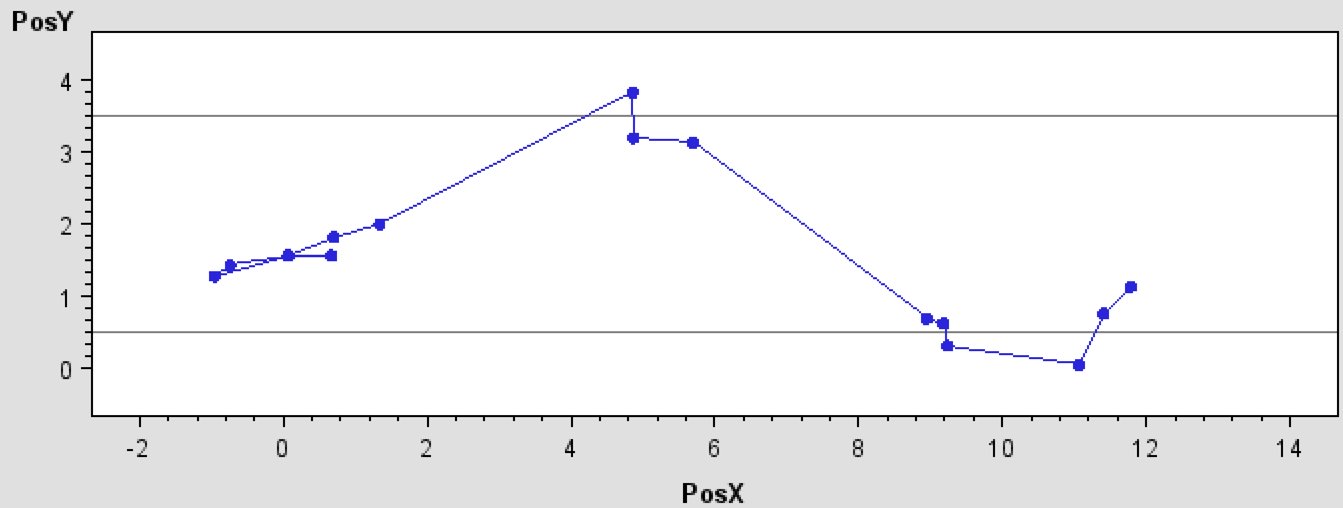
Smolt Tracks, Treatment = Control

Trial=100518A ID=155



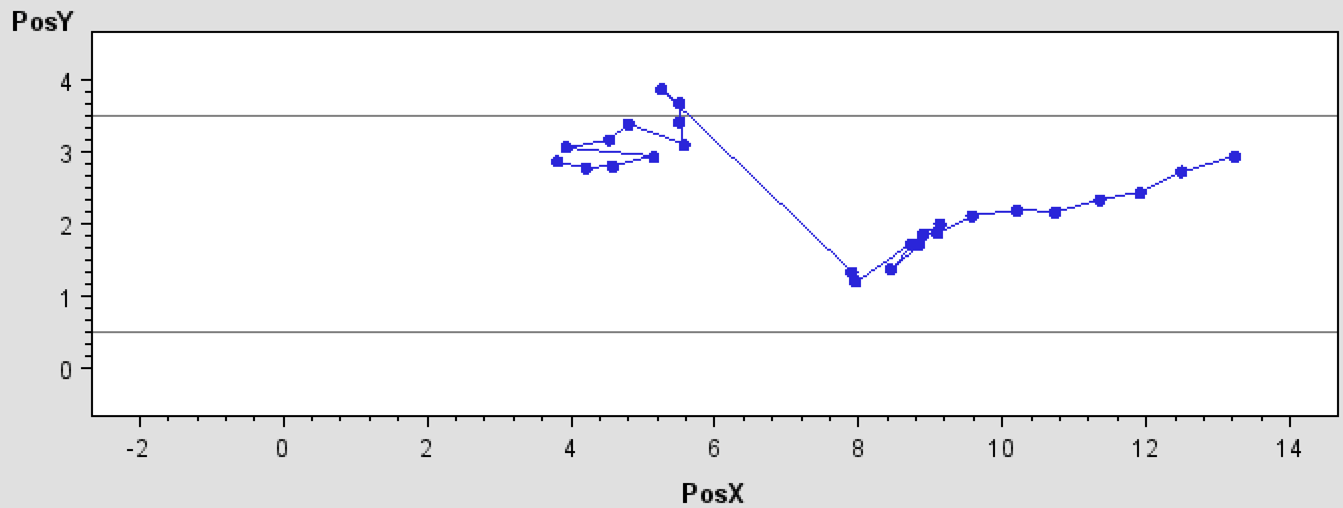
Smolt Tracks, Treatment = Control

Trial=100518A ID=158



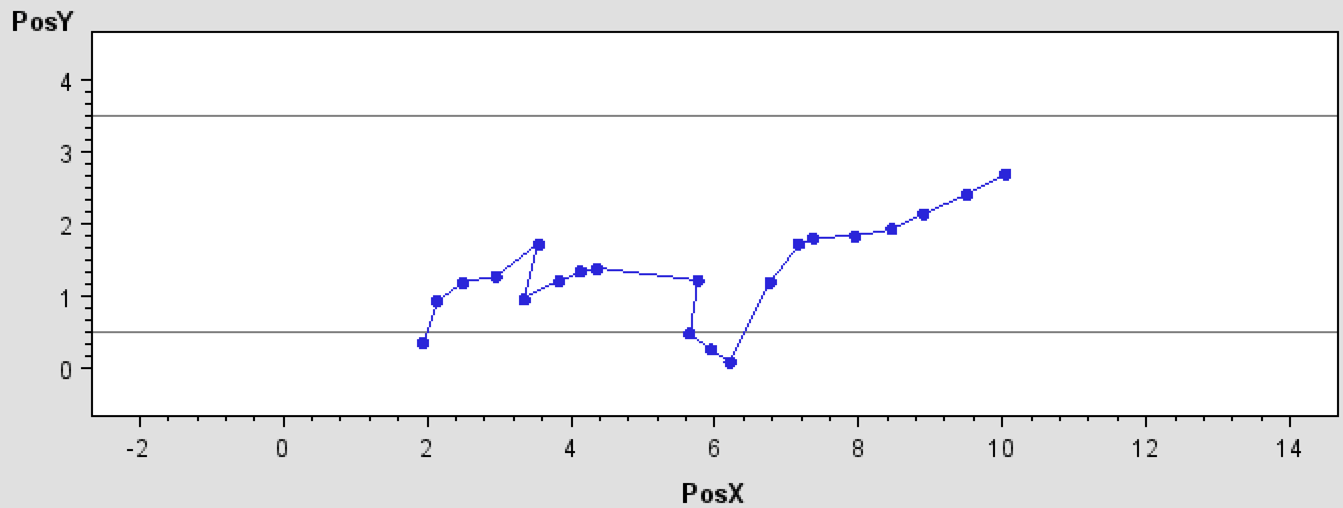
Smolt Tracks, Treatment = Control

Trial=100518A ID=161



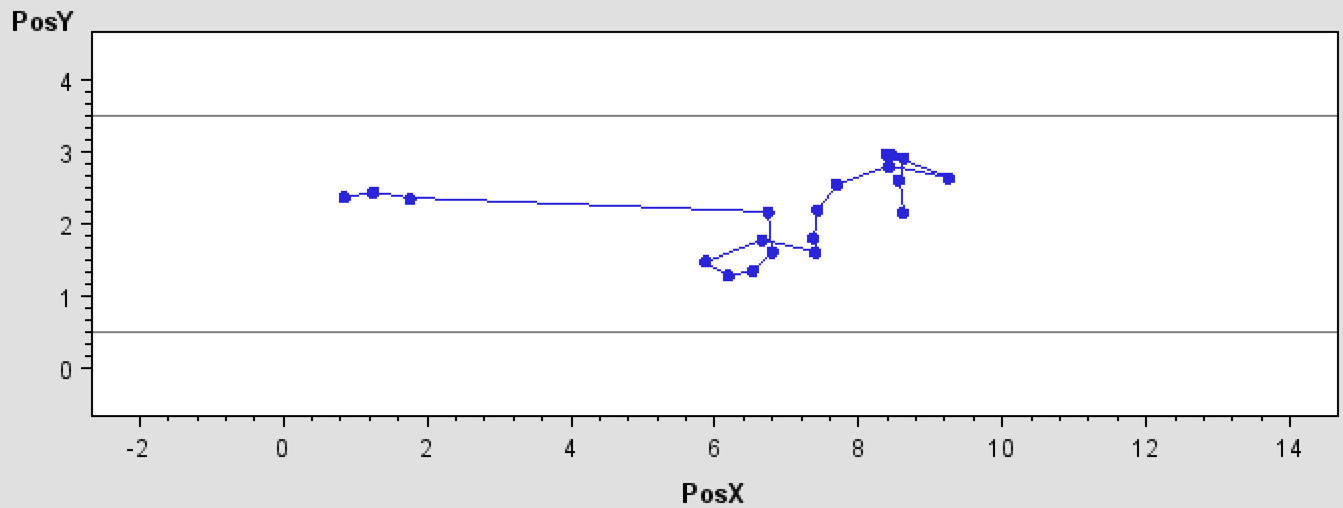
Smolt Tracks, Treatment = Control

Trial=100518A ID=162



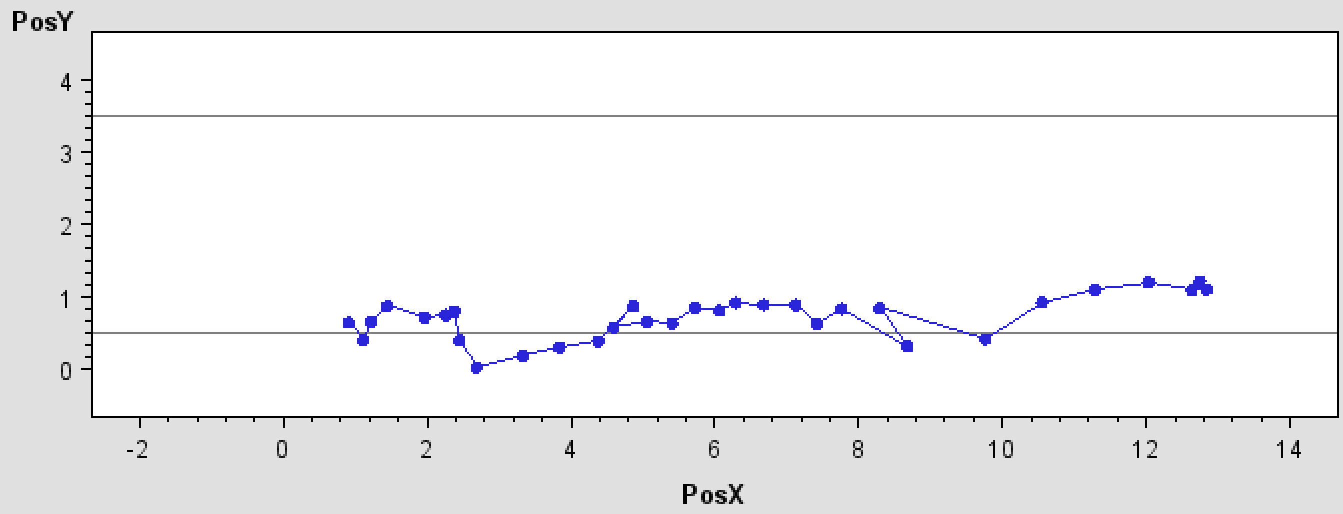
Smolt Tracks, Treatment = Control

Trial=100518A ID=168



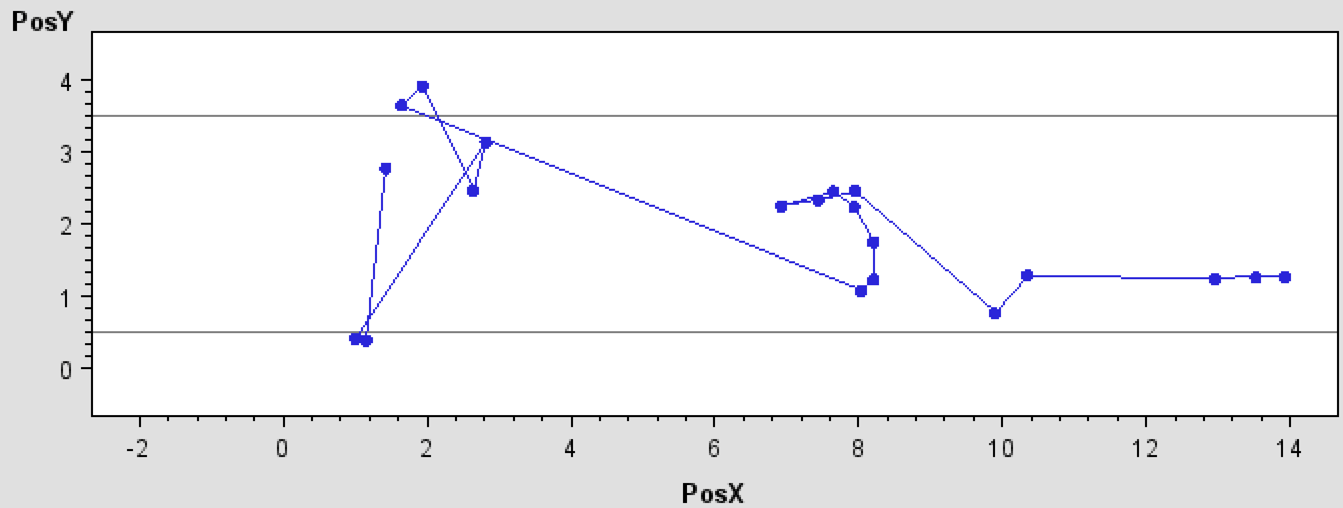
Smolt Tracks, Treatment = Control

Trial=100518A ID=172



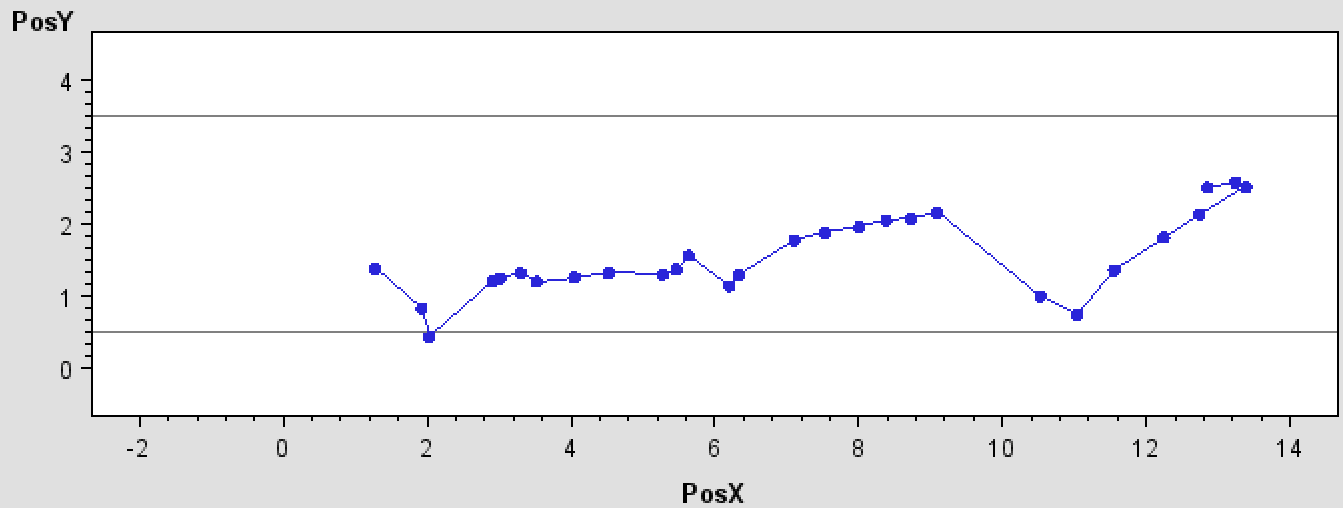
Smolt Tracks, Treatment = Control

Trial=100518A ID=179



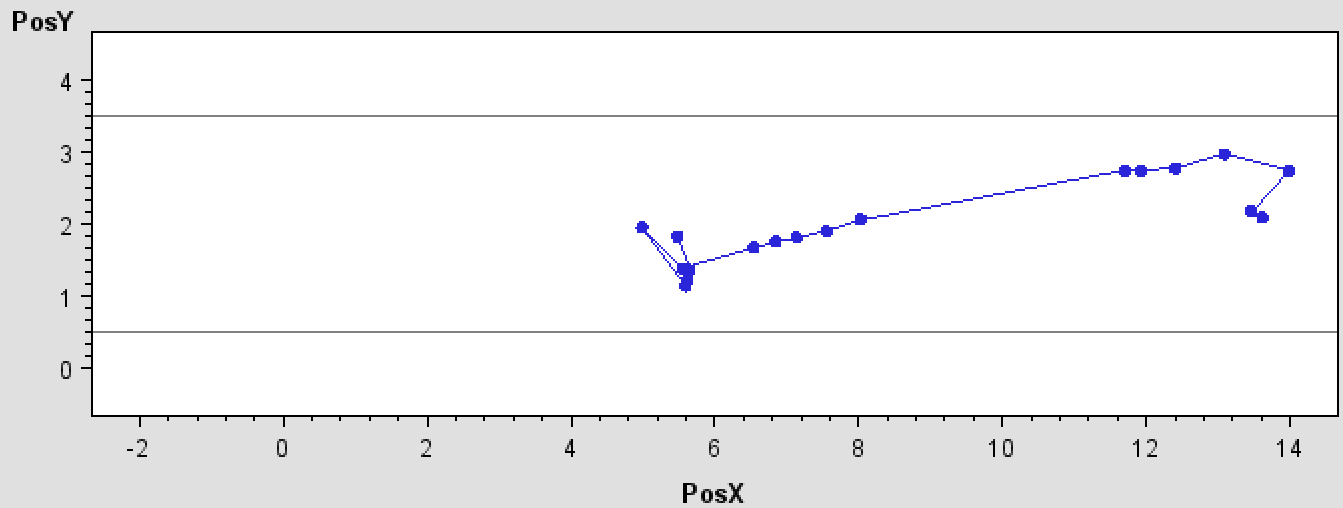
Smolt Tracks, Treatment = Control

Trial=100518A ID=183



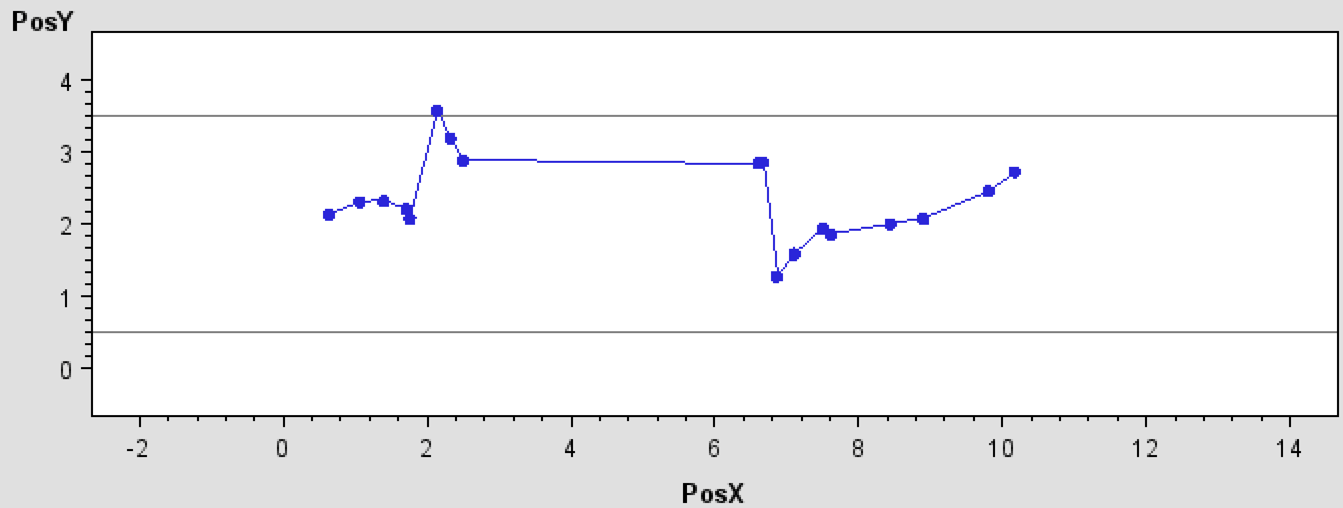
Smolt Tracks, Treatment = Control

Trial=100518A ID=185



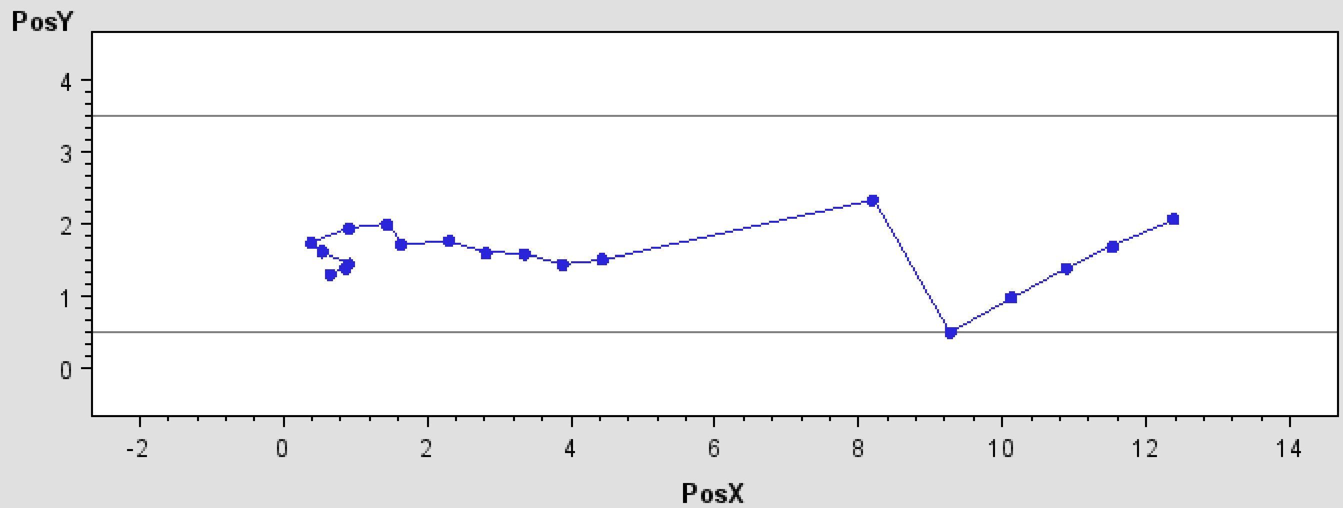
Smolt Tracks, Treatment = Control

Trial=100518A ID=194



Smolt Tracks, Treatment = Control

Trial=100518A ID=195



Smolt Tracks, Treatment = Control

Trial=100518A ID=201