MEMORANDUM

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Date: **September 23, 2015** PNNL-SA-113213

To: **All Viewers and Participants of the PNNL Webinar – Evaluation of the Whooshh Fish Transport System (WFTS)**

From: **David Geist**

Subject: **Sensor Fish Acceleration (g forces) through WFTS**

During the recent PNNL webinar (Evaluation of the Whooshh Fish Transport System [WFTS], https://pnnl.eventbuilder.com/event?eventid=y6s5l5), several questions were submitted concerning the acceleration data recorded by the Sensor Fish during the 2014 PNNL study of the WFTS. These data were collected as part of a proof-of-concept test to demonstrate that the Sensor Fish could be used to measure the physical forces within the WFTS. We stated in the webinar that the acceleration from the 2014 study would unlikely lead to fish injury. This conclusion was based on our previous experience with using the Sensor Fish to study the acceleration of juvenile Chinook salmon exposed to shear forces (Deng et al., 2010) and also on the fact that we did not measure physical injury to the adult salmon that we tested in the WFTS. However, we were not able to spend sufficient time during the webinar to adequately explain the data, our interpretation of the data, or even how these values relate to what we know about acceleration in general. Therefore, the purpose of this memo is to provide further clarification on the 2014 study. In addition, given the importance of the acceleration questions raised, we provide herein the results of several measurements we recently made in our lab that supports our prior conclusion that the acceleration experienced by fish in the WFTS are unlikely to lead to injury for the two configurations we evaluated.

To set the stage for the discussion, consider what is known about the impact of acceleration on humans. The maximum acceleration measured in the WFTS and presented in the webinar was around 17 g which caused several participants to comment that this acceleration is injurious to humans. We are aware of concerns on fighter pilots when acceleration exceeds 9 g (note that a typical person can bear acceleration of about 5 g but modern pilots using g-suits and special training can tolerate higher levels), but the key to that impact is the magnitude of the acceleration combined with the length of time for which it is applied, its direction and location, and body posture. The sustained acceleration experienced by a fighter pilot deprives the pilot of blood to the head. It is the duration and the resulting loss of blood flow, rather than the instantaneous acceleration (like those recorded by the Sensor Fish), that cause pilots to black out. To put this into the perspective of normal living, according to a 1994 article in the journal *Spine* (Allen et al., 1994), routine everyday experiences can result in acceleration greater than 1 g. For example, the average sneeze creates acceleration of 2.9 g, a slap on the back of 4.1 g, and a plop down into a chair of 10.1 g. If you jump one meter up in the air and land stiff-legged on one foot (barefoot), you'll feel about 100 g momentarily (Herman, 2007). It has been suggested that an injury threshold of 70 to 75 g be used for sustaining concussion based on the linear acceleration of a football player's head (Pellman et al., 2003). Another study also reported that less than 0.35% of impacts greater than 80 g resulted in concussion based on self-reported symptoms by collegiate football players (Mihalik et al., 2007).

Unfortunately, even though the maximum acceleration values that we reported in our webinar are only slightly above everyday activities and well below the levels that football players experience, the attention has incorrectly focused on these maximum values instead of on what the values mean. The measurements of the Sensor Fish are more akin to the instantaneous acceleration experienced by sudden movements of the body in your living room when you sneeze or after a sudden impact during a football game. The Sensor Fish device acquires data at an extremely high sampling rate (2,048 Hz) and is very sensitive to changes in acceleration (Deng et al., 2015). The figure in the webinar (reproduced below with more information) represents the instantaneous acceleration that the Sensor Fish recorded while the fish entered, went through, and exited the WFTS; each data point represents the acceleration over approximately 0.5 msec.

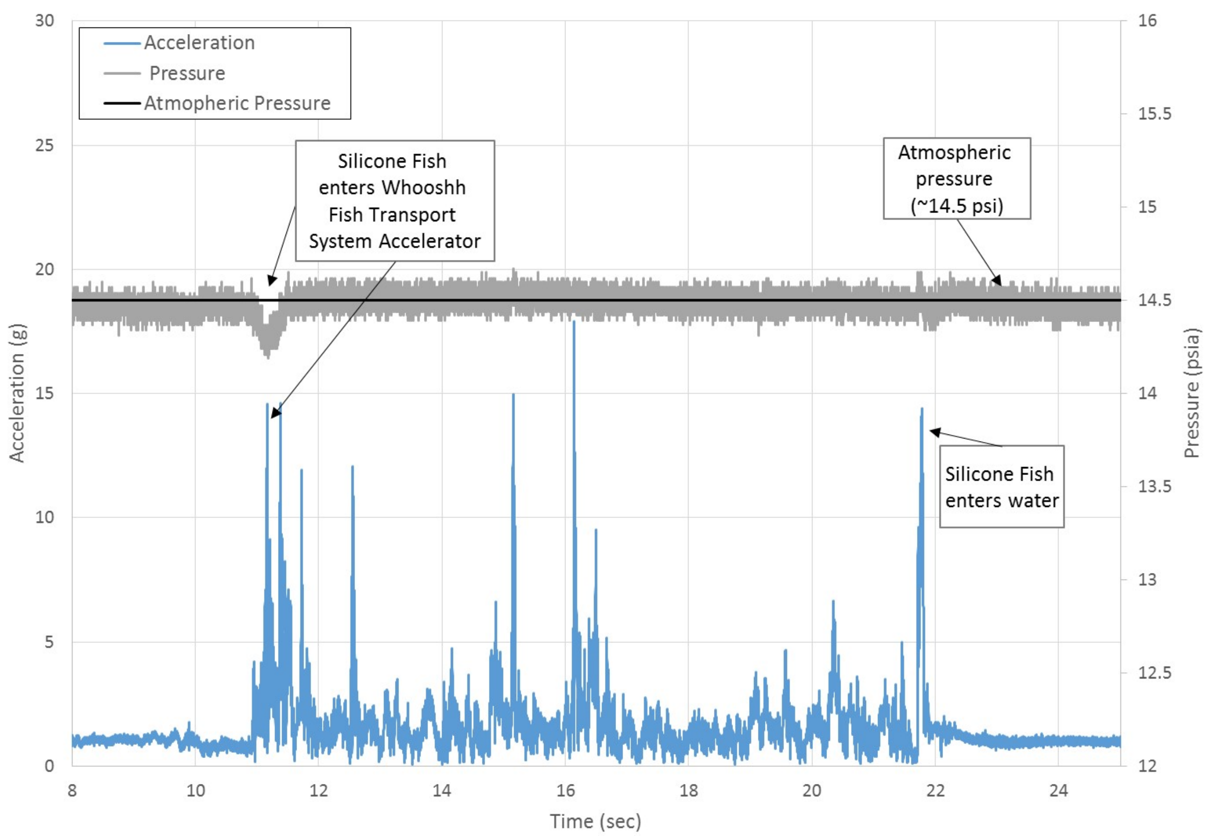

Figure 1. The instantaneous acceleration and pressures measured by the Sensor Fish as it moved into, through, and out of the Whooshh Fish Transport System (WFTS) on November 5, 2014. Entrance to the WFTS is noted by the slight increase in pressure, and exit from the WFTS is noted by the slight decrease in pressure (return to pre-passage pressure). There were peaks in the acceleration measurements as the Sensor Fish moved through the tube, the largest likely as the

Sensor Fish moved around 90 degree corners. It is not clear how well these values represent acceleration associated with live fish in a WFTS tube in a straight path, which would be the normal configuration in a fish passage scenario. Mean instantaneous acceleration during this trial was 1.9 g (SD = 1.6 g; SE = 0.01 g) and the median was 1.5 g (range: 0.06 to 17.92 g) from 11 sec until 22 sec (corrected time) of the trial.

Further, it is important to recognize that the Sensor Fish portion of the 2014 study was not an objective of our biological/physiological project, and instead served as a proof-of-concept to demonstrate that the Sensor Fish could be used to evaluate the physical conditions adult fish experience in complex hydraulic environments. The silicone fish (implanted with a Sensor Fish) was not designed to act as or replace live fish. Prior to the beginning of the study, we created a silicone fish that was based upon a mold of a real, but small fall Chinook salmon. Unfortunately, the circumference of the silicone fish was too small for the system we were testing, so prior to testing we added a sponge around the middle of the silicone fish to create a seal which would enable the WFTS to transport the device. The sponge altered the shape and weight of the silicone fish which could change the acceleration dynamics compared to a live fish.

Given the questions about momentary acceleration on salmon, and the common misunderstandings that have arisen around acceleration in general, on September 20, 2015, using the same silicone fish (#1; Figure 2) and Sensor Fish (#56) that were used in the 2014 study, we conducted some measurements in our lab to better understand the instantaneous acceleration a salmon may experience. The maximum instantaneous acceleration reported in the 2014 study and shown on the webinar was 17.92 g. We wanted to compare that information to what our sensor recorded when the silicone fish (implanted with the Sensor Fish) was either dropped into the water, or onto the ground, from a height of 36 inches. This height was selected because we have observed salmonids routinely jumping this high in the air and falling back into the water; or instances where fish are dropped back into the water from waist height; or occasionally when fish are inadvertently dropped on the ground during handling. Four conditions (treatments) were evaluated and there were two replicates per treatment:

1) Belly to Water: The silicone fish was dropped belly first from a height of 36 inches into approximately 30 inches of water
2) Head to Water: The silicone fish was dropped head first from a height of 36 inches into approximately 30 inches of water
3) Belly to Ground: The silicone fish was dropped belly first from a height of 36 inches onto a flat concrete floor
4) Head to Ground: The silicone fish was dropped head first from a height of 36 inches onto a flat concrete floor

Figure 2. Silicone Fish #1 was used for all treatments. An internal Sensor Fish (Sensor Fish #56) was embedded in the silicone fish. Wires connect the internal Sensor Fish to the outside which enables data download. Two samples were collected for each treatment. Atmospheric pressure was about 14.3 psi during testing on September 20, 2015.

The measurements (see Table 1 below) demonstrate that the instantaneous acceleration experienced by a silicone fish that falls through air from a height of 36 inches are generally higher than the instantaneous acceleration values recorded during passage through the WFTS (maximum acceleration = 17.92 g); the exception is when the silicone fish was dropped head first into the water (maximum acceleration = 7-8 g). The fact that fish do not routinely suffer physical injury when they are dropped from 36 inches into the water suggests that these data would appear to corroborate our initial conclusions that the maximum instantaneous acceleration recorded as the silicone fish passed through the WFTS were not likely to lead to injury for the two configurations we evaluated. Furthermore, the average acceleration during passage through the WFTS was ~ 2 g and the peak accelerations were only sustained briefly (0.5 msec).

Table 1. Maximum acceleration measured by the Sensor Fish inside a silicone fish dropped from 36 inches into water or onto a concrete floor.

Sample #	Treatment	Max acceleration (g)
1A	Belly to water	38
1B	Belly to water	30
2A	Head to water	7
2B	Head to water	8
3A	Belly to concrete	69
3B	Belly to concrete	111
4A	Head to concrete	43
4B	Head to concrete	42

Beyond the limited measurements described above, controlled laboratory studies with larger sample sizes and live fish would be required to develop response relationships between the silicone fish and live fish. The response relationships could then be used to derive the physical conditions that live fish experience. Given what we learned about accelerations within the WFTS, it may be just as instructive to use the Sensor Fish to test the instantaneous acceleration adult salmonids experience using traditional methods such as trap and haul and fish ladders to establish a baseline for comparison.

In summary, we believe that the momentary accelerations measured in the 2014 PNNL study of the WFTS that were presented in the webinar were sufficiently small as to be unlikely to cause injury in adult salmon. This conclusion is based on controlled laboratory testing with juvenile Chinook salmon; our limited tests described above; and the lack of injury or physiological effects measured on the adult fall Chinook salmon used in the 2014 WFTS study. However, due to several factors (e.g., differences in the size and shape of the testing device [silicone fish/sponge] compared to a real salmon; the dynamic activity of a salmon compared to the Sensor Fish device; a lack of response relationship between the Sensor Fish and adult fish; the pilot-scale nature of the Sensor Fish deployment in the 2014 study) we suggest that the results should not be considered definitive in interpreting the acceleration that adult salmon experience in the WFTS. The biological/physiological study that we described in the webinar where results from fish that experienced the WFTS were as good as or better than control groups may be the ultimate indicator of how fish respond to the WFTS.

Further Information

Allen ME, Weir-Jones I, Motiuk DR, Flewin KR, Goring RD, Kobetitch R, Broadhurst A. (1994). Acceleration Perturbations of Daily Living. Spine 19(11): 1285-1290.

Cameron JR, Skofronick JG, Grant RM. (1992). Physics of the Body. Medical Physics Publishing.

Deng Z, Guensch GR, McKinstry CA, Mueller RP, Dauble DD, Richmond MC. (2005). Evaluation of fish-injury mechanisms during exposure to turbulent shear flow. Canadian Journal of Fisheries and Aquatic Sciences 62:1513-1522.

Deng Z, Lu J, Myjak MJ, Martinez JJ, Tian C, Morris SJ, Carlson TJ, Zhou D, Hou H. (2014). Design and Implementation of a new Autonomous Sensor Fish to Support Advanced Hydropower Development. Review of Scientific Instruments 85(11):115001.

Deng Z, Mueller RP, Richmond MC, Johnson GE. (2010). Injury and Mortality of Juvenile Salmon Entrained in a Submerged Jet Entering Still Water. North American Journal of Fisheries Management, 30:623-628.

Herman, IP. (2007). Physics of the Human Body. Springer Science and Business Media. New York, NY.

Higgins, M. (2009). Football Physics: The Anatomy of a Hit. Available: http://www.popularmechanics.com/adventure/sports/a2954/4212171/

Mihalik, JP, Bell DR, Marshall SW, Guskiewicz KM. (2007). Measurement of head impacts in collegiate football players: an investigation of positional and event-type differences. Neurosurgery, 61(6), 1229-1235.

Pellman EJ, Viano DC, Tucker AM, Casson IR, Waeckerle JF. (2003). Concussion in professional football: Reconstruction of game impacts and injuries. Neurosurgery 53:799–814,.

Tyson, P. (2007). All About G Forces. Inquiry: An Occasional Column. Available: http://www.pbs.org/wgbh/nova/space/gravity-forces.html