PRELIMINARY RESEARCH PROPOSAL
SUBMITTED TO THE U.S. ARMY CORPS OF ENGINEERS

I.A. Title of Project	Juvenile Lamprey Acoustic Microtransmitter Development
I.B. Technical POC:	Brad Eppard (Portland District)
I.C. Project Leaders	Zhiqun (Daniel) Deng, Principal Investigator PO Box 999 Richland, WA 99352 Tel: 509/372-6120 Email: zhiqun.deng@pnl.gov
I.D. Anticipated Duration:	August 2013 – September 2017
I.E. Date of Original Submission:	July 2013 (Original);
I.F. Date of Revised Submission:	October 2014

CONFIDENTIAL

II. Project Summary
II.A. Background

In the Columbia River Basin (CRB) Pacific lampreys (Entosphenus tridentatus) are of special concern because their populations have severely declined in the past 40 years (Close et al. 1995; Kareiva et al. 2000). Construction and operation of hydroelectric facilities may negatively impact juvenile lamprey because these declines occurred after the period of major hydroelectric development (Moursund et al. 2003; Dauble et al. 2006). Knowledge of lamprey behavior and survival are critical for developing mitigation strategies for downstream passage, including design of bypass systems at hydroelectric facilities and for irrigation diversion structures. Mueller at all (2006) demonstrated the feasibility of tagging juvenile Pacific lampreys with Passive Integrated Transponders (PIT). However, the detection probability of PIT-tagged fish on their downstream migration is relatively low; generally ranging from 5% to 70% of the fish passing a specific hydroelectric facility, varying depending on features of the juvenile bypass facilities and dam operations (Muir et al. 2001). It is probable that because of differences in migratory behavior the detection probability of PIT tagged lamprey would be significantly lower that that for juvenile salmonids.

The American eel has been proposed for listing under the Endangered Species Act (ESA) due to significant population decline (US Fish and Wildlife Service). Because of American eels' complex life histories, this ESA listing could potentially impact a significant number of hydropower projects totaling 32,719MW of existing nameplate capacity, most likely in the Great Lakes / St Lawrence River basin, New England and the Mid-Atlantic states (Jager et al. 2013).

Knowledge of eel and lamprey behavior and survival are critical for developing mitigation strategies for downstream and upstream passage, including design of bypass systems at hydroelectric facilities and for irrigation diversion structures.

The U.S. Army Corps of Engineers (USACE) and PNNL have developed and are currently using throughout the Federal Columbia River Power System and at locations in the Willamette River basin, a juvenile salmon acoustic telemetry system (JSATS) consisting of acoustic micro-transmitters (tags) and autonomous, cabled, and portable receivers to evaluate the behavior and survival of juvenile salmonids migrating past dams, through reservoirs and the lower Columbia River estuary to ocean entry (McMichael et al. 2010, Weiland et al. 2011, Deng et al. 2011). Considerable effort has been expended to understand the biological effects of implantation of acoustic transmitters in yearling and subyearling Chinook salmon. With funding from the USACE, PNNL also developed a new generation transmitter that can be implanted using injection instead of surgery. It was successfully evaluated in a field study (Deng et al. 2014). It substantially reduces adverse effects of implantation, and provides additional biological benefits for tagged fish and will become the a critical technology for studying migration behavior and survival of species and sizes of fish that have never been studied in the past, leading to critical information for salmon recovery and the development of fish-friendly hydroelectric systems. However, the new injectable transmitter, which is only slightly larger than a PIT tag, is still too large to be implanted in juvenile lamprey. Still smaller, perhaps flexible, transmitters are needed for species with thin and flexible bodies such as juvenile lamprey and eel.

II.B. Goals

The goals of this project are to design, prototype, and perform laboratory and field tests of an acoustic microtransmitter that can be used to study the behavior and survival of juvenile lamprey.

II.C. Objectives

1. Describe the planned range of applications of the new lamprey acoustic microtransmitter.
2. Develop design alternatives based on the application space identified in objective 1.
3. Integrate the functionality of the transmitter onto an integrated circuit
4. Identify or design alternatives to the batteries designed for the juvenile salmon injectable microtransmitter. The alternatives should be lighter in weight, smaller in size, and has form that permits transmitter shapes amenable to the thin and flexible body of juvenile lamprey.
5. Determine the most efficient piezoelectric material for this application and optimize the transducer design for converting electrical energy into acoustic signals
6. Develop a procedure for implantation of the new transmitter that minimizes the time required for implantation and biological effects in juvenile lamprey.
7. Determine form factors that permit transmitter shapes amenable to applications identified in objective 1 and design options identified in objectives 1-4.
8. Prototype transmitters with parts and form identified in objectives 1-7 and perform bench top and test tank evaluation to ensure that acoustic functions of the prototype transmitter meet the required specifications.
9. Assess manufacturability of the parts and whole unit in quantities required for juvenile lamprey studies using the new acoustic microtransmitter.
10. In collaboration with others identified by the USACE, design and perform laboratory and field trials of the implantation of microtransmitters in juvenile lamprey and the detection, tracking, and estimation of survival of the juvenile lamprey passing through the FCRPS and/or elsewhere as identified in plans of study. This objective is a placeholder for now. We will provide a budget and delivery schedule when we are close to the completion of the prototype lamprey transmitter.
11. Reporting

II.D. Methodology

1. **Objective 1: Applications space**

   In collaboration with USACE, we will facilitate the development of application space for all parties interested in the development of the lamprey transmitter to meet specific lamprey study objectives.

CONFIDENTIAL

We will then identify the design and performance requirements of lamprey microtransmitters required to meet these objectives.

2. **Objective 2: Design alternatives**
We will develop specifications for microtransmitter design alternatives based on the application space requirements identified in objective 1. We will then evaluate and document each alternative, assess the trade-offs for the alternatives, and in collaboration with the USACE and others select a preferred alternative for development.

3. **Objective 3: Integrated Circuit**
We will develop an efficient driving circuit for the eel/lamprey transmitter based on the design we created for the JSATS injectable transmitters. Potential designs depend on the application space and design alternatives identified in Objectives 1 and 2. Potential options will include:
Passive integrated transponder (PIT) tag integration: Currently juvenile salmon are injected with a PIT tag in addition to the acoustic tag. The PIT tag contains a radio frequency (RF) antenna connected to the circuit. An external reader generates a strong RF field that provides sufficient energy to activate the circuit. The circuit then transmits a unique tag code back to the reader over the antenna. Because the PIT tag contains no battery, the maximum communication distance is on the order of 1 meter. However, the tags can last for many years as they require no internal energy source. If the application study requires the use of both PIT and acoustic tags for ee/lamprey, integrating both tags into one would have significant advantages. The combined tag would first lower costs by simplifying the injection process.
Flexible circuit board: The downsized tag for may need to be flexible to minimize biological effects to the eel/lamprey. Although the discrete components of the acoustic tag are rigid, attaching the components to a flexible circuit board provides some freedom of movement. Flexible circuit boards also provide size and weight advantages, but with a slight increase in cost at production quantities.
Circuit Design Improvements: We will evaluate various components to reduce the size and weight while maintaining required driving efficiency.
Programming Options: We will evaluate various programing options including light, acoustic, and RF. The final choice will be determined by the capabilities of the fabrication process and the application requirements and design alternatives identified in Objectives 1 and 2:

4. **Objective 4: Batteries**

Previous JSATS transmitter uses two size-337 watch batteries stacked in serial to produce 3-V output (Figure 1). Each battery weights 0.13 g with a typical volume of 0.03 cm^3. Single 337 battery delivers a capacity of 8.3 mAh but 50% of the battery weight is from the packaging materials. Following the methods used to develop the injectable juvenile salmonid microtransmitter battery, we have developed several design alternatives based on the application space and power requirements identified in Objective 1 and 2.

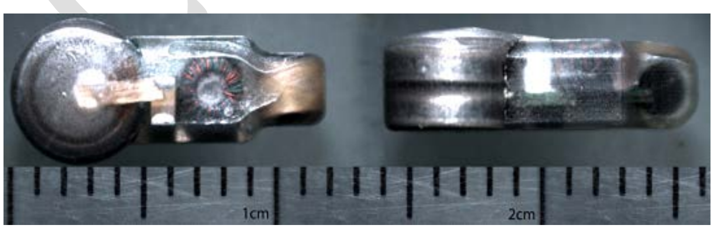

Figure 1. Fish tags using two stacked watch batteries as power source.

5. **Objective 5: PZT ceramics**

CONFIDENTIAL

In the current JSATS microtransmitter design, the orientation of the PZT tube transducer relative to the hydrophone is shown in Fig. 2 below. This orientation allows the PZT to operate at "hoop" mode to achieve an omnidirectional beam pattern, which optimized the detection probability of tagged fish. However, the minimum diameter of the tag is limited by the value of $\sqrt{\mathrm{OD}^2 + \mathrm{L}^2}$ (OD and L are respectively the outer diameter and length of the PZT tube). As a sound projector, the PZT tube needs to operate near its fundamental resonance frequency to maximize the signal output. Because the JSATS transmitters operate at a fixed frequency of 416.7 kHz, the OD of the PZT tube is required to be in the range of 2.3-2.54 mm in order to achieve a hoop-mode resonance near that frequency. To reduce the size of the PZT transducer for a juvenile lamprey microtransmitter, we will identify the most efficient piezoelectric material and optimize the transducer design for maximum energy conversion and optimum beam patterns based on the application requirements and design alternatives identified in Objective 1 and 2.

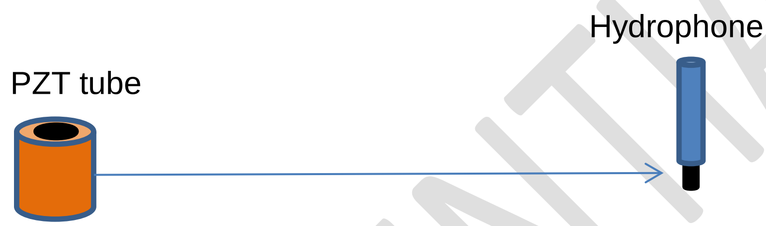

Fig. 2: The orientation of the PZT transducer relative to the hydrophone

6. Objective 6: Bio-evaluation

We will develop a procedure for implantation of the new transmitter that minimizes the time required for implantation and biological effects in juvenile lamprey. The results from this task will also provide guidance to the engineering team for the size range of downsize transmitters that meet project biological objectives. We will follow standard biological evaluation protocols and the Columbia Basin Surgical Protocol Committee tagging guidelines.

7. Objective 7: Forms

We will design form factors that permit transmitter shapes amenable to applications and alternatives identified in objectives 1 and 2. Due to the thin and flexible body of juvenile lampreys, further size and weight reduction is required. In addition, the transmitter may need some flexibility to match the natural movement of the juvenile lampreys.

PNNL has developed a proven moisture barrier solution that is light weight, flexible and is compatible with flexible lithium thin film batteries, aqueous and non- aqueous. For thin-film lithium battery applications there are two moisture barrier process methods that can be used to provide the required level of protection and flexibility. In one case the multi-layer barrier can be deposited directly on the thin film battery. In another the multi-layer barrier can be deposited on a thin light weight substrate and a pouch made for the battery as well as the entire tag (Figure 3). For this lamprey application the pouch would be preferred.

CONFIDENTIAL

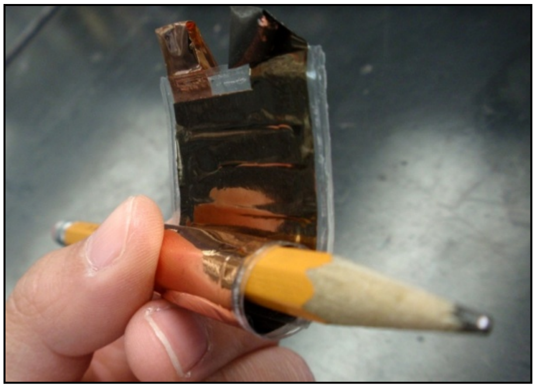

Figure 3 Thin film battery with flexible moisture barrier pouch sealing

8. Objective 8: Prototyping

Prototype transmitter with parts and form identified in objectives 1-8 and perform bench top and test tank evaluation to ensure that acoustic functions of the prototype transmitter meet the required specifications of the lamprey transmitters. Criteria and procedures for each test will follow the Evaluation/Selection Criteria document in USACE's procurement contract solicitation.

8.1. Make functional prototypes

8.2. Bench top testing

8.2.1. Dimensional: measure external dimensions and weight, and visually inspect for rough edges.

8.2.2. Environmental: Perform shock, vibration and pressure depth test followed by an operational test

8.2.3. Electrical: Measure battery voltage, battery internal resistance, Microprocessor current while on standby and transmitting mode, and transit interval.

8.3. Test tank in-water evaluation will be performed in an anechoic tank (Deng et al. 2010)

8.3.1. Frequency using a calibrated hydrophone (Reson TC4035, or equivalent) and data acquisition system

8.3.2. Transducer power level using calibrated hydrophone and data acquisition system

8.3.3. Pitch axis

8.3.4. beam pattern , +/-90 degrees every 10 degrees intervals using a calibrated hydrophone and data acquisition system

9. **Objective 9: Manufacturability**

Assess manufacturability of the parts and whole unit in qualities required for required for juvenile lamprey studies using the new acoustic microtransmitter.

9.1.1. Vendors

9.1.2. Cost and schedule

10. Objective 10: Laboratory and Field Trials with Juvenile Lamprey

10.1. In collaboration with the USACE and others develop experimental designs for laboratory and field trials,

10.2. Either perform or assist in the conduct of the laboratory and field trials as determined by the experimental designs.

11. Objective 11: Reporting

A review and final reports will be prepared. A review draft report will be submitted to USACE by the end of March 2015 and the final study report will be delivered by the end of June 2015. It will include:

CONFIDENTIAL

11.1.1. Documentation of the application space and derived transmitter specification for the lamprey transmitter

11.1.2. Circuit schematics of each integrated circuit design, layout in standard format ready for fabrication, documentation of the simulation results demonstrating the functionality and performance of each circuit, and documentation of laboratory test results of each fabricated integrated circuit design. Deliverable to be recast if necessary to meet requirements provided by USACE for inclusion of integrated circuit design and fabrication details in competitive procurement documents.

11.1.3. Documentation of the chemistry, output characteristics, energy capacity, and the laboratory standard testing results of each batteries design.

11.1.4. The design schematics of each form design, layout in standard format for fabrication, and documentation of the damp heat accelerated testing results of each transmitter form design. Deliverable to be recast if necessary to meet requirements provided by USACE for inclusion of transmitter form design and layout details in competitive procurement documents.

11.1.5. Documentation of prototyping process, bench top testing results, and test tank testing results of each downsized prototype transmitter.

11.1.6. Documentation of the manufacturability of the parts and whole unit in qualities required for juvenile lamprey studies using the lamprey transmitters. Deliverable to be recast if necessary to meet requirements provided by USACE for inclusion of transmitter manufacturability details in competitive procurement documents.

11.1.7. Documentation of encoding alternatives for the transmitters and associated estimated cost for implementation in order to allow flexibility in code space for USACE.

II.E. Schedule

- The first two tasks (The application space and design alternatives) for lamprey tag have been completed.
- The anticipated date for additional funding is November, 1 2014 at this time. The proposed project study period is from August 1, 2013 to June 30, 2018.
- First design (note that this will not be the final design) will be submitted for first round of prototyping by September 30, 2015.
- Final design will be submitted for prototyping by September 30, 2016.
- The final design and testing will be completed by December 31, 2016.
- A review draft report will be submitted to USACE by April 30, 2017
- The final study report for the design and testing will be delivered by July 31, 2017.
- Focused laboratory and field trials with juvenile lamprey will be completed by July 31, 2017, a review draft report will be submitted to USACE by March 2018, and the final study report will be delivered by June 30, 2018. This is only a placeholder for now.

III.A. Facilities and Equipment

PNNL have all of facilities and most of the equipment required for this project and will purchase about $20k equipment for batteries, coating, prototyping and testing.

III.B. Impacts

At this time no impacts to other projects have been identified.

III.C. Collaborative Arrangements and Sub-Contracts

This will be collaborative effort between USACE and DOE EERE Wind and Water Program office. DOE EERE Wind and Water Program office has committed $500k funding for FY15 and plans to continue at least at the same funding level until FY2017.

CONFIDENTIAL

IV. List of Key Personnel and Project Duties

PNNL Bio-Acoustics & Flow Laboratory (BAFL) is accredited by The American Association for Laboratory Accreditation (A2LA) to ISO/IEC 17025:2005, which is the international standard for calibration and testing laboratories. The scope (Certificate Number 3267.01) includes hydrophone sensitivity measurements and power level measurements of sound sources for frequencies from 50 kHz to 500 kHz for both military equipment and commercial components. This certification permits us to not only perform primary certified testing on instruments made by others but also permit us to perform certified testing on instruments that we build ourselves. This eliminates what can be a large external cost item and provides significant flexibility in the scope of acoustic work we may pursue in the future while maintaining the high standards expected of a national laboratory.

Our cross-organizational team consists of fisheries biologists, materials scientists, chemists, electrical engineers, and mechanical engineers. We have extensive experience with batteries development, microelectronics, and thin-film coating. In addition to our experience with development and instrumentation of JSATS (McMichael et al. 2010; Weiland et al. 2011; Deng et al. 2011; Brown et al. 2012; Deng et al. 2012), We developed and implemented an autonomous underwater sound recording device to monitor the underwater sound and pressure waves generated by anthropogenic activities such as underwater blasting and pile driving (Martinez et al. 2011). We also mapped the broadband acoustic Environment at a proposed tidal energy site in Puget Sound at different depths using a cabled vertical line array (Xu et al, 2012). We have successfully completed many large multi-disciplinary and multi-organizational projects. The PNNL team is eminently qualified to fulfill this project. Below are the bio-sketches of our key team members:

Dr. Daniel Deng, Principal Investigator, has been instrumental in the development and implementation of a new acoustic telemetry system for use on very small fish since 2004. He is a co-developer of the Juvenile Salmon Acoustic Telemetry System (JSATS) cabled system. He co-led the development of external and neutrally buoyant acoustic transmitters for turbine passage evaluation. Dr. Deng has supported the U.S. Army Corps of Engineers' Portland District efforts to competitively procure JSATS equipment by assisting in the development of technical specifications and leading the acceptance testing of prototype transmitters and receivers. He is the PNNL lead engineer for both the Snake River and Lower Columbia River multi-dam performance studies , leading or co-leading several tasks including equipment performance testing, tag life study, cabled data reduction, three-dimensional tracking and passage route assignment, and software and equipment development. Dr. Deng led a team consisting of chemists, batteries engineers, electrical engineers, mechanical engineers, materials scientists, and fisheries biologists, for the development of injectable acoustic microtransmitters for juvenile salmon. He has authored >50 peer-reviewed journal articles and >70 technical reports, and has given invited talks at a number of international conferences. He serves as an associate editor (responsible for hydroelectric energy) of the Journal of Renewable and Sustainable Energy, an editorial board member of Nature Scientific Reports, Sensor Letters, and PLOS ONE. Dr. Deng was selected as one of 78 outstanding young engineers (30-45 years old) in the nation to participate in the National Academy of Engineering (NAE)'s Annual Symposium on Frontiers of Engineering in September 2012. He was selected as one of 30 outstanding young scientist/engineers (30-45 years old) in the U.S. to participate in the National Academy of Sciences & NAE's first Brazil-US Frontiers of Science and Engineering.

V. Technology Transfer.

Technology transfer will be through reporting of study results in regional forums and in written reports. We will also follow the IP strategy created for the injectable transmitter development project.

References

CONFIDENTIAL

Close, D., Fitzpatrick, M.S., Li, H.W., Parker, B., Hatch, D., and G. James. 1995. Status report of the Pacific lamprey (Lampetra tridentata) in the Columbia River Basin. Report to the Bonneville Power Administration, Contract 95BI39067, Portland, OR.

Deng Z, MA Weiland, TJ Carlson, and MB Eppard. 2010. "Design and Instrumentation of a Measurement and Calibration System for an Acoustic Telemetry System." Sensors 10(4):3090-3099.

Deng Z, MA Weiland, T Fu, TA Seim, BL Lamarche, EY Choi, TJ Carlson, and MB Eppard. 2011. "A Cabled Acoustic Telemetry System for Detecting and Tracking Juvenile Salmon: Part 2. Three-Dimensional Tracking and Passage Outcomes." Sensors 11(6):5661-5676.

Deng Z, JJ Martinez, AHA Colotelo, TK Abel, AP LeBarge, RS Brown, BD Pflugrath, RP Mueller, TJ Carlson, A Seaburg, RL Johnson, and ML Ahmann. 2012. "Development of External and Neutrally Buoyant Acoustic Transmitters for Juvenile Salmon Turbine Passage Evaluation." Fisheries Research 113(1):94-105.

Deng Z, et al. 2014. Performance Evaluation of the Newly Developed Injectable JSATS Transmitter. PNNL-23261, Pacific Northwest National Laboratory

Dauble DD, RA Moursund, and MD Bleich. 2006. "Swimming behaviour of juvenile Pacific lamprey, Lampetra tridentata." Environmental Biology of Fishes 75(2):167-171.

Jager, H. I., B. Elrod, N. Samu, R. A. McManamay, and B. T. Smith. "ESA Protection for the American Eel: Implications for US Hydropower." (2013). http://info.ornl.gov/sites/publications/files/Pub45569.pdf

Kareiva, P., Marvier, M., and M. McClure. 2000. Recovery and management options for spring/summer chinook salmon in the Columbia River Basin. Science 290:977–979.

Martinez JJ, JR Myers, TJ Carlson, Z Deng, JS Rohrer, KA Caviggia, CM Woodley, and MA Weiland. 2011. "Design and implementation of an underwater sound recording device." Sensors 11(9):8519-8535.

McMichael GA, MB Eppard, TJ Carlson, JA Carter, BD Ebberts, RS Brown, MA Weiland, GR Ploskey, RA Harnish, and Z Deng. 2010. "The Juvenile Salmon Acoustic Telemetry System; A New Tool." Fisheries 35(1):9-22.

Meduri P, H Chen, X Chen, J Xiao, ME Gross, TJ Carlson, J Zhang, and Z Deng. 2011. "Hybrid CFx-Ag2V4O11 as a high-energy, power density cathode for application in an underwater acoustic microtransmitter." Electrochemistry Communications 13(12):1344-1348.

Mueller RP, RA Moursund, and MD Bleich. 2006. "Tagging Juvenile Pacific Lamprey with Passive Integrated Transponders: Methodology, Short-Term Mortality, and Influence on Swimming Performance." North American Journal of Fisheries Management 26(2):361-366.

Muir, W. D., S. G. Smith, J. G. Williams, E. E. Hockersmith, and J. R. Skalski. 2001. Survival estimates for migrant yearling Chinook salmon and steelhead tagged with passive integrated transponders in the lower Snake and Columbia rivers, 1993-1998. North American Journal of Fisheries Management 21:269-282.

Moursund RA, DD Dauble, and M Langeslay. 2003. "Turbine Intake Diversion Screens: Investigating Effects on Pacific Lamprey." Hydro Review XXII(1):40-46.

CONFIDENTIAL

US Fish and Wildlife Service. 2011. Endangered and Threatened Wildlife and Plants; 90-Day Finding on a Petition To List the American Eel as Threatened. http://www.gpo.gov/fdsys/pkg/FR-2011-09-29/pdf/2011-25084.pdf

Weiland MA, Z Deng, TA Seim, BL Lamarche, EY Choi, T Fu, TJ Carlson, AI Thronas, and MB Eppard. 2011. "A cabled acoustic telemetry system for detecting and tracking juvenile salmon: Part 1. Engineering design and instrumentation." Sensors 11(6):5645-5660.

Xu J, Z Deng, JJ Martinez, TJ Carlson, JR Myers, and MA Weiland. 2012. "Broadband Acoustic Environment at a Tidal Energy Site in Puget Sound." Marine Technology Society Journal 46(2):65-73.

CONFIDENTIAL