Pacific Northwest
NATIONAL LABORATORY

PNNL-36555

Enhancing Lifetime and Reducing Costs for Fish Diversion Netting Structures

Final report for CRADA 529

September 2024

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U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

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NOTICE

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Pacific Northwest National Laboratory
Richland, Washington 99354

Cooperative Research and Development Agreement (CRADA) Final Report

Report Date: September 2024

In accordance with Requirements set forth in the terms of the CRADA, this document is the CRADA Final Report, including a list of Subject Inventions, to be provided to PNNL Information Release who will forward to the DOE Office of Scientific and Technical Information as part of the commitment to the public to demonstrate results of federally funded research. **PNNL acknowledges that the CRADA parties have been involved in the preparation of the report or reviewed the report.**

Parties to the Agreement:

Battelle Memorial Institute, Operator of Pacific Northwest National Laboratory under its

U.S. Department of Energy Contract No.DE-AC05-76RL01830

AND

Dry Surface Technologies LLC

AND

Lorama Group Inc.

AND

Pacific Netting Products

AND

Prometheus Innovations LLC

AND

River Connectivity Systems, LLC

AND

Taylor Shellfish Company, Inc.

CRADA number: 529

CRADA Title: Enhancing Lifetime and Reducing Costs for Fish Diversion Netting Structures

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Sponsoring DOE Program Office(s):

Office of Technology Transitions

Water Power Technologies Office

Joint Work Statement Funding Table showing DOE funding commitment:

	Funding Amounts			
CRADA Parties	**DOE Funding**	**Funds-In**	***In-kind**	**Total**
Participant(s)	N/A	N/A	$230,000	$230,000
DOE Funding to PNNL	$220,000	N/A	N/A	$220,000
Total of all Contributions	$220,000	$0	$230,000	$450,000

Provide a list of publications, conference papers, or other public releases of results, developed under this CRADA:

Presentation of research results at the Clean Currents 2023 conference in Cincinnati, OH on October 11, 2023.

MCount software to accurately count mussel larvae in images was open-sourced 10/17/2023 and is available at https://github.com/pnnl/MCount.

Provide a detailed list of all subject inventions, to include patent applications, copyrights, and trademarks:

This agreement resulted in a new invention disclosure: “A simple one-step process for paintable superhydrophobic lubricant infused composite surface”, IPID 32854-E. Submitted 8/21/2023.

Executive Summary of CRADA Work

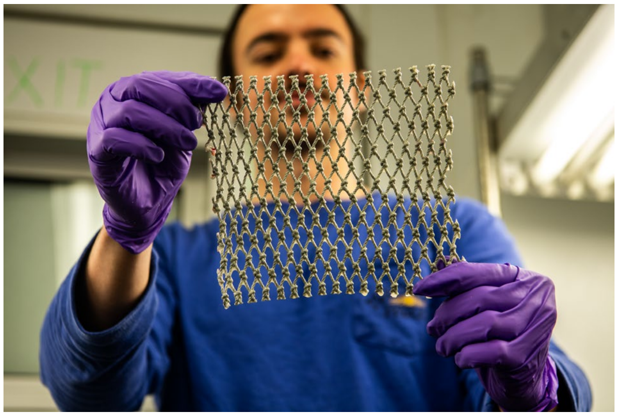
In this effort Pacific Northwest National Laboratory (PNNL) developed and demonstrated an anti-fouling coating that is effective on fish diversion structures. The coating was based on a previously developed superhydrophobic lubricant infused composite (SLIC) coating but modified for application to flexible substrates. We showed that the new reformulated coating – FlexiSLIC – can be applied to flexible fibrous structures to significantly reduce biofouling of netting and anchor lines, to enable longer operational lifetimes, reduced costs, and more reliable operations. The coating developed in this effort was tested on relevant fish diversion structural netting and rope materials (e.g. nylon, Dyneema, polypropylene) to reduce biofouling. Engagement with industry in the development and demonstration further supported progress toward commercialization of the materials. Specifically, the project addressed the following technical and commercialization issues:

• Adhesion to flexible structures. A key challenge for non-stick foul resistant coatings is developing a method to make the coating stick to the surface of interest.

• Application process. This effort investigated cost effective application processes for the tightly woven 3D structure of nets and rope.

• Durability and lifetime. The durability of the coating was validated under realistic environmental conditions including flexing, bending, impinging debris, etc.

• Environmental compliance. Previous efforts demonstrated that our coating materials are non-toxic, and the new coating developed in this effort was tested for its overall toxicity.



The coating developed under this effort, FlexiSLIC, can be applied to netting to prevent attachment of invasive mussels. Credit: Andrea Starr, PNNL.

Currently, fish diversion netting is not protected with a fouling resistant coating. Fouling on netting is extensive and difficult to remove, resulting in hydropower facilities replacing netting on an annual basis. Further, in river systems infested with invasive zebra and quagga mussels, netting structures provide a substrate that promotes the growth of these species. The economic impact of invasive zebra and quagga mussels in the U.S. is between \$100M-\$1B/year in operations and maintenance costs, not including secondary environmental impact costs.

This project matured (from TRL 3 to 5) a coating with the unique ability to function on flexible and elastomeric materials, including netting and rope. This effort built partnerships between PNNL and private companies to optimize, mature, demonstrate, and commercialize the PNNL-developed technology to addresses a critical coating need of the hydropower industry to protect fish diversion netting and mooring lines. As a result of the work conducted in this effort, several commercial partners have agreed to continue developing, testing, and deploying the FlexiSLIC technology. A commercial license is expected to follow.

Acknowledgments

PNNL acknowledges funding from the US Department of Energy's Office of Technology Transitions through the Technology Commercialization Fund. This work is the result of award number TCF-21-25067.

PNNL also wishes to acknowledge the collaboration and participation of Dry Surface Technologies, Lorama Group, Prometheus Innovations LLC, BioBlend Renewables LLC, Taylor Shellfish Farms, Pacific Netting Products Inc, and the US Bureau of Reclamation.

Acronyms and Abbreviations

ASTM: American Society for Testing and Materials
BOR: Bureau of Reclamation
CRADA: Cooperative research and development agreement
DOE: Department of Energy
FlexiSLIC: Flexible Superhydrophobic Lubricant-infused Composite
Inc: Incorporated
IP: Intellectual property
LLC: Limited liability corporation
O&M: Operation and maintenance
PNNL: Pacific Northwest National Laboratory
POC: Point of contact
SLIC: Superhydrophobic lubricant-infused composite
TCF: Technology Commercialization Fund
TRL: Technology readiness level

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1.0 Project Summary

This effort focused on technology transfer and commercialization of antifouling coatings with the support of an engaged and collaborative industrial team. Environmental requirements and operational demands call for a nontoxic coating/paint to prevent fouling on fish passage guidance netting at hydropower facilities. For example, one netting customer estimated the capital cost for compliance at $12 million to $15 million. This project built partnerships between PNNL and private companies to optimize, demonstrate, mature, and commercialize a novel PNNL-developed technology that addresses this critical coating need of the hydropower industry. The effort modified existing PNNL-developed coating technology for application to flexible netting structures.

With focus on commercialization, the project team leveraged prior experience in the Energy I-Corps program. Industrial partners included commercial coating development specialist (Lorama), hydrophobic material manufacturer and paint developer (Dry Surface Technologies), nontoxic biodegradable lubricants manufacturer (BioBlend), aquatic applications specialist (Prometheus Innovations), and hydropower netting producer (Pacific Netting Products). Engagement with the US Bureau of Reclamation (BOR), a hydropower operator, throughout the project provided expertise on real-world performance requirements. Taylor Shellfish Farms provided organisms and fouling expertise as well as a perspective of potential broader impacts for the blue economy. Coated netting samples were tested to demonstrate performance in a range of environments for key hydropower applications. PNNL worked with industrial partners to overcome commercialization barriers as well as beginning to address manufacturing and regulatory issues.

1.1 Product Innovation, Target Market, Value Relative to Existing Products/Solutions

PNNL's antifouling coating technology is novel and transformative. Prior testing by PNNL and others has shown *no cost-effective technology presently exists in the commercial market* to prevent colonization of hydropower structures, including fish diversion netting, by invasive mussels and other types of damaging organisms that contribute to biofouling. New cost-effective and environmentally acceptable (nontoxic) antifouling coatings are needed for this target market. Fish guidance and exclusion systems and structures are critical operational components of many hydroelectric facilities. They are often required to meet legal, regulatory, environmental, social requirements and can affect economic viability of power production through both their capital cost and operations and maintenance expenses.

Growth of organisms on these structures, and the associated weight, drag, and in some case head loss, result in increased loading and reduced power generation, increased operations and maintenance expenses and decreased life of the structure or system. A coating on these structures that prevents biological fouling would result in significant cost savings, increase reliability, and allow industry to respond to the legal, regulatory, environmental, and social requirements of hydropower energy production.

The EPRI *Report Design Considerations and Specifications for Fish Barrier Net Deployment at Cooling Water Intake Structures* (October 2006) confirmed that "a barrier net is a relatively inexpensive alternative when compared to other options." However, operation and maintenance (O&M) issues have limited successful deployment of barrier nets at some sites as a result of aquatic growth. Current coatings to prevent fouling typically have short installed life (1 year) and have negative effect on the performance of the dynamic surfaces that flex or stretch. Without competing products, as well as a large and growing (literally) problem there is an enormous commercial opportunity for environmentally compliant anti-fouling coatings. Application of protective coatings is already a part of regular maintenance at hydropower facilities, but netting poses a new challenge due to the flexible nature and harsh environment. The new approach developed in this effort would provide an environmentally acceptable solution and enable significant cost savings.

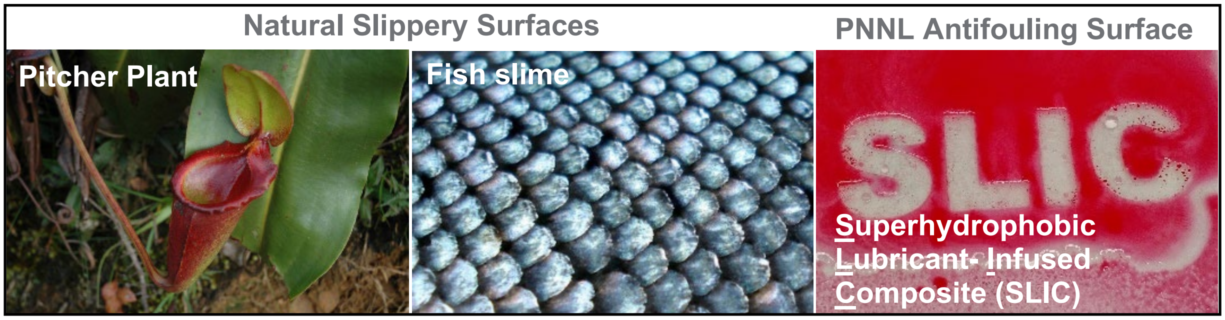

Figure 1: PNNL's antifouling coating is inspired by nature's best fouling prevention strategies. The pitcher plant (left) has a slippery liquid surface at its lip that helps it capture insect prey. Fish scales (center) have a patterned microtexture and surface layer of slippery slime to prevent adhesion. Fine texture on SLIC coating is similar to the self-cleaning lotus leaf helps to retain and stabilize the slippery liquid at the surface of the coatings.

PNNL has developed and patented a novel coating technology that represents a significant advance in materials engineering. *Superhydrophobic Lubricant Infused Composite (SLIC)* technology uniquely combines multiple antifouling mechanisms to provide good performance without using toxic materials. Using an inexpensive nontoxic polymer, with the lowest known adhesion, a sprayable coating has been created that has a "slippery" surface. The slippery surface is the result of an infusion of a nontoxic biodegradable lubricant. This creates a surface that resembles those found in nature (Figure 1) and has been shown to be resistant to mussel colonization. In addition to being durable, economical, and nontoxic, the coating is self-healing and has a low-friction surface that maintains good hydrodynamics. Results prior to the start of this work showed SLIC to be resistant to fouling from a large range of organisms. A prior Phase 1 TCF effort determined the coating was effective at reducing mussel settling and adhesion. That effort resulted in significant development toward an effective antifouling coating for hard surfaces. The goal with this effort was to adapt the SLIC technology for fish passage guidance netting to help hydropower facilities to keep operating costs low while maintaining peak power potential and environmental stewardship.

1.2 Competing Technologies and Barriers Impacting Product Acceptance:

Currently, fish passage guidance netting is not protected with a fouling resistant coating. Many existing antifouling coatings use environmentally unacceptable toxic materials and are designed for application on rigid surfaces. Paints that release toxic metals and other poisons have been effective but contaminate waterways and are discouraged or illegal due to environmental concerns. Once matured, FlexiSLIC will provide a simple nontoxic solution that will mitigate the impact of fouling at a lower cost than existing maintenance and replacement practices.

The Energy I-Corps efforts by team members extensively explored competing technologies as well as barriers to adoption and market issues for this new coating. Insights from our prior and separate Phase 1 efforts and in-depth conversations with the expanded industrial team identified remaining barriers to product commercialization. This effort addressed commercialization challenges including:

- Enhanced durability, operational lifetime of coating, and functionality of the coatings when applied to flexible rope/netting
    - Specific requirement for hydropower, not required by larger commercial markets, include coatings effective on surfaces exposed to low flow velocities (< 5 m/s).
- Demonstrated sustained coating performance under field conditions relevant to hydropower operations.
    - A key to customer acceptance is demonstrated performance of the product. Fortunately, engagement with partners provided a large range of field-testing options to enable extending operational testing and performance demonstrations.
- Addressed regulatory issues necessary for production.

In summary, our Energy I-Corps work gave us an extensive knowledge of user needs as well as the competing approaches available to solve hydropower's specific needs to combat fouling on fish passage guidance netting. The barriers impacting product acceptance with users and our industrial partners led to plans to address the challenges and issues involved in bringing this technology to market.

1.3 Enabling Technology Maturation and Commercial Success

This effort was focused on technology optimization for application to fish passage guidance netting and technology validation as verified by independent testing. The goal of this effort was to demonstrate FlexiSLIC for netting applications at technology readiness level (TRL) 5. The field test data collected in this effort will allow optimization of FlexiSLIC formulation and performance which is key to enabling technology transfer of a mature proven technology to industry and production of a viable commercial product specifically focused for hydropower needs.

For commercial success, the new technology must appeal to a broader range of applications for manufactures to significantly engage. Fortuitously, Energy I-Corps interviews with industry discovered many related applications and significantly expanded the commercial market for the coating. In these conversations we identified many markets for a nontoxic, nonstick, inexpensive durable coating that can be simply applied (spray or paint) to flexible surfaces like ropes and netting. These larger markets segments are key in helping support product development for hydropower needs.

1.4 Technical Background

Fish passage guidance netting structures are important operational components for many hydroelectric facilities and are expensive to purchase and maintain. Growth of organisms on these fish passage guidance netting (see Figure 2) is the leading cause for degradation and is responsible for much of the replacement and maintenance costs. A coating on these structures that prevents biological fouling would result in significant cost savings while improving the reliability and lifetime of the structures.

Figure 2: Heavily fouled netting placed at a water intake.

Current coatings to prevent fouling typically form a hard, heavy, inflexible layer that is not suitable for dynamic surfaces such as ropes, nets, and other materials that flex or stretch. This effort adapted and demonstrated an antifouling coating that is effective on flexible fish passage guidance structures. The FlexiSLIC coating must have the ability to be applied to flexible fibrous structures and significantly reduce biofouling on netting, anchor lines, etc., to enable longer operational lifetimes, reduced costs, and more reliable operations.

To be successful FlexiSLIC must be tested on relevant fish passage guidance netting and rope materials (e.g., nylon, Dyneema, polypropylene, polyethylene) to reduce biofouling. Fish barrier nets have been successfully installed at hydroelectric projects and thermoelectric power plants to exclude fish from water intakes. Barrier nets are considered a viable method to meet Phase II of the Clean Water Act §316(b) impingement mortality reduction standard (80% to 95% mortality reduction) and have been shown to be 84% to 98% effective. An effective antifouling coating that reduces biological growth on these netting structures, while remaining compliant with the Clean Water Act, would result in significant cost savings and improved reliability for fish passage guidance netting.

1.5 Technology Development and Commercialization Efforts

The SLIC coating was developed and demonstrated in laboratory tests at PNNL beginning in 2015. Early lab experiments showed the ability of the lubricant coating to shed water and prevent adhesion of a range of organisms including mussels. SLIC coatings were initially developed for a niche marine application and commercialization was focused on marine antifouling coatings for ships and other vessels. The coating was adapted for use in hydropower and marine hydrokinetic facilities through a fiscal year 2019 TCF Phase 1 award. This effort also conducted extensive testing to demonstrate the ability of the coating to prevent invasive mussel adhesion. In 2020 the project team completed the Energy I-Corps training with the SLIC technology as the focus.

The netting market has technical requirements that were not met by SLIC. When considering application to flexible netting, the technology is at TRL 3 and this effort was designed to mature and demonstrate the technology to TRL 5. At the conclusion of this effort, it is expected that commercial companies will have confidence to commit to final product development, scale-up, and commercialization. Thus, the aim was to optimize SLIC coatings for use on fish passage guidance netting and demonstrate resistance to colonization fouling organisms.

2.0 Project goals and objectives

This project aimed to mature and demonstrate PNNL proprietary coating technology for mitigating fouling on fish passage guidance netting at hydropower facilities. The following specific objectives and tasks were aimed at maturing a promising laboratory technology and rapidly removing barriers to commercialization.

Specific Objectives:

- Develop and demonstrate flexible, durable, nontoxic, light-weight antifouling coating for barrier netting and other relevant hydropower surfaces
- Optimize coating for minimal cost and weight
- Develop and capture new IP (building on prior IP) to provide secure licensing opportunities
- Engage industrial partners to enable technology transfer and commercialization in the next phase
- Engage stakeholders to facilitate acceptance and environmental compliance of technology

2.1 Project Plan

The project addressed the following technical risks:

- Adhesion to flexible structures. A key challenge in applying a non-stick foul resistant coating is developing a method to make the coating stick to the surface of interest.
- Application process. There is a need for a cost-effective application processes for the tightly woven 3D structure of nets and rope.
- Durability and lifetime. The durability of the coating must be validated under realistic environmental conditions including flexing, bending, impinging debris, etc.
- Environmental compliance. The market for antifouling coatings is trending strongly to nontoxic foul release systems. Any new coating must be tested for its overall toxicity.

The following tasks were designed to address key technical and commercial risks or barriers that would prevent FlexiSLIC from being used on fish guidance netting

Task 1. Modify existing SLIC coating for application and adhesion to flexible rope/netting

- Tailor chemistry and physical structure for compatibility with flexible substrates
- Evaluate any new component materials and coatings for toxicity.
- Test new coating(s) for adhesion to relevant surfaces with the ASTM D3359 method.

Task 2. Laboratory characterization, performance testing, and optimization of coating variations

- Critical physical properties of the coatings measured include: tensile strength, hardness, durability to abrasion and damage, flexibility, surface adhesion, and contact angle (a measure of hydrophobicity and nonstick surface properties). Coatings are compared to standard and best in class industrial materials. Focus is to improve coating structure for longevity, durability and antifouling performance.

Task 3. Biological performance testing in a field environment

- The best coatings identified from lab tests are tested at in field conditions, including operational fish passage guidance netting. Samples will also be sent to Taylor Shellfish Farm for testing in commercial environments.

The project was formulated to minimize technical and commercial risks. Commercial risks are mitigated by using inexpensive, common paint components and traditional application methods to keep costs low and aligned with existing expenses. Commercialization risks are mitigated by engaging potential industrial partners early and on a regular basis as well as having a highly experienced technology licensing/commercialization professional on the team. The project collaborated with BOR, providing early engagement with the largest future users to facilitate acceptance and early adoption of a new netting product. Creating a new solution to mitigate fouling without the use of toxic materials is challenging. To maximize the probability of success we combined multiple proven antifouling mechanisms into a coating that is damage resistant and has self-healing capabilities.

2.2 Team and Resources

This effort integrated a multidisciplinary project team of experts supported with world class scientific facilities. It included major hydropower operators (BOR) who understand and routinely address fouling problems on fish passage guidance netting. This effort was supported by a team of cost share partners that represent a significant portion of the ecosystem for coatings for hydropower applications. For example, Dry Surface Technologies and BioBlend will supply raw materials to feed into PNNL's coating formulation. Lorama and Prometheus Innovations have experience bringing novel coatings to market. Pacific Netting Products is actively building and maintaining fish passage guidance nets at hydropower facilities across the US. BOR operates hydropower facilities and are the end user of foul-resistant nets.

Lorama Group, Inc. is a leading manufacturer and distributor of colorants and additives in the paints and coatings industry. They specialize in manufacturing and distribution of custom coating solutions. Lorama focused on optimizing PNNL's coating formulation for commercialization, addressing issues related to storage, distribution, and application.

Prometheus Innovations, LLC is a science and technology consultancy with diverse expertise in robotics, renewable energy, and fish protection. Prometheus is a former DOE Fish Protection Innovation Prize award winner who is developing technology to remotely monitor integrity of fish protection netting.

Pacific Netting Products, Inc. is the industry leader in design, construction, installation and service of exclusion, guidance, and collection solutions to protect, guide and keep fish healthy as they migrate downriver past hydroelectric dams.

Dry Surface Technologies, LLC makes custom formulations of superhydrophobic additives under the name Barrian in both powder and liquid forms to improve the performance of a wide range of paints, coatings, and other materials. They harness the power of superhydrophobic technology to protect surfaces from water, ice, and corrosion challenges faced by energy producers operating in extreme environmental conditions and provided sample materials to integrate PNNL's coating technology.

BioBlend Renewables LLC is a leading producer of environmentally friendly lubricants used for a variety of applications. BioBlend provided lubricants for testing.

BOR is the second largest operator of hydropower dams in the US. PNNL will collaborate with BOR for field testing of coated netting samples at Parker Dam on the Colorado River and leverages BOR staff expertise and experience with antifouling coatings.

Taylor Shellfish Farms, Inc. has been farming in the waters of the Puget Sound for 130 years. They use nets, ropes and other flexible structures to sustainably raise oysters, clams, and mussels. Taylor provided mussels for laboratory testing and insight as a commercial user of ropes and nets for aquaculture.

3.0 Research results

3.1 Modification of SLIC coating for netting application

The main technical objective of this effort was to modify the formulation of the superhydrophobic lubricant infused composite coating that was previously developed at PNNL. The prior formula was designed for flat rigid surfaces. For the applications targeted in this effort (netting and ropes) a more flexible coating was required. Thus, under this effort FlexiSLIC was developed. The formulation, which includes a binding polymer, two different particles, and a lubricant, was changed to allow for more flexibility and for adhesion to surfaces with different chemical makeup. The details of these modifications were described in an invention disclosure and forthcoming patent application.

3.2 Laboratory characterization of coating variations

3.2.1 Abrasion

Fish diversion structures are moved around often during deployment and subsequent service, and this motion puts these structures in direct contact with other hard surfaces, which will damage their surfaces after repetitive rubbing. Coatings applied to ropes and nets will fall prey to similar abrasive forces, and thus, their resistance to abrasion must be quantified. The abrasion resistance of FlexiSLIC and a commercial competitor Intersleek 1100SR was measured according to ASTM D4060. Samples of each material were coated on 3 in x 3 in acrylic squares (five replicates each) using a 10 mL pipette. Samples were placed into an Elcometer 1720 Abraser (Elcometer USA, USA) and sandpaper (120 grit) was cut into 4 cm x 7.62 cm rectangles and fastened to the universal sample tool (Elcometer USA, USA). Parameters for the abrasion cycles were as follows: stroke length – 45 mm, speed – 54 cycles/minute, mass on sample tool – 500 g, number of total cycles – 1000. Every 100 cycles, the machine was stopped, and the sandpaper on the universal sample tool and the sample coating’s surface were brushed with a 4-inch paint brush and a Kimwipe respectively. Mass of coating plus substrate was recorded before and after 1000 abrasion cycles, and the percent mass retention was reported. FlexiSLIC lost slightly more mass during the abrasion cycles when compared with Intersleek 1100SR with a 3% difference in mass retention (Figure 3). This level of mass loss was expected as flexibility naturally trades off with abrasion resistance. A more rigid coating can be more abrasion resistant, but it will not be flexible enough for application on netting. We concluded that the level of abrasion resistance observed in this test was sufficient. In the future, abrasion resistance of FlexiSLIC could easily be raised, though only if a high level of flexibility is not required.

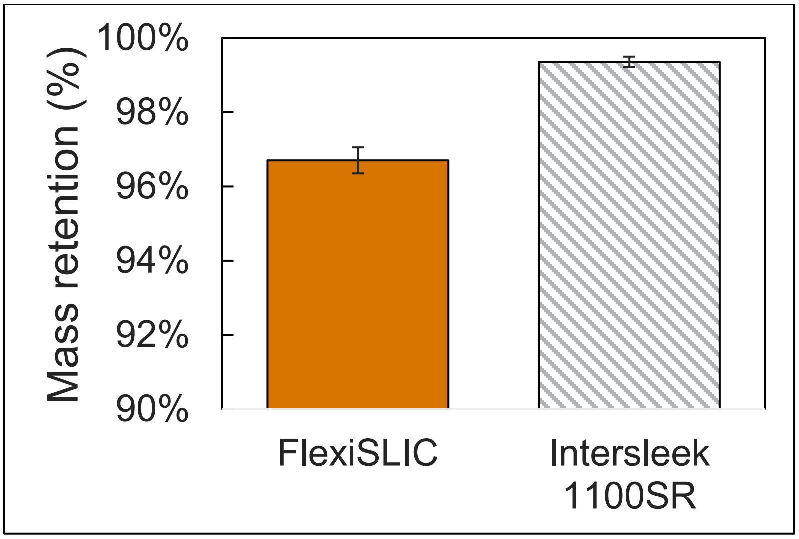

Figure 3: Mass retention of FlexiSLIC and Intersleek 1100SR coated on acrylic coupons after 1000 abrasion cycles. Sample size for each material was n = 5.

3.2.2 Adhesion

Aquatic coatings are effective only when they are securely attached to their underlying substrate. Reduced adhesion can lead to partial delamination, or worse, total detachment of the coating from the underlying substrate, which is why the adhesive forces between a coating and its substrate must be measured. Adhesion for FlexiSLIC is especially challenging because the substrate materials typically have unique woven structures and are made of synthetic plastics that have lower surface energy than concrete or steel. Use of a primer to aid adhesion is not desirable as it complicates the application process and thickens net strands that are already controlled to achieve desired hole sizes. The adhesion strength of FlexiSLIC and Intersleek 1100SR to polypropylene was measured according to ASTM C1583 using a PosiTest AT-A adhesion tester (DeFelsko, USA). FlexiSLIC and Intersleek 1100SR were applied to 3 in x 3 in, sanded polypropylene squares (three replicates each) using a 3/8-inch camel hair brush. 50 mm aluminum dollies (DeFelsko, USA) were sanded with 50 grit sandpaper prior to application of cyanoacrylate glue. Permabond POP Primer (Chemical Concepts, USA) was sprayed on the surface of the samples 1-2 min prior to adhesion of the dollies to the coatings. Permabond 268 cyanoacrylate (Chemical Concepts, USA) glue was applied to the bottom of the aluminum dollies until they were entirely covered (~40 drops), and then the dollies were placed onto the samples with light pressure applied to ensure complete glue coverage. The glue was allowed to cure for a minimum of two days, after which a 50 mm serrated cutting tool (DeFelsko, USA) was used to separate the glued coating perimeter from the rest of the coating and the PosiTest adhesion test was executed on the prepared samples. FlexiSLIC adhered to the polypropylene substrate better than Intersleek 1100SR (Figure 4).

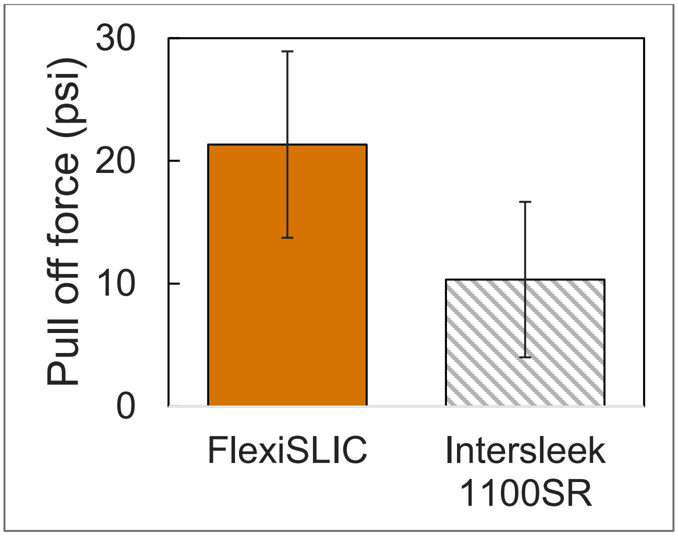

Figure 4: Pull off force of FlexiSLIC and Intersleek 1100SR coated on polypropylene coupons. Sample size for each material was n = 3.

3.2.3 Contact angle

Curating a proper surface chemistry for an antifouling coating is key to maximizing its antifouling potential because it changes the way the coating interacts with water and aquatic fouling organisms. One key metric in surface chemistry is surface energy, which is inversely proportional to hydrophobicity (contact angle) and proportional to roll off angle. A low surface energy will yield high hydrophobicity and a low roll off angle, which will reduce aquatic fouling. The water contact angle, roll off angle, and surface energy of FlexiSLIC and Intersleek 1100SR were measured using a ramé-hart model 590 goniometer. Coatings were applied to 1 in x 1 in acrylic coupons with a a10 mL pipette (five replicates each). Water was used for the water contact angle and roll of angle, and diiodomethane was used alongside the Owens-Wendt Theory to calculate surface energy. FlexiSLIC had a higher water contact angle, lower roll off angle, and lower surface energy than Intersleek 1100SR.

Table 1: Water contact angle, roll off angle, and surface energy of FlexiSLIC and Intersleek 1100SR

Coating	Water Contact Angle (deg)	Roll off Angle (deg)	Surface Energy (mJ/cm^2)
FlexiSLIC	85	18	24
Intersleek 1100SR	68	25	34.5

3.2.4 Flexibility

Flexible aquatic surfaces are regularly bent and moved in ways that require any applied coating to also be pliable. FlexiSLIC was coated on a 1/8-inch nylon rope and one half of the rope was bent back and forth 360°, five times. No visible detachment of the coating from the rope was noted (Figure 5) and antifouling efficacy of bent ropes was subsequently measured (see Figure 8).

Figure 5: FlexiSLIC coated on nylon rope and bent. This illustrates the ability of the coating to flex as required for application on netting and ropes.

3.2.5 Tear Resistance

In any body of water, there are debris and other objects present that may cause damage to coatings on deployed aquatic structures. One mode of damage is tearing where an object gets caught on a coating, and a sliver (or more) of the coating rips off due to the applied force. The tear resistance of FlexiSLIC and Intersleek 1100SR was measured according to ASTM D264-00. A 10 mL pipette was used to transfer FlexiSLIC and Intersleek 1100SR onto a 6 in x 6 in stainless steel square with a 2B mill finish (five replicates each). A razor blade was used to cut the proper shape out of the coated steel coupon with a 3D-printed stencil on top of the coating. The sample was then peeled off the steel coupon and pulled to failure in a Mark-10 ESM303 force test stand (Mark-10, USA) using a Shimpo FG-3003 10 N force gauge (Shimpo, USA) at 330 mm/min pull speed. The failure strength was recorded and thickness of the sample was measure prior to the experiment to report tear strength per unit thickness. FlexiSLIC exhibited greater resistance to tearing than Intersleek 1100SR as seen in Figure 6.

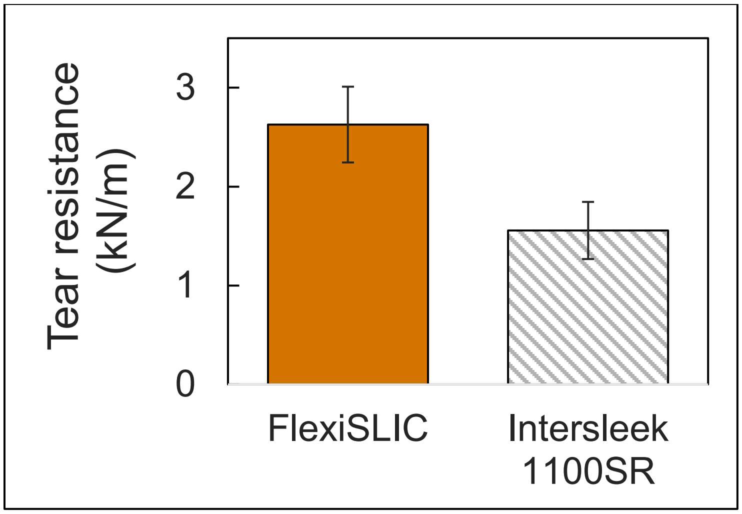

Figure 6: Tear resistance of FlexiSLIC and Intersleek 1100S. Sample size for each material was n = 5.

3.3 Biological performance testing

3.3.1 Mussel larvae testing

The performance of fish diversion nets dramatically decreases if their holes become clogged with aquatic fouling, and antifouling coatings can help prevent this buildup of micro and macroorganisms. The antifouling efficacy of FlexiSLIC was measured against uncoated ropes using PNNL's novel mussel larvae assay. FlexiSLIC was coated on 9-inch sections of 1/8-inch Dyneema and polypropylene rope and were placed into a 76-liter aquaria with uncoated Dyneema and polypropylene ropes (five replicates each) during two separate experiments. The aquaria were kept at 30 ppt salt concentration and ~700,000 mussel larvae (*Mytilus galloprovincialis*) were added into the tank. Larvae were fed 4 mL of Reef Phytoplankton every other day. Ropes were spaced out evenly throughout the tank and were exposed to mussel larvae for one week before data collection (Figure 7). After the exposure period, a 3-inch portion of the middle of each rope was photographed, and the larvae present on each rope were counted manually. Some of the coated ropes were bent (as described in section 3.2.4) before mussel larvae exposure. Both normal FlexiSLIC ropes and bent FlexiSLIC ropes had less mussel larvae on their surfaces than the uncoated Dyneema ropes did after one week of larval exposure (Figure 8). FlexiSLIC coated polypropylene ropes were also effective against reducing mussel larvae settlement when compared with uncoated polypropylene ropes (Figure 9) and a picture of each sample type can be seen in Figure 10.

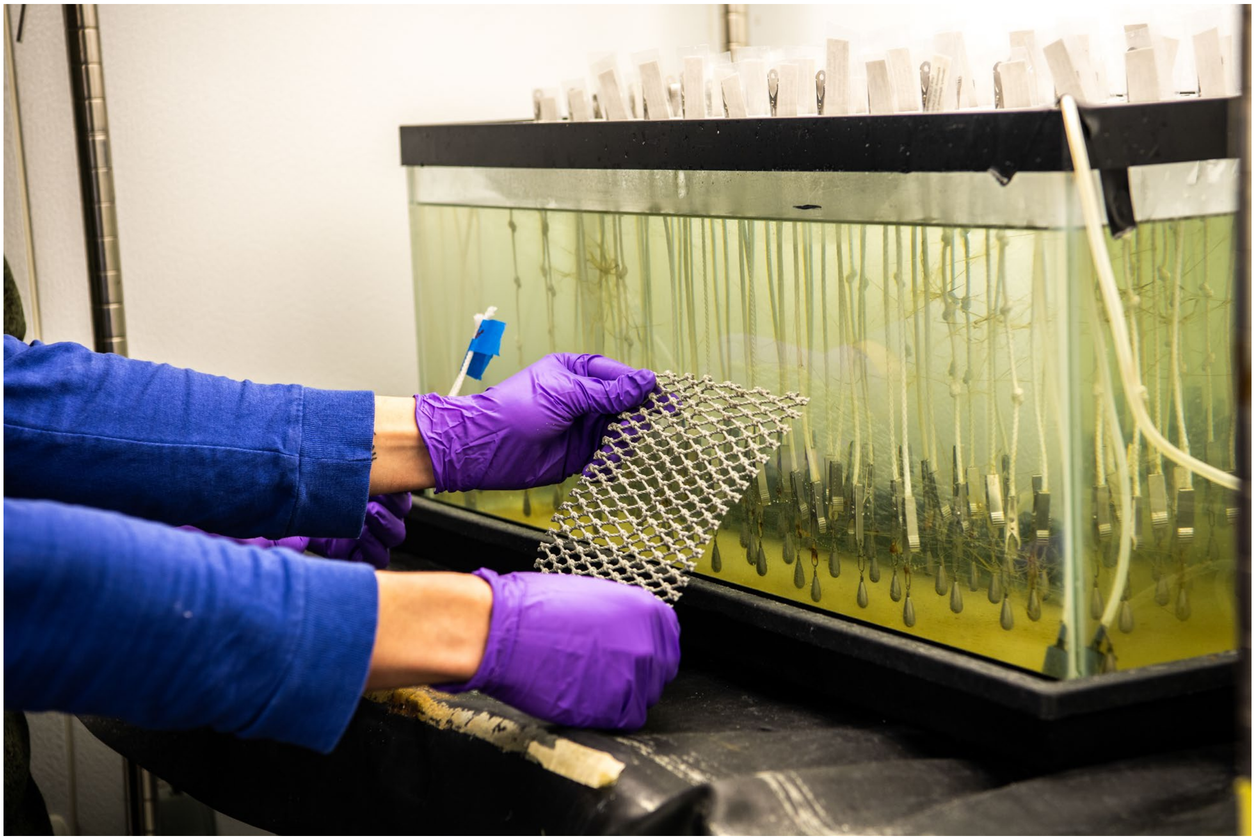

Figure 7: Dyneema and nylon ropes (coated with FlexiSLIC and uncoated) in an aquarium during a mussel larvae assay test. Webs of sticky proteins secreted by the larvae can be seen between many ropes.

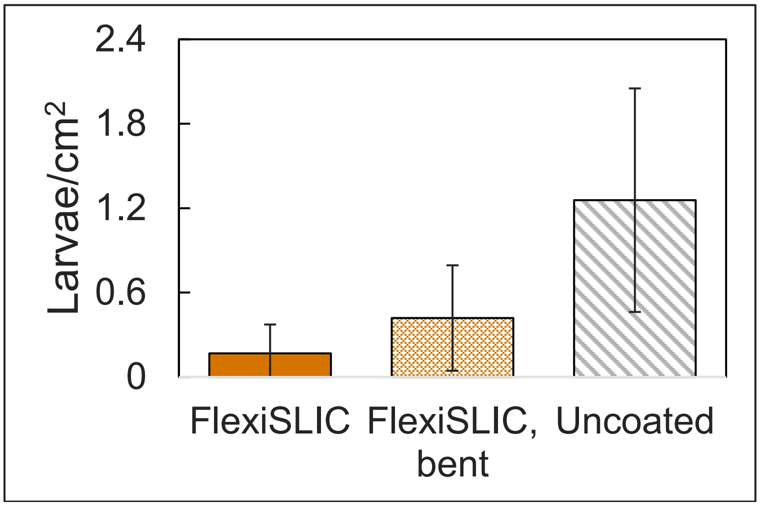

Figure 8: Mussel larvae assay performed on bent and unbent Dyneema ropes coated with FlexiSLIC. Sample size for each material was n = 5.

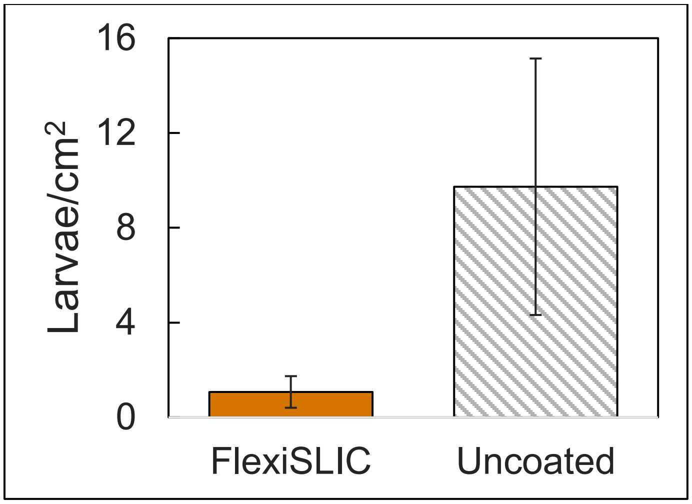

Figure 9: Mussel larvae assay performed on polypropylene ropes coated with FlexiSLIC. Sample size for each material was n = 5.

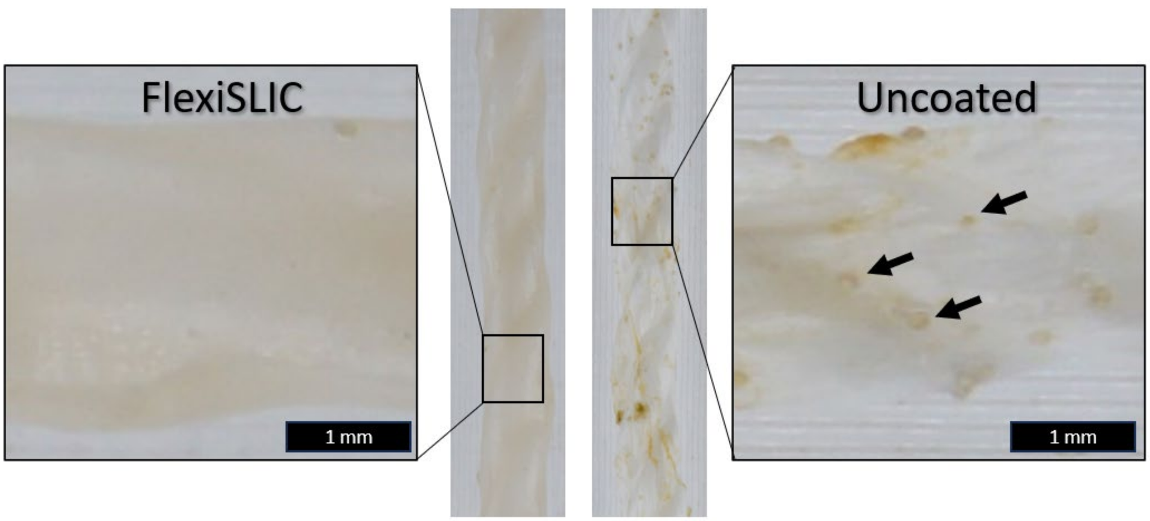

Figure 10: Fouling present on a FlexiSLIC-coated polypropylene rope (left) and uncoated polypropylene rope (right). Arrows on the uncoated rope point to a few of the mussel larvae present.

3.3.2 Field testing

Laboratory tests are intended as a precursor to the real-world results that come from testing materials in the field, especially when it comes to exposing materials to all fouling organisms present in natural waterways. The California Department of Water Resources asked PNNL to test the antifouling efficacy of FlexiSLIC by coating nets to be deployed off their juvenile salmon collection system in the McCloud River, CA. FlexiSLIC was coated on 15 in x 20 in Dyneema netting with ¼-inch holes and placed in PVC frames alongside uncoated netting (three replicates each). The frames were submerged off the collection system for ~1 month and the FlexiSLIC-coated nets fouled heavily (Figure 11) with a diatom known as “Rock Snot”, which is an invasive species established in the McCloud River. The presence of this fouling organism was unexpected and will require a separate future effort to mitigate its effects on nets within the McCloud River. Additional field tests are currently underway.

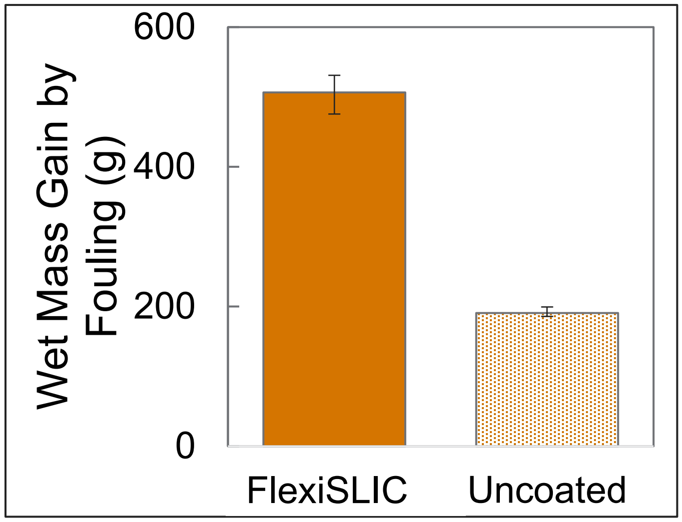

Figure 11: Wet mass of fouling gained by FlexiSLIC coated on Dyneema netting in the McCloud River, CA. Sample size for each material was n = 3 and nets were 15 x 20 inches.

4.0 Commercialization

The main goal for this work was to mature and advance the FlexiSLIC coating so it can be transferred to industry for commercialization and introduction to the market. This effort strategically de-risked several key areas of concern. Close coordination with commercial partners enabled us to make substantial progress towards these goals. Dry Surface Technologies dedicated their technical effort to understanding and meeting commercial requirements for the coating. Lorama Group supplied valuable information about blending with pigments and other additives that would be desirable or required for market introduction. Pacific Netting products provided valuable perspective as a producer and vendor of netting that is in use in American waterways. Prometheus Innovations focused their effort on additives to FlexiSLIC that would provide enhanced functionality such and reflectivity of sonar. River Connectivity Solutions helped to ensure FlexiSLIC would meet future requirements for fish and thermal barriers that are currently being designed and tested in several locations in the US. Finally, we are grateful for the valuable input from Taylor Shellfish Farms, who provided both expert knowledge of mussel development and behavior, but also provided mussel larvae for testing. They have graciously agreed to conduct field tests at the site of their commercial mussel farm in the near future.

As a result of the work conducted in this effort, PNNL has strengthened its position to license the SLIC and FlexiSLIC intellectual property. Multiple commercial entities contacted PNNL during the course of the project to learn more about the technology and several have agreed to participate in future develop, testing, and deployment. It is expected that a license to commercialized will follow.

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