Ocean Visions Expert Advising and Evaluation Team for Safe Elevation of Alkalinity for the Mitigation of Acidification Through Electrochemistry (“SEA MATE”)

Progress Report 1

Introduction

Ocean Visions works to develop innovative and durable solutions to complex challenges facing our ocean. In furtherance of this mission, Ocean Visions has partnered with the Grantham Environment Trust to evaluate and advance ocean-based climate solutions. Ocean Visions and the Grantham Environmental Trust work together to evaluate the science and engineering of proposed ocean-climate innovations, and Ocean Visions provides third-party advice and assistance on research, development, field testing, impact analysis, and optimization to Grantham Environmental Trust grantees.

Under this initiative, Ocean Visions ("OV") has assembled a team of experts ("The Expert Team") to advise and independently evaluate the research project Safe Elevation of Alkalinity for the Mitigation of Acidification Through Electrochemistry ("SEA MATE") led by Matthew Eisaman, Ph.D., an associate professor at Stony Brook University. Brendan Carter, Ph.D., a research associate at the National Oceanic and Atmospheric Administration's Pacific Marine Environmental Laboratory, serves as the co-investigator of the SEA MATE project. In the second half of 2021, the SEA MATE investigators recruited several postdoctoral researchers and PhD students to assist in executing the research activities described in this report.

The Technology

The SEA MATE project is focused on developing an electrochemical approach to mitigating ocean acidification and enhancing ocean carbon sequestration through technology developed by Professor Eisaman and colleagues to separate seawater into slightly acidic and basic components[1]. By removing the slightly acidic portion, the remaining product is de-acidified seawater, which can be returned to mitigate ocean acidification and sequester additional carbon dioxide in seawater (Figure 1).

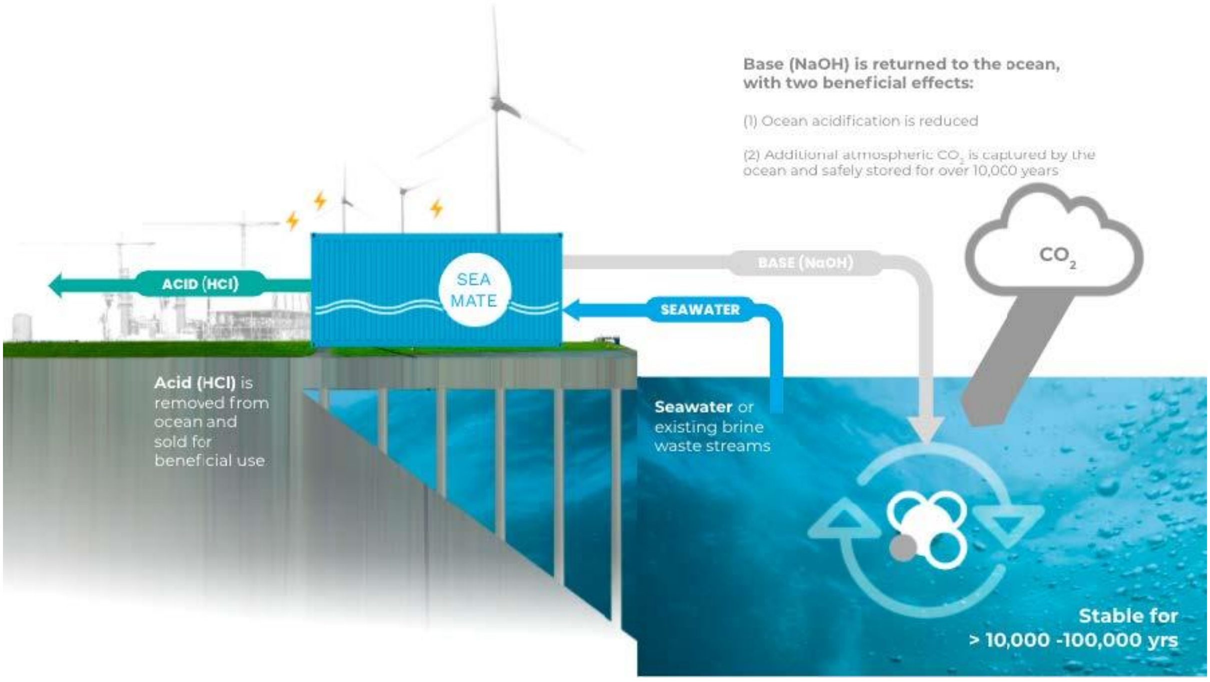

Figure 1: Schematic of the SEA MATE process (credit: Matthew Eisaman)

---

[1] Interested readers are directed to the following references:

Eisaman, Matthew D., et al. "CO_2 extraction from seawater using bipolar membrane electrodialysis." *Energy & Environmental Science* 5.6 (2012): 7346-7352.

de Lannoy, Charles-Francois, et al. "Indirect ocean capture of atmospheric CO2: Part I. Prototype of a negative emissions technology." *International Journal of Greenhouse Gas Control* 70 (2018): 243-253.

Eisaman, Matthew D., et al. "Indirect ocean capture of atmospheric CO2: Part II. Understanding the cost of negative emissions." *International Journal of Greenhouse Gas Control* 70 (2018): 254-261.

Eisaman, Matthew D. "Negative Emissions Technologies: The Tradeoffs of Air-Capture Economics." *Joule* 4.3 (2020): 516-520.

The Expert Team

OV Expert Team members include Ellen Briggs, Ph.D., David Ho, Ph.D., Kristy Kroeker, Ph.D., and William Tarpeh, Ph.D. The Expert Team is coordinated by Ocean Visions' Science Director David Koweek, Ph.D.

The Expert Team provides third-party external review of SEA MATE's research and development plan, and provides specific feedback in the following areas:

1. Advice on ways to optimize the design and implementation of the research and development plan to maximize overall performance, efficacy, and data integrity.
2. Provides review on potential environmental risks and upstream and downstream impacts of the electrodialytic process and advise on how to minimize any potential negative impacts.
3. Provides review and advice on design of monitoring systems and protocols to measure overall performance, and in particular, carbon sequestration and environmental impacts of the electrochemical process
4. Review results of the laboratory testing, field tests, and model results as they become available.

The Expert Team, OV staff, and SEA MATE investigators were brought together in April 2021 with a kickoff meeting that set the terms of reference for the engagement between SEA MATE investigators and the Expert Team. During the first several months of the engagement, Expert Team members met with the SEA MATE team on a weekly basis as an entire group. After several months, these structured meetings have transformed into ad hoc meetings with one or more members of the Expert Team. Due to the COVID-19 pandemic, all meetings have occurred virtually.

This document describes progress on the areas of engagement laid out in the joint research plan between SEA MATE and The Expert Team. Interested individuals can read the full joint research plan. Briefly, the joint research plan summarizes collaboration around these key areas:

1. Laboratory tank testing of the technology at Stony Brook University
2. Development and testing of a unit for a field-based deployment of the SEA MATE technology
3. Modeling to support the research and development of the SEA MATE technology
4. Additional recommendations pertaining to the SEA MATE project

This progress report is produced by The Expert Team and Ocean Visions independent of SEA MATE principal investigators. SEA MATE investigators were given an opportunity to review a draft of this report to ensure that it did not unintentionally disclose confidential information.

Statement Regarding the Relationship Between SEAMATE and Ebb Carbon

SEA MATE and Ebb Carbon are legally separate entities with mutual interests. SEA MATE is focused on scientific discovery and knowledge generation for the public good. Ebb Carbon is commercializing the approach being explored by the SEA MATE project. Dr. Eisaman is a co-founder and serves as the Chief Technology Officer of Ebb Carbon, in addition to his lead investigator role on SEA MATE. Ebb Carbon is currently in discussions with Stony Brook University to license intellectual property that was generated as part of the SEA MATE project.

Areas of Engagement

Laboratory Tank Testing

The SEA MATE team initiated a series of laboratory tank tests of the electrodialysis technology at Stony Brook University's Flax Pond Marine Laboratory. These tank tests are designed to verify the functionality of the electrodialysis unit, test out a feedback control system to maintain constant chemical conditions in the treatment tank, and test out various chemical sensors for monitoring eventual field deployments. At this early stage of research, laboratory testing and validation offers greater flexibility in collecting water samples and utilizing instrumentation that is more difficult to deploy and maintain in the field.

Key areas of progress towards the execution of the laboratory tank tests include:

- Finalized plans for tank setup, including:
    - Tank volumes – several cubic meters
    - Tank flow rates
    - Source waters, and any necessary pre-treatments
    - Plans to mitigate biofouling during tank experiments
    - Sampling frequency of continuous and discrete samples
    - Plans to monitor atmospheric CO_2 levels in the laboratory to account for any effects they may have on tank results

- Outlined plan for validating electrodialytic technology in test tanks through use of continuous pH measurements (SAMI-pH *in situ* sensor) in the tanks, coupled with discrete bottle samples for additional carbonate system parameters
    - Advisor Briggs has offered to test her prototype Total Alkalinity (A_T) and pH sensor in the test tanks to provide an *in situ* A_T measurement to complement bottle sample measurements.

- Conducting a series of pre-experiments to identify pH levels that would induce carbonate precipitation and should be avoided

The Expert Team notes that the SEA MATE team has made some important progress towards completing the proof-of-technology testing, despite setbacks such as fouling of the seawater in the lab, shortage of supplies like sample bottles, and delays in receiving instruments from vendors.

Development of an Electrodialysis Unit for Field Testing

Concurrent with the laboratory experiments, the SEA MATE team has been designing and building a field-ready electrodialysis unit for testing pending successful laboratory tests of the technology. Field tests are intended to benefit from the learning of the laboratory tank tests and represent a progression of the technology readiness of the electrodialytic approach. The field test unit is being designed to fit within a twenty-foot equivalent shipping container so that it is easy to transport to field test sites.

Expert Team members have played an important role in helping to identify candidate testbed locations, primarily marine laboratories and ports along the U.S. west coast, that meet SEA MATE's specification for a test site. These specifications include, but are not limited to stable, shore-based electrical power, already permitted for seawater intake, and locations which have available space to host the shipping container that encapsulates the field test unit. Expert Team members have brokered introductions and helped evaluate candidate test sites. Although a final test site has not yet been chosen by the SEA MATE team, the collaboration with the Expert Team members has helped narrow down the list of finalist candidate sites.

Remaining questions from the Expert Team regarding field testing include:

- How will the SEA MATE verify the amount of alkalinity added and additional carbon dioxide captured during field tests? Which observational platforms and/or sensors can support this validation process?
- What role may pilot facilities with desalination brine play in the upscaling of SEA MATE and translation to actual ocean carbon dioxide removal?
    - Advisor Tarpeh has led conversations with SEA MATE regarding typical desalination brine composition.

Modeling Efforts to Support Research and Development

Modeling efforts to support the SEA MATE research program have focused on the science and engineering of the SEA MATE process. The science modeling has been led by co-investigator Carter, who is working to represent the SEA MATE process within a regional-scale ocean model. The purpose of this effort is to simulate and understand potential regional-scale effects on ocean biogeochemistry in a hypothetical scaled deployment of the SEA MATE process. The SEA MATE team is currently focused on implementing this model in the sub-Arctic north Pacific, where they have identified a candidate location in the Bering Sea particularly amenable to alkalinity additions in the model.

Expert Team members Kroeker, Briggs, and Ho highlight both the value and shortcomings of this initial modeling effort. They note that the model results provide important information on the potential spatial and temporal scales of CO_2 drawdown. The advisors also note that the model is ill-suited to address ecosystem responses to ocean alkalinity enhancement from the SEA MATE process because complex ecosystem processes are not well-represented in the model. As with any model, high quality observational data sets for calibration and validation will be important for ground truthing the model results. The modeling is also location specific, so just because the team has successfully implemented the SEA MATE process in a model of the sub-Arctic north Pacific does not mean that it will have success with a model for the locale that will be chosen for the field test.

The modeling to support the engineering of the SEA MATE process has involved a unique collaboration between advisor Tarpeh and the SEA MATE team. A team of chemical engineering seniors in Tarpeh's Chemical Engineering Plant Design course in Fall 2021 worked directly with Professor Eisaman on evaluating calcium and magnesium pretreatment for SEA MATE in the context of the planned pilot. The team of three students prepared a comprehensive report and presentation over the course of ten weeks, both of which were shared with Professor Eisaman. They considered topics like key reactor units, separator units, process economics, process safety, environmental impacts, and catalogued equipment for the pilot facility. The team found that producing magnesium and calcium hydroxide is not yet profitable, although there may be future opportunities to reduce costs and maximize revenue from pretreatment methods.

Considering Next Steps

Environmental Response to Acid Removals

Experimental assessments of the biological effects of acid removals/alkalinity additions were not originally included in the research plan, and progress on this has been limited to conversations regarding future collaborations with biologists and/or ecologists to design experiments. Quantitative assessments of the biological effects will be helpful in permitting for the pilot project and should be prioritized in future work.

Monitoring, Reporting, and Verification of Carbon Dioxide Removal

As with all other carbon dioxide removal techniques, the protocols must be developed for the SEA MATE process to monitor, report, and verify the carbon dioxide removal. As a first step towards building these protocols, the advisors recommend tracking the acid removal and alkalinity additions of the pilot field unit. As the project develops, next steps could include directly tracking carbon dioxide uptake in an enclosed lagoon subject to alkalinity additions from SEA MATE electrodialysis units.

Developing Co-Products from the SEA MATE process

The SEA MATE process may be able to generate valuable co-products that provide additional revenue streams and lower total system cost, including the cost of carbon dioxide removal. Specific recommendations for evaluating potential co-products include:

- SEA MATE could be used for ocean-based carbon dioxide removal, desalination brine-based carbon dioxide removal, or both. Business models (value propositions, markets, customers) and site-specific constraints and opportunities should be compared between these two settings. Valorizing the oxygen or hydrogen gas produced in the bipolar membrane setup as additional products in the SEA MATE portfolio.

- Acquiring additional guidance from sodium hydroxide and hydrochloric acid consumers to guide product formulations and purity requirements. It would be useful to establish tradeoffs for process operation, cost, energy consumption, and environmental impacts relative to product formulations.

This report is approved by

Ellen Briggs

Ellen Briggs, Ph.D.

Assistant Professor of Ocean and Resource Engineering

University of Hawaiʻi at Mānoa

David Ho

David Ho, Ph.D.

Professor of Oceanography

University of Hawaiʻi at Mānoa

Kristy Kroeker

Kristy Kroeker, Ph.D.

Associate Professor of Ecology and Evolutionary Biology

University of California Santa Cruz

William Tarpeh

William Tarpeh, Ph.D.

Assistant Professor of Chemical Engineering

Stanford University

David Koweek

David Koweek, Ph.D.

Science Director, Ocean Visions

2022-01-24

Date

Signature Certificate

Reference number: IJPCZ-W3Z47-ACCKK-U8YYJ

Signer	Timestamp	Signature
Kristy Kroeker Email: kkroeker@ucsc.edu Shared via link		Kristy Kroeker
Sent:	18 Jan 2022 22:22:06 UTC	
Viewed:	18 Jan 2022 22:47:54 UTC	IP address: 73.71.56.52
Signed:	18 Jan 2022 22:48:29 UTC	Location: Davenport, United States
Ellen Briggs Email: embriggs@hawaii.edu Shared via link		Ellen Briggs
Sent:	18 Jan 2022 22:22:06 UTC	
Viewed:	18 Jan 2022 23:05:07 UTC	IP address: 72.130.218.233
Signed:	18 Jan 2022 23:05:56 UTC	Location: Honolulu, United States
William Tarpeh Email: wtarpeh@stanford.edu Shared via link		William Tarpeh
Sent:	18 Jan 2022 22:22:06 UTC	
Viewed:	19 Jan 2022 07:08:44 UTC	IP address: 24.5.48.30
Signed:	19 Jan 2022 07:09:18 UTC	Location: Palo Alto, United States
David Ho Email: ho@hawaii.edu Shared via link		David Ho
Sent:	18 Jan 2022 22:22:06 UTC	
Viewed:	22 Jan 2022 06:18:53 UTC	IP address: 217.181.193.84
Signed:	22 Jan 2022 06:20:03 UTC	Location: Montoire-sur-le-Loir, France

Document completed by all parties on:

24 Jan 2022 15:50:57 UTC

Signature Certificate

Reference number: IJPCZ-W3Z47-ACCKK-U8YYJ

Signer	Timestamp	Signature
David Koweek Email: david.koweek@oceanvisions.org		David Koweek
Sent:	18 Jan 2022 22:22:06 UTC	IP address: 73.63.242.134
Viewed:	18 Jan 2022 22:22:07 UTC	Location: Mountain View, United States
Signed:	24 Jan 2022 15:50:57 UTC	

Document completed by all parties on:
24 Jan 2022 15:50:57 UTC