electrorock

By

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ABSTRACT

Current construction methods tend to deconstruct our landscapes in order to establish infrastructure, leaving behind a desolate and non-biologically productive terrain. In order to move forward, we have an obligation to redefine sustainable design and discontinue the use of rudimentary processes that deplete our planets resources.

This thesis will explore the potential of a new biologically engineered system and its implementation to benefit our society and bionetworks. The technology is referred to as electrodeposition of minerals, which is a chemical reaction that mimics the shell formation process of marine organism. The strength and porosity of the precipitate, calcium carbonate, can be determined by the electrical parameters set forth during the growth procedure.

The objective is to produce reinforced architectural panels that are grown from natural minerals on an industrial scale. Through quantitative research, experiments, and interviews; this study will investigate how to maximize the growth process and how to design a closed loop production facility in Saint John. This new biological frontier will open up endless possibilities for future building materials and will encourage cross-disciplinary collaboration.

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INTRODUCTION

Biomimicry: is an approach to innovation that seeks sustainable solutions to human challenges by emulating nature's time-tested patterns and strategies

Biomining: is the process by which living organisms produce minerals, often to harden or stiffen existing tissues. Such tissues are called mineralized tissues.

Hermitic: reef-building coral.

Electrodeposition: is the process of coating a thin layer of one metal on top of a different metal to modify its surface properties.

Electrodes: a conductor through which electricity enters or leaves an object, substance, or region.

Precipitate: is the creation of a solid from a solution.

Accrete: grow by accumulation or coalescence

Electrolysis: is a technique that uses a direct electric current (DC) to drive an otherwise non-spontaneous chemical reaction

*I have always been fascinated with **biomimicry** and its implementation within the realm of architecture that seeks sustainable solutions to solve complex design challenges. Many innovative strategies and production of materials, structures, and systems have been derived from biological entities and processes. Upon further investigation into this topic, I discovered a group of marine biologist that were in the midst of replicating the shell formation process of marine organism in hopes of restoring and growing artificial reefs. This research captivated my curiosity and inspired me to further explore the potential of this technology and its application.*

*This thesis explores a new method of additive manufacturing as an alternative to concrete construction. It introduces a new building material that is composed entirely of renewable resources that are readily and abundantly available. Entitled Electrorock, it uses electricity to bind dissolved calcium minerals in seawater to a predetermined metal matrix. This system has been modified from previous research to develop new architectural building panels such as columns, beams, and purpose built panel systems. Rather than being fabricated, Electrorock products are grown through a synthetic **biomineralization** process. The technology was derived from **hermitic** calcareous organism that extract carbonates from surrounding seawater to build up their own exoskeletons, shells, spicules or other elements of their bodies.¹ They achieve this by using metabolic energy to create an internal chemical condition that overcomes nucleation barriers.² In chemistry this reaction is referred to as **electrodeposition** of minerals. Electrorock is able to mimic this metabolic process by applying an electrical current between two **electrodes** submerged in seawater to **precipitate** targeted ions. This method allows us to **accrete** solid calcium carbonate, similar to limestone, onto any metal framework, giving us the freedom to grow an array of products to any desired geometry.*

*Developed by Professors of marine biology, Wolf H. Hilbertz and Thomas J. Goreau this process was originally entitled as mineral accretion technology (MAT). In the late 1970's they began to experiment with **electrolysis** of seawater and concluded that they could not only precipitate solid minerals, but could control which minerals were accreted by varying the electrical parameters.³ They created a series of underwater reef-like pavilions that used MAT to enhance the growth rates and the life span of marine organism transplanted onto the structures, refer to Figure 1.⁴*

So far this methodology has only been applied to the restoration and protection of coral reefs in attempts to counteract global warming, sedimentation, and pollution. However, Hilbertz and Goreau mention in their research that this technology can be utilized in a number of ways such as protecting shorelines from erosion and global sea level rises by growing struc-

Bionetworks: is any network that applies to biological systems

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Figure 1. Biorock Pavilion, Maldives. Image taken from google images.

tural barriers along the coast.⁵ This dissertation, will explore the potential of MAT within the field of architecture and attempt to remodel current construction methods to one that is less harmful and more cost-efficient. Electrorock will achieve this by reducing the need for deforestation, mining, excavating, industrial plants, transportation, and total waste.

Today, current manufacturing and construction methods are depleting our natural resources at an alarming rate. As our population is steadily increasing, so is our demand for infrastructure as nearly 60 percent of the population lives in and around cities.⁶

Concrete has become one of the leading construction materials in the world as it is relatively inexpensive and structurally reliable. However, the production of concrete is quite energy-intensive and is responsible for large CO₂ emissions.⁷ The majority of concrete is composed of natural aggregates that have been extracted from the earth through different mining methods. Sand, gravel, and crushed stone are mined worldwide and account for the largest volume of solid materials extracted globally.⁸ This industry is accountable for the consumption and destruction of millions of acres of fertile lands, which ultimately have a negative effect on their surrounding environments and local **bionetworks**, refer to Figure 2.

If we continue depleting our natural resources at this rate we will soon outpace the sustainable capacity of our ecosystems and find ourselves with contaminated non-biologically productive landscapes. In order to counteract this overconsumption we must solve for new innovative building materials and technologies that are resource-efficient and environmentally responsible. Construction materials today should be governed by ecological consideration to prevent any further damage to our planet.⁹

Closed-loop: is a control system which uses the concept of an open loop system as its forward path but has one or more feedback loops or paths between its output and its input.

Figure 2. E.L. Smith Quarry, Vermont. Image taken from google images.

INTRODUCTION

*Over the course of this dissertation I will explore the origins and history of MAT as well as the fundamental chemistry and biology implemented, experiments and analytic research, its application within the realm of architecture, and its ecological benefits. This research aims to identify and understand current construction issues in order to propose a new solution to building materials and their production. Electrorock will challenge current architectural approaches and provide designers which much more freedom pertaining to the built form. The thesis concludes with a factory design proposal that will be the first **closed-loop** facility to mass produce Electrorock products. It will provide new standards for future factories to strive for as it will run solely off renewable energy.*

¹ Yuri Sorokin, *Ecological Studies: Coral Reef Ecology*, (Springer, 1995), 4.

² Thomas Goreau, *Marine Electrolysis for Building Materials and Environmental Restoration*, (Intech, 2012), 280.

³ *Ibid*, 274.

⁴ Biorock Inc., “Biorock Technology”, (Biorock Technology), Accessed June 10, 2016.

<http://www.biorock.net/Technologies/index.html>

⁵ Thomas Goreau, *Marine Electrolysis for Building Materials and Environmental Restoration*, (Intech, 2012), 288.

⁶ Kumar Mehta, *Concrete: Microstructure, Properties and Materials*, (McGraw-Hill, 2006), 636.

⁷ *Ibid*, 638.

⁸ Pascal Peduzzi, “Sand, rarer than one thinks”, UNEP Global Environmental Alert Service (2014), Accessed January 16, 2016.

http://na.unep.net/geas/getUNEPPageWithArticleIDScript.php?article_id=110

⁹ Kumar Mehta, *Concrete: Microstructure, Properties and Materials*, (McGraw-Hill, 2006), 22.

Definitions provided by Merriam-Webster. <http://www.merriam-webster.com/dictionary/definition>

CHAPTER 1

Cathodic Protection: is a technique used to control the corrosion of a metal surface by making it the cathode of an electrochemical cell.

Mineralization: the process through which an organic substance becomes impregnated by inorganic substances

Macromolecular: is a very large molecule, such as protein, commonly created by polymerization of smaller subunits (monomers). They are typically composed of thousands or more atoms.

Cations: An ion with net positive charge, having more protons than electrons.

*In 1970, Professor Wolf H. Hilbertz, a marine scientist at the University of Texas began to explore a new approach to architecture. One that would incorporate integrated systems within a building's design that would not only respond to but be in dialogue with their environment, a concept Hilbertz referred to as Cybertecture which he previously developed at the Southern University in Baton Rouge, Louisiana. Hilbertz continued his research into non-traditional building materials and began to investigate mineral accretion (MA) in 1974. MA is a "building process that obtains a natural solid material through the extraction of minerals from seawater."*¹⁰

*This technology expanded upon **cathodic protection** (CP), patented in 1947, which applies an electrical current through metallic surfaces submerged in seawater to clean and protect against corrosion. It achieves this by cathodically coating the metals with a layer of magnesium and calcium salts.¹¹ CP is the synthetic version of biomineralization that certain marine organism use to grow their skeletal structures in an organic matrix.¹² There is still much to be learned about how these inorganic materials are capable of forming complex geometries.*

*However, we do know that this process can be divided into two categories based upon their degree of biological control referred to as biologically induced mineralization (BIM) and biologically controlled mineralization (BCM). BIM processes are not specifically designed for **mineralization**, but do in fact result in mineral being formed, whereas BCM processes set up specific machinery for the purpose of mineralization.¹³*

*For the sake of this dissertation, I will primarily be focusing on BCM. The first step of this process is for the cell to produce a **macromolecular** matrix around its exterior shell where the mineralization will take place. This organic matrix refers to a sheet-like structure that's composed of proteins, polysaccharides or glycoproteins that self-assembles into a three-dimensional framework. "The structure and composition of these organic frameworks are genetically programmed to perform essential regulating and/or organizing functions that will result in the formation of composite biominerals."*¹⁴

*BCM can be achieved through two separate methods. The first of which actively pumps **cations** though the membrane of the cell into the surrounding aqueous environment. Once released, ion diffusion establishes and maintains the supersaturation level of the fluid over large distances to the organic matrix, refer to Figure 3.A. In the second method the cations are "concentrated within the cell into cation-loaded vesicles, exported though the membrane and later broken down by precursor compounds at the organic matrix"¹⁵, refer to Figure 3.B. Both these methods involve the cell consis-*

Nucleation: is the first step in the formation of either a new thermodynamic phase or a new structure via self-assembly or self-organization.

Calcification: is the accumulation of calcium salts in a body tissue

tently supplying cations to an external organic matrix for on-site **nucleation and growth**.¹⁶

Figure 3. Image taken from google images.

This **calcification** process inspired Hilbertz to strive towards organically grown structures in a precisely controlled manner.¹⁷ He was fascinated by the degree of sophistication obtained by these organism who could control the nucleation, growth, and morphology of their micro-structures using cellular activity. Hilbertz and his colleague Dr. Thomas J. Goreau quickly began running a series of their own experiments exploring the potential of mineral accretion technology (MAT).

They began conducting trials within aquariums ranging from 15-20 gallons supplied with raw seawater at a rate 4.5 gal/min and quickly graduated to large scale pavilions in the Caribbean, Indian Ocean, and Southeast Asia.¹⁸ Hilbertz and his group of scientist conducted numerous projects taking place in over 20 countries which gradually improved after learning more and more about all the factors at play.

The majority of these experiments took place in warm tropical waters as higher temperatures and salinity levels greatly accelerate reaction rates, as well as increase electrical conductivity and reduce resistivity between electrodes.¹⁹ Thus, biominerals grow faster and harder in very salty waters and brines which minimizes the amount of electrical work required, ultimately saving on energy consumption.²⁰ Hilbertz' underwater reef-like pavilions were generally positioned close to shore lines for maintenance and convenience purposes. These areas were also known to be rich in oxygen, nutrient salts and minimal fresh water that "would reduce salinity and bring undesirable terrigi(e)nous debris."²¹ Nevertheless, Hilbertz and

Cathode: is the electrode from which a conventional current leaves a polarized electrical device.

Anode: is an electrode through which conventional current flows into a polarized electrical device.

Electrolyte: is a substance that produces an electrically conducting solution when dissolved in a polar solvent, such as water.

Calcite: is a carbonate mineral and the most stable polymorph of calcium carbonate (CaCO_3).

Aragonite: is a carbonate mineral, one of the two common, naturally occurring, crystal forms of calcium carbonate, CaCO_3 .

Goreau still ran two separate experiments under the same electrical parameters with one at a depth of 1' and the other at 45' and identical accretion was achieved from both trials, proving that depth did not appear to be a factor.²²

*These artificial reefs are composed of three major components; the **cathode**, the **anode**, and the power supply. The cathode is the metal framework in which the accretion will adhere to and is usually constructed of galvanized hardware cloth. In order to prevent any additional upkeep the anode should be a special non-corrodible and non-toxic material to avoid having to replace it, as elementary metals would dissolve in these corrosive conditions.²³ These electrodes have to be good electrical conductors to create a strong electric field between the two and to prevent any short-circuits. "Every electrochemical component is made up of a positive and negative electrode, separated by an **electrolyte** which...has to be a good ion conductor and good electron insulator."²⁴ Electrolysis of seawater causes either electrodes to lose electrons through oxidation or gain electrons through reduction. During this process hydrogen is produced around the cathode due to the reduction reaction and oxygen is produced around the anode from the oxidation reaction, making the local environment both oxidizing and acidic.²⁵ The electrochemical process is driven by a DC power source which can generally collect its own renewable energy from on-site resources such as wind, solar, or tidal currents.²⁶*

*The electrical field emitted from the electrodes is considered a vector force because it applies a directional strength towards the negative electrode. This force helps thrust **calcite** and **aragonite** ions towards the cathode where they will begin to calcify. Hilbertz and Goreau realized that in order to maintain uniform growth they had to position an array of anodes at equivalent distances, as previous tests showed a decrease in thickness with more distance between the anode and cathode.²⁷ They also began to alter the electrical parameters set forth for different experiments by changing the voltage and current in order to find the ideal settings for maximum accretion rates. The team quickly realized that could accrete extremely hard calcium carbonate (CC) limestone deposits under low electrical conditions. The CC precipitated was composed of the mineral aragonite which is the same compound that makes up coral skeletons. When the electrical conditions were set to high it caused the growth of the mineral brucite, or magnesium hydroxide which are structurally weak and tend to break off easily. "Through experimentation it proved possible to grow rock-hard limestone coatings of any desired thickness on steel frames of any desired shape or size, at up to 1-2cm per year, with a compressive (load-bearing) strength up to 80 Newton's per square millimeter (MegaPascals), or about three times the strength of concrete from ordinary portland cement."²⁸ The ideal*

voltage setting is 1.23 which is also the minimum requirement to initiate electrolysis of seawater.²⁹

The underwater structures that Hilbertz and his team were testing proved to be ideal habitats for local corals and marine organism to thrive. The pavilions and their surrounding areas showed an increase in settlement, growth survival, and resistance to environmental stress with the presence of the electrical fields.³⁰ Because these trials were so successful at replenishing local marine ecosystems, Hilbertz and Goreau decided to focus on the restoration of coral habitats. Throughout his time as a professor, Hilbertz conceived many projects that incorporated this accretion technology that would run off of renewable energy and have a mutually beneficial relation with its environment. Most notably was his visionary Autopia project that consisted of an entirely grown island that was self-sustaining and self-generating, refer to Figure 4. After his death in 2007, Thomas Goreau continued his research with MAT as acting president of Global Reef Alliance.³¹

Figure 4. Autopia by Wolf Hilbertz. Image taken from google images.

- ¹⁰ Francesco Manacorda, *Radical Nature: Art and Architecture for a Changing Planet*, (Koenig, 2009), 168.
- ¹¹ Wolf Hilbertz, *Electrodeposition of Minerals in Seawater*, (University of Texas, 1979), 699.
- ¹² Yuri Sorokin, *Ecological Studies: Coral Reef Ecology*, (Springer, 1995), 18.
- ¹³ Heinz Lowenstam, *On Biomineralization*, (Oxford University Press, 1989), 26.
- ¹⁴ Steve Weiner, *An Overview of Biomineralization Processes and the Problem of the Vital Effect*, (WIS, 1986), 11.
- ¹⁵ *Ibid.*, 12.
- ¹⁶ *Ibid.*
- ¹⁷ Thomas Goreau, *Marine Electrolysis for Building Materials and Environmental Restoration*, (In-Tech, 2012), 274.
- ¹⁸ Wolf Hilbertz, *Electrodeposition of Minerals in Sea Water: Experiments and Applications*, (IEEE, 1979), 108.
- ¹⁹ Thomas Goreau, *Marine Electrolysis for Building Materials and Environmental Restoration*, (In-Tech, 2012), 273.
- ²⁰ John Andrews, *Energy Science: Principles, Technologies, and Impacts*, (Oxford University Press, 2007), 359.
- ²¹ Jones Endean, *Biology and Geology of Coral Reefs*, (Academic Press, 1977), 5.
- ²² Wolf Hilbertz, *Electrodeposition of Minerals in Sea Water: Experiments and Applications*, (IEEE, 1979), 95.
- ²³ *Ibid.*, 280.
- ²⁴ Marie-Cécile Péra, *Electrochemical Components*, (ISTE Ltd and John Wiley & Sons Inc., 2013), 4.
- ²⁵ *Ibid.*, 45.
- ²⁶ Thomas Goreau, *Marine Electrolysis for Building Materials and Environmental Restoration*, (In-Tech, 2012), 286.
- ²⁷ Wolf Hilbertz, *Electrodeposition of Minerals in Sea Water: Experiments and Applications*, (IEEE, 1979), 99.
- ²⁸ Thomas Goreau, *Marine Electrolysis for Building Materials and Environmental Restoration*, (In-Tech, 2012), 275.
- ²⁹ *Ibid.*, 279.
- ³⁰ *Ibid.*, 286.
- ³¹ Biorock International Corporation, "Biorock Technology", Biorock Technology, Accessed December 2, 2015. <http://www.biorock.org/content/method>

Definitions provided by Merriam-Webster. <http://www.merriam-webster.com/dictionary/definition>

CHAPTER 2

The objective of this thesis is to develop a new manufacturing technique that will grow architectural products out of calcium carbonate (CC). The starting point for this endeavor was to recreate the experiments executed by Hilbertz and Goreau. Seeing how their artificial reefs proved mineral accretion technology (MAT) was possible in oceanic settings, I wanted to see if these results could be replicated within an enclosed system. I decided to conduct a series of experiments to test this theory in hopes of achieving similar outcomes. These trials also aimed to solve the limiting factors of accretion rates in order to maximize and accelerate growth. Though the CC precipitated on the underwater pavilions had equivalent or superior strength to concrete, it simply cannot compete with its manufacturing time frame, as concrete is cured after 28 days.³² If Electrorock wanted to compete with modern day technologies, it must find a way to speed up its process.

This chapter will chronologically analyze and discuss nine trials conducted over seven months that strived to enhance Hilbertz and Goreau's results. Each iteration tested individually variables required for mineral accretion (MA) in attempts to find any restricting forces acting against calcification. These findings and further research gradually led to the acceleration of accretion rates and proved that Electrorock could be grown more efficient in a controlled environment.

To conduct these experiments I set-up a temporary laboratory with the necessary equipment, supplies, and documentation. This included a twenty gallon tank, a DC power supply, an assortment of metals, electrolyte solution, electric water pump, fluorescent lighting, mechanical ventilation, and a camera for incremental documentation, refer to Figure 5.

Figure 5. Laboratory set-up.

Electrolytic Dissolution: the deterioration of metals exposed to high electrical currents and saline

Noble Metal: are metals that are resistant to corrosion and oxidation in moist air

CHAPTER 2: Research & Methodology

My experiment used Hilbertz and Goreau's synthetic process of biomineralization as a starting point. The technique used an electrical current through an electrolyte bath to precipitate CC on the targeted electrode. The positive end from the power supply was connected to the anode and the negative end to the cathode, both submerged in saltwater. Electrodeposition causes dissolved minerals in the saltwater solution to deposit and accrete calcium and magnesium rich substrates onto the cathode structure.³³

The first trial was conducted on August 3rd, 2015 to confirm I could achieve MA within an enclosed system. To mimic an oceanic-like solution the product Instant Ocean Mix was used. Instant Ocean Mix is a powder base mixture that is formulated to simulate sea conditions for aquariums, containing all the essential elements such as chloride, sodium, sulfate, magnesium, calcium, potassium, etc. A 6" copper pipe was used as the anode and a 6" piece of steel rebar for the cathode. The metals were selected because they are highly conductive and would provide a strong electrical field between the electrodes. The electrical parameters were set to 5.00 volts and 12.0 amps, which was the average of Hilbertz and Goreau's experiments when conducted in the ocean. These settings proved too high for this scale, as the surplus of hydrogen was released triggering the gas alarm. Though this experiment was terminated after a few hours of operation, it provided much key information concerning the electrical parameters.

In the second iteration of the experiment the electrical settings were lowered to 2.00 volts with a current of 0.30 amps to try and diminish the amount of hydrogen produced. The anode, cathode, and saltwater solution remained constant to maintain consistency with the first trial. On August 7th, 2015 the cathode steel rebar successfully accreted 2.00 grams of CC onto the exterior matrix after 25 hours of operation. Improvements considered after the experiment included: changing the anode material, copper proved to be a poor inert anode for electrolysis of seawater as it quickly began to dissolve once introduced to the saline solution and electrical conditions, refer to Figure 6. The anode lost a significant portion of mass and stained the solution cyan hindering documentation. This was the result of copper ions absorbing red light wavelengths.³⁴

*After further analysis into metallic structures it was concluded that lead would be more suitable for the anode because its compounds are not soluble.³⁵ After procuring a sheet of lead a third trial was conducted on August 18th, 2015. Lead did not experience any **electrolytic dissolution** and was able to maintain its mass throughout the trial. The 6" lead bar did however show signs of corrosion, refer to Figure 7. Corrosion could only be avoided by using a **noble metal**. Ideally a noble metals such as gold, silver, or plati-*

num would be used, however this was financially unfeasible. Nevertheless, as they have no replacement cost in principle they would be more efficient in the long-run.

Figure 06. Copper Anode.

Figure 07. Lead Anode.

The fourth trial was conducted on September 7th, 2015. It investigated if higher mineral concentrations in the electrolyte would accelerate growth rates. It used an enriched Instant Ocean Mix that is specially formulated for reef crystals with extra calcium to ensure growth of corals and coral-line algae.³⁶ This trial was conducted using the same electrical parameter as trial three but ended with the same results after 190 hours. It was concluded that mineral concentration levels did not appear to influence accretion rates. One noteworthy observation from this trial is that as the cathode continued to precipitate CC over its structure the electrical current between the electrodes began to slowly diminish. This occurred because the minerals surrounding the steel cathode are poor electrical conductors and are acting as partial insulators. The electrons however, continue to flow because they escape through the hydrogen pores created from the electrolytic reactions. These pores are formed by hydrogen gas bubbles that channel through the crystallization into the electrolyte, ultimately allowing the cathode to maintain an electrical connection with the anode.³⁷

As I was able to successfully accrete solid minerals on the perimeter of my

cathodes, I wanted to see if I could precipitate enough minerals to enclose openings within a metal mesh frame.

The fifth trial was conducted on September 19th, 2015. It used a 4" by 4" nickel mesh with $\frac{1}{2}$ " spacing as the cathode. Nickel proved to be a poor electrode because its edges began to corrode under the electrical conditions, ultimately creating a weak surface for mineral deposition. Although this experiment ran for approximately 8 days, the results were disappointing. The metal grid managed to accrete 3 grams of CC. In comparison trial three and four accreted two grams of CC, in 25 hours. One key finding was the additional growth where the nickel mesh intersected, suggesting that a stronger electrical field exist where two pieces are fused, refer to Figure 8.

Figure 08. Nickel Cathode.

Throughout these experiments I was periodically taking water samples from the aquaria for analysis. The water sample was extracted before the ocean mix was added, with the ocean mix, and one after the trial was terminated. These samples were tested by a generation RB 3000 analysis system for accurate readings of changes in pH levels, total alkalinity, calcium hardness, and total chlorine. The analysis was verified that I was in fact precipitated CC, as the calcium hardness levels in the solution significantly dropped over the duration of the trial, refer to Figure 9.

Over the course of this research, I had the privilege to meet with several faculty members from different Faculties at Carleton University to further my knowledge on this subject. Firstly, I met with Dr. Jeff Dawson, an Associate Professor in the Department of Biology. Dr. Dawson suggested a closer-knit mesh with thinner wires because it would provide more available surface area for accretion. He also confirmed that I would benefit from switching my anode to a precious or noble metal to avoid corrosion and ad-

Amphoteric Oxide: s a molecule or ion that can react both as an acid as well as a base.

ditional maintenance.³⁸

CHAPTER 2: Research & Methodology

Summary of Data Analysis: Before					
Customer Information Brandon Lawrence p5g 7u7 Phone: 613.558.2039 Email: lawrencebrandon8@gmail.com			Date: 2015-08-20 Pool Capacity: 20 Gallon Aquaria Filter Type: Sand Type of Disinfectant: Salt System Location: Indoor		
Temperature:	0 °C	T.A.:	111 ppm (80-120)	C.H.:	2450 ppm (200-300)
pH:	8.5 (7.2-7.8)	F.C.:	0.09 (1-3)	Br:	
Phosphate:		Salt:		Fe:	
Cu:	0.5 ppm (0-0.05)			CYA:	0 ppm (30-60)
				T.C.:	0.09 ppm (1-3)
				T.D.S.:	
Summary of Data Analysis: After					
Customer Information Brandon Lawrence p5g 7u7 Phone: 613.558.2039 Email: lawrencebrandon8@gmail.com			Date: 2015-08-20 Pool Capacity: 20 Gallon Aquaria Filter Type: Sand Type of Disinfectant: Salt System Location: Indoor		
Temperature:	0 °C	T.A.:	122 ppm (80-120)	C.H.:	1826ppm (200-300)
pH:	8.5 (7.2-7.8)	F.C.:	2.87 (1-3)	Br:	
Phosphate:		Salt:		Fe:	
Cu:	0.5 ppm (0-0.05)			CYA:	0 ppm (30-60)
				T.C.:	3.94 ppm (1-3)
				T.D.S.:	

Figure 09. Water sample analysis.

I also met with Dr. Robert Burk, an Associate Professor in the Department of Chemistry on September 30th, 2015. Dr. Burk provided information pertaining to the electrochemical procedures and the factors and reactions occurring in the trials. It clarified many of my questions on the process. He provided me with additional contacts on campus that would assist in identifying the exact minerals precipitated and provide details of their chemical composition and matrix.

Iteration six and seven aimed to achieve the same results in two separate trials. This was crucial for the Electrorock thesis because as a proposed building product, the research required consistency and uniformity. In October, 2015 two trials under the exact same conditions using aluminum mesh as the cathode were able to replicate identical results.

It was later discovered that aluminum was a poor choice because it is an “**amphoteric oxide** and is the only common metal that readily dissolves under both alkaline and acidic conditions, so it can’t be used as either anode or cathode.”³⁹ Refer to Figure 10.

An additional variable was the evaporation rate of the electrolyte solution. After some calculation I released that approximately 0.02 litres per hour was lost. Therefore, as the work developed it would be necessary to intermittently replenish the saltwater solution during the course of the experiment.

On October 19th, 2015 I met with Dr. Nigel Waltho, a Professor from the

Crystallographic: is the experimental science of determining the arrangement of atoms in the crystalline solids (see crystal structure).

Orthorhombic Crystals: refer to one of several classes of space groups, lattices, point groups, or crystals.

the Department of Biology at Carleton University. Dr. Waltho raised questions regarding my process including the current conditions of the electrical fields, optimum temperature, minerals being accreted, and pH levels. He suggested to have the CC samples examined to confirm whether calcite, brucite, or aragonite minerals were being crystalized. Both calcite and aragonite have the same chemical formula but different crystalline structures.⁴⁰ Dr. Waltho believed that the pH level and temperature would greatly affect the rate of reactions. Dr. Waltho's concerns proved to be accurate. In order to accrete calcium salts and avoid the growth of brucite, pH levels must be lower than 9.00, making it a base solution.⁴¹

CHAPTER 2: Research & Methodology

Figure 10. Aluminium Cathode.

Succeeding this interview, I arranged to meet with Dr. Jianqun Wang, manager of the Nano Imaging Facility at Carleton University to examine a number of the samples. Using an X-ray Powder Diffraction (XRD) machine, Dr. Wang identified and inspected the **crystallographic** structure and matrix of the precipitated minerals. The electron images confirmed that the samples were primarily composed of calcium, refer to Figure 11. After reviewing the microscopic images with Dr. George Dix, a Professor from the Department of Earth Science, Dr. Dix was able to precisely match the mineralogy with the Aragonites. Aragonite forms **orthorhombic crystals** which are much more structural than the tabular plate crystals formed by the mineral Brucite,⁴² refer to Figure 12.

After gathering this new information and advice a few modifications were made to the setup to try and increase the accretion rates by addressing the limiting factors.

The first alteration was adding a tank heater, because materials tend to

Amphoteric Oxide: s a molecule or ion that can react both as an acid as well as a base.

grow faster and harder in warm water.⁴³ The electrolyte solution was heated to approximately 80°F, since the majority of Hilbertz and Goreau's experiments transpired in waters ranging from 78-82°F.⁴⁴

CHAPTER 2: Research & Methodology

Figure 11. XRD image and analysis.

The second alteration was periodically adding liquid calcium to the saltwater solution to replenish the calcium absorbed in the hardened CC precipitate. As I had the strongest electrical field connection during trials 1 to 4, steel once again was used as the cathode structure.

With these new amendments the eighth trial began on November 11th, 2015 and effectively accreted 9.00 grams of limestone over a period of approximately six days. The accretion occurred around all major intersecting areas on the steel frame and eventually cultivated over the perforated sheet welded in between the grid, refer to Figure 13. This was the first sign of being able to completely fill in voids on a panel, as well as show physical signs of hydrogen escape pores merging from the mesh, refer to Figure 13.

While taking photographs of the panel I realized that one could easily affect the light penetrating through these panels by simply customizing its cathodic structure. So Electrorock could potentially offer built in design patterns or openings to alter how light enters the space, adding an aesthetic appeal to the product.

Figure 12. XRD images of aragonite and brucite.

Figure 13. Cathode analysis.

On February 16th, 2016 I conducted last trial (nine) which ran for approximately 25 days and precipitated +26 grams of CC. This electrochemical procedure was now capable of encasing an entire flat panel. The next phase would be to attain similar results with an undulating surface. I decided to bend the panel to create an irregular plane curve in the X, Y, and Z direction. I suspended the panel at the bottom of the aquaria to ensure the whole cathode was exposed for the same duration of time, as the solution slowly evaporated. The form of the panel did not affect accretion rates as minerals calcified uniformly, refer to Figure 14. This demonstrated that this technology could accrete panels of any geometry as long as they remain fully submerged in the electrolyte.

These nine trials were crucial for my understanding of electrodeposition of minerals in seawater and the development of Electrorock. They led me to find the ideal settings in which to grow solid CC from dissolved minerals in the seawater. These included water temperature, pH levels, salinity, electrical parameters, and conductive metals that hold strong electrical fields. These trials also informed me that I could control which minerals were being accreted based on the electrolyte bath and the voltage applied, giving Electrorock the option to form multiple products with different strength and mineral structure. Trial 5, 8, and 9 led me to believe that MA could not only be used as panels but as small pavilions and structures as the calcification process occurs naturally at intersection points reinforcing its own joints. Where this product separates from other construction materials is its ability to grow from raw materials extracted from seawater into any solid geometry with minimal energy consumption.

Figure 14. Time lapse of trial nine.

Please refer to Appendix A for further inquiry concerning the nine trials.

³² Salmon Bay Sand & Gravel, "Concrete FAQs", Salmon Bay Sand and Gravel, Accessed February 18, 2016.

<http://www.sbsg.com/concrete/faqs/>

³³ Underwater Chocolate Hills, "Phase 3: The Electro Mineral Accretion (EMA) System", the Underwater Chocolate Hills, Accessed January 27, 2016.

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⁴² Hershel Friedman and Minerals, "The Mineral Aragonite", Minerals, Accessed February 14, 2016.

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⁴³ Thomas Goreau, Marine Electrolysis for Building Materials and Environmental Restoration, (Intech, 2012), 282.

⁴⁴ Wolf Hilbertz, Electrodeposition of Minerals in Sea Water: Experiments and Applications, (IEEE, 1979), 94.

Definitions provided by Merriam-Webster. <http://www.merriam-webster.com/dictionary/definition>

CHAPTER 3

Symbiotic: refers to any diverse organisms that live together, but in this case, the relationship is not necessarily beneficial to both.

Green-House Gases: occur naturally in the atmosphere, such as carbon dioxide, methane, water vapor, and nitrous oxide, while others are synthetic.

*For centuries, architects have often looked to biologist for groundbreaking design solutions, encouraging cross-disciplinary collaboration. Over the past millennia, construction materials have evolved from clay, to stone, to wood, and most currently to steel and concrete.⁴⁵ Electrorock would introduce an entirely new approach to the production and application of building materials, challenging the notion of what and how it means to build. It will use biology as its technological partner to create a **symbiotic** relationship between buildings and environment. This system will have many associated benefits in regards to biology, ecology, economics, and energy consumption.*

*Nature would greatly profit from the implementation of mineral accretion technology (MAT) because it relies on the copious source of dissolved minerals in the sea, and requires very minimal energy. This process would reduce the demand for concrete and aggregates, minimizing open-pit mining and quarrying. Electrorock uses renewable energy gathered on-site to avoid the use of fossil fuels and its associated issues regarding pollution, and soil and groundwater contamination, refer to Figure 15.⁴⁶ As well as cut energy-intensive procedures to diminish **green-house gases** released into the atmosphere.*

Figure 15. Oil Spill. Image provided by google images.

Bio-designs are the next step within the field of architecture to ensure future infrastructure merges within its natural settings.⁴⁷ Hilbertz and Goreau's artificial reef structures have indicated that ecosystems can immensely benefit from the presence of MAT. While analyzing the formation of accretion on these underwater pavilions, the team of scientist realized they had created an improved habitat for corals, oysters, fishes, and other sea

CHAPTER 3: Application & Potential

Overfishing: is a form of overexploitation where fish stocks are reduced to below acceptable levels.

Overexploited: refers to harvesting a renewable resource to the point of diminishing returns.

creatures.⁴⁸ They not only provided enriched bionetworks and shelter from grazing predators for indigenous organisms, but actually increased growth rates, survival rates, and helped restore reefs, fisheries, and eroded beaches.⁴⁹

*Electrorock could help revert the consequences of **overfishing** as reef-like structures like Hilbertz's provide a "place of propagation and juvenile growth of many pelagic fish species important to fishery. The reefs should be recognized as a prospective zone for development of aquaculture."⁵⁰ Thus, these complex systems could assistance in re-populating aquatic species that have been **overexploited**, as current global fishing fleets are 2-3 times larger than what the oceans can sustainably support.⁵¹*

As formerly mentioned in Chapter 3, we are aware that electrolysis of seawater produces both oxygen at the anode through an oxidation reaction, and hydrogen at the cathode through a reduction reaction.⁵² The oxygen gas produced generally tends to dissolve within the electrolyte bath, whereas the hydrogen gas, being less soluble, tends to bubble out of the solution. If properly designed this gas could be trapped and used as a valuable by-product. This could be achieved within an enclosed system but would be more difficult at sea due to currents and wave surge.⁵³ Electrorock's facility will harness this alternative energy source and use it to power the equipment through industrial hydrogen generators, refer to Figure 16. Therefore, these products could, in small part, deliver their own fuel required for self-accretion through this electrochemical procedure as "Proponents of the hydrogen economy see electrolysis of water...as a green method of generating [electricity]."⁵⁴

Figure 16. Hydrogen Generator. Image provided by google images.

We could greatly benefit from this proposal because it introduces a new factory type that solely runs off clean energy and emits zero emissions. The only manufactured material that Electrorock requires is steel, in order to create the pre-fabricated frameworks. Because MAT requires little amounts of electricity, approximately 1Kg/KWh, the factory will have a considerably smaller carbon footprint than other concrete manufacturing facilities of equivalent size.⁵⁵ It will be able to run off sustainable energy sources such as tidal power, wind turbines, solar panels, and hydrogen generators. In addition, its products will absorb natural carbon from seawater into their crystallographic matrix, allowing the oceans to absorb more CO₂.

The electrical cost of Electrorock ranges from \$0.03-0.30/Kg which is economically feasible considering the current production cost of concrete is approximately \$0.12/Kg. This cost does not include the cost of steel required for reinforced concrete which increases the cost to \$1.65/Kg.⁵⁶ One advantage of Electrorock is that it does not require formwork during its production, as mineral accretion (MA) occurs evenly over any immersed structures. This reduces the cost of construction because it eliminates the materials required for formwork, reduces the amount of labour and trades, and minimizes the amount of heavy equipment on-site

After analyzing and researching the manufacturing process of current architectural precast panels, I realized that Electrorock could not only eliminate many of the compulsory steps but provide the same results through an abridged process, refer to Figure 17. For instance, Central Precast Inc., a local concrete distributor in Ottawa, requires a millwork crew, steel crew, concrete crew, modifying crew, installation crew, as well as daily loads of aggregates, sand, and cement.⁵⁷ Whereas my proposed factory would only require a steel crew and installation crew, which clearly diminishes the quantity of labourer's and does not need any excavated aggregates, refer to Figure 18.

Today, "over a billion tons of construction and demolition wastes are being disposed of in road-bases and landfills every year, in spite the fact that cost-effective technologies are available to recycle most of it as a partial replacement for coarse aggregate in concrete mixtures."⁵⁸ Electrorock is composed primarily of calcium carbonate (CC), which constitutes +/-50% of all known biogenic minerals.⁵⁹ It is one of the few building materials that can be grown from natural minerals and can eventually be returned to nature without using waste treatment or cleaning plants. Therefore, it produces no waste and all of its materials can be recycled or given back to the environment with few negative effects.

Figure 17. Electrorock Process vs. Concrete Process

Figure 18. Electrorock Manufacturing Process.

MAT can successfully accrete around any prefabricated structure of all shapes and sizes, but it also has the ability to repair and recondition itself if damaged, refer to Figure 19.⁶⁰ One would simply return the impaired section to the facility, where it would be re-submerged into the electrolyte

bath. Once the electrochemical procedure begins, the minerals will automatically be attracted to the weakened surface area as it would possess the strongest electrical field. This occurs because it would have considerably less minerals insulating the steel frame, making it more conductive than the rest of the structure. MAT building elements can also be repaired by “placing an anode in the vicinity of the damaged portion, thus facilitating, for instance, cementation of cracks, replacement of lost materials, and reinforcement of previous deposited mineral later.”⁶¹

Figure 19. Biorock Pavilion Rehabilitation.

Electrorock would offer an array of products that vary in design, size, density, and porosity. These modifications are achieved by altering the electrolyte with appropriate minerals, and by varying the electrical parameters set forth during the growth period. The different levels of porosity and

strength will provide architects with a range of design freedom. They could design with different densities, which will fluctuate the amount of light able to penetrate through, allowing for diverse spatial conditions.

CHAPTER 3:
Application & Potential

*This proposal will strive to cross the boundaries of traditional designs and materials to offer a renewable **biogenetically** synthesized product that is grown from organic materials. MAT accretes solid limestone into panels and structures that can be implemented as “floating habitats and industrial islands, settlement on banks, mariculture facilities, tunnels and [infrastructure], and sea wall.”⁶² This system will encourage other bio-designs and strategies to emerge in hopes of solving our current eco-crisis.⁶³*

- ⁴⁵ Mitchell Joaquim, "Don't build your home, grow it!" TED Conferences LLC. www.ted.com.
- ⁴⁶ William Langer, *Aggregate and the Environment*, (American Geological Institute, 2004), 46.
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- ⁵³ Thomas Goreau, *Marine Electrolysis for Building Materials and Environmental Restoration*, (In-Tech, 2012), 279.
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- ⁵⁶ Sidney Mindess, *Developments in the Formulation and Reinforcement of Concrete*, (CRC Press, 2008), 64.
- ⁵⁷ Stephano Mion, Personal Interview. October 23, 2015.
- ⁵⁸ Kumar Mehta, *Concrete: Microstructure, Properties and Materials*, (McGraw-Hill, 2006), 638.
- ⁵⁹ Heinz Lowenstam, *On Biomineralization*, (Oxford University Press, 1989), 17.
- ⁶⁰ Wolf Hilbertz, *Electrodeposition of Minerals in Sea Water: Experiments and Applications*, (IEEE, 1979), 109.
- ⁶¹ Wolf Hilbertz, *Electrodeposition of Minerals in Seawater*, (University of Texas, 1979), 705.
- ⁶² Wolf Hilbertz, *Electrodeposition of Minerals in Sea Water: Experiments and Applications*, (IEEE, 1979), 110.
- ⁶³ Mitchell Joaquim, "Don't build your home, grow it!" TED Conferences LLC. www.ted.com.

Definitions provided by Merriam-Webster. <http://www.merriam-webster.com/dictionary/definition>

CHAPTER 4

Biotope: is an area of uniform environmental conditions providing a living place for a specific assemblage of plants and animals.

CHAPTER 4: Design Proposal

This dissertation began by questioning current construction methods and materials, as well as their adverse effects on our planet. The following chapter introduced a new building material, Electrorock, which will help resolve many current ecological issues we face today such as overexploitation, energy consumption, CO2 emissions, and waste management. The history and evolution of mineral accretion technology (MAT) is then further expanded upon in preceding chapters. The succeeding segments are primarily focused on my electrochemical explorations and the potential benefits of implementing this technology. Lastly, this chapter will focus a factory design proposal that will be responsible for the commercial manufacturing of Electrorock products and their distribution.

*The Hazen Creek Facility (HCF) will become a beacon for future factories, as it will exclusively rely on renewable energy. It will not only harness the power of natural resources, but will also run-off of natural gases produced in-house from electrolysis procedures. The building's design will include a prefabricated structure that will house the manufacturing section, as well as a more dynamic wing that intersects through the factory at an oblique angle that contains the sales and information center for Electrorock. In addition to the pragmatic programs required, this proposal will also include a series of **biotope** pavilions spread throughout the site. HCF and its eco-habitats will serve as a place for locals to retreat from their polluted city centers and reconnect with nature. It will also provide new shelter nodes for indigenous and migrating animals to help re-activate and rehabilitate the site. The exterior shell of the factory will demonstrate the flexibility of these products, ranging from basic flat panels to custom dynamic panels.*

The site selected for Electrorock's facility is an area near Hazen Creek in Saint John, Canada. This location was primarily chosen for its accessibility, proximity to major trading ports, surrounding marsh lands, neighboring industrial and residential zones, and direct access to seawater, refer to Figure 20. Unfortunately, the site has been neglected over that past few decades and has experienced significant damage to its bionetworks. The degradation of Red Head Marsh lands began with the construction of a small dam in 1980 that was built to help stabilize water levels between the marsh and the Bay of Fundy. Ecologist later realized the dam was preventing back-and-forth flow between the two bodies of water, which killed off many fish species, leading to the failure of nearby ecosystems. Since this discovery, the dam has been removed and the area has shown significant signs of improvements.⁶⁴

Fortunately, the site is situated on the northern shore of the Bay of Fundy, which constantly delivers HCF a fresh supply of seawater. This was a

major factor in decided the final location of the factory since MAT requires both saline to keep the electrolyte conductive, and calcite minerals to successfully accrete calcium carbonate (CA) products. Thus, by having an unlimited source of seawater collected from the North Atlantic Ocean, HCF will not have to import any salts or minerals, making this location cost-effective.

Figure 20. Site Plan.

According to Sorokin's studies, nearly 15% of total area of modern reefs are situated in the Atlantic Ocean, signifying that this oceanic region is saturated with rich nutrients and minerals.⁶⁵ Hilbertz and Goreau's experiments were all conducted in tropical waters, because warm temperatures increase the rate of reaction. The average temperature of the North Atlan-

tic Ocean is $\pm 38^{\circ}\text{F}$ which is considerably cooler than 80°F , which was the average temperature for the Seacrete explorations.⁶⁶ However, HCF is an enclosed system and can merely heat the tanks in which the products are being grown to any desired temperature using geothermal energy and photovoltaic panels.

The Bay of Fundy area possess many untapped natural resources that appealed to me during my site selection phase. For instance, this bay is home to the highest tides in the world, cycling through 160 billion tonnes of seawater per day, refer to Figure 21.⁶⁷ This large influx and efflux of water provides raw power that can be harnessed through an in-stream tidal turbine to generate additional power for the factory. Another renewable energy source that is readily available here, are the predominant coastal winds. Saint John is among the top 10 cities in Canada that receive the strongest winds annually, making it a perfect site for wind powered generators.⁶⁸

Figure 21. Bay of Fundy tide. Image provided by google images.

Port Saint John is a stone throw away from Hazen Creek and offers HCF direct access to the global market and convenience for any imported or exported materials. This accessibility will help Electrorock grow and prosper worldwide, refer to Figure 22. The surrounding area of the site includes many industrial buildings, such as the Wastewater Treatment Facility, and Canaport LNG, which makes this proposal slightly more feasible as this factory will not stand out. It will also endeavor to enhance the local ecosystems through its design and biotope pavilions to help revitalize Red Head Marsh to its former glory.

Figure 22. Distribution Map.

Hazen Creek Facility design is composed of two separate volumes that intersect one another diagonally. These volumes are oriented to maximize total sun exposure throughout the day, between all seasons. This will help keep heating and electrical cost down, and will provide enough solar exposure for the photovoltaic panels to be effective. To minimize the amount of new infrastructure required, the plant is positioned along an existing street, Red Head Road. The footprint and scale of the factory was based on the Central Precast plant, located in Ottawa. Their budding footprint is approximately 60,000 sq.ft. plus a massive yard used for temporary storage and finalization of their panels.⁶⁶ I was able to significantly reduce the footprint size to 35,000 sq.ft. because Electrorock's products can be manufactured vertically, which requires much less ground floor area.

The first wing, facing east-west is dedicated to the manufacturing of Electrorock products. Its form follows its function, as this portion of the building is composed of a linear prefabricated steel structure that is clad with its own merchandise. The shell of the structure is intermittently penetrated with a sequence of windows, skylights, and a large clearstory above to allow indirect light to enter the space and provide a bright working space. The factory floor is subdivided into four major sections; the steel workshop, the accretion tanks, the drying zone, and the loading zone, refer to Figure 23. The factory also includes essential programs such as offices, control center, and all work related amenities.

Figure 23. Ground floor plan.

There are two types of stainless steel tanks used for the mineral accretion (MA) process. Type A is dedicated to producing standard panels offered from Electrorock's catalogue, and Type B is to produce customized panels, refer to Figure 24. Type A tanks are efficiently designed to house eight standard panels that can vary in height. To ensure optimal and uniform electrical field strength, the tanks interior is coated with platinum, and there is a platinum rod suspended in the center. The cylindrical shape of the tanks guarantees that the eight submerged steel frames are exposed to the exact same electrical conditions, creating uniform growth. The electrolyte solution (seawater) is continuously pumped through all the tanks, constantly replenishing the mineral concentration, increasing accretion rates. The circular profile was also chosen because it allows for the most panels within a small volume, ultimately reducing the total amount of heated water required. Customized panels however, require larger tanks to compensate for any geometry that might be demanded. Thus, Type B tanks are essentially large pools of seawater that allow steel frameworks of all shapes and sizes to be submerged and accreted to specified thickness. All the tanks are equipped with a small hatch, in case samples or additional minerals need to be added. The lid of each tank is connected to a ventilation system that extracts the hydrogen gas to the mechanical room, where it is transferred into electricity using hydrogen generators. The system also collects the oxygen off-gassed from the electrolysis process and releases it into the factory to create a healthy work environment.

Figure 24. Interior perspective render of factory floor.

The floor plan was designed to be as efficient as possible, to diminish the amount of staff. Thus, there is an automated overhead crane system implemented to lift and transport the products from the very beginning of the process right until the end. This system will allow employees to move the products safely with precision, while not exhausting any downtime. The west-end of the factory has a private employee entrance, as well as two large loading bays to allow flatbed trucks to back in and load the products, refer to Figure 25.

Figure 25. Interior perspective render of loading bay.

The second wing, running parallel to Red Head Road contains the main sales and information center for Electrorock, that will educate visitors on the mineral technology used and its ecological benefits. This volume completely contradicts the factory, as its design is purely organic and spatial. This portion disregards any traditional architectural principles and ex-

plores new structures and spaces that playfully interact with one another in the X, Y, and Z plane, refer to Figure 26. The ends of this volume cascade down from the tall factory walls to meet the surrounding marsh lands and relate to a more human scale near the public entrance. These dynamic panels begin to simplify their geometry as they approach the standardized panels of the factory wall, eventually seamlessly blending together. This approach was used to show the viewer's Electrorock's full spectrum, ranging from standard architectural cladding panels to extremely complicated forms. This fluid-like portion of the building is intended to be overgrown by the surrounding nature, allowing natural moss and plants to cover its surface, and indigenous animals to inhabit its skin, refer to Figure 27.

Figure 26. Short Section.

Figure 27. Exterior perspective render of factory.

The Hazen Creek Facility (HCF) is designed to produce anywhere between two to four thousand architectural panels annually to be able to compete with precast companies within the same vicinity.⁷⁰ As mentioned in preceding chapters, MAT allows one to control its porosity level and strength value. These modifications can be achieved by altering the electrical parameters set during the accretion process, and by varying the chemical mixture of the electrolyte bath. This gives the client more freedom to modify their order by specifying the exact qualities desired. Electrorock's catalogue delivers an array of different products ranging from screens, panels,

, insulated panels, reinforced panels, and slabs that are available in several modular sizes. It also provides the option for completely customized panels that require a prefabricated metal formwork for the minerals to adhere to. These products are different from precast products because they are 100% recyclable, and can easily be repaired.

To guarantee proper alignment and installation, the panels are equipped with adjustable connection points to help with any complications on site. They also include fastener clips to ease transportation and positioning, as well as a tongue and groove joint along its edges to fit seamlessly, refer to Figure 28. The edges of the metal scaffolding are temporarily covered with rubber during the accretion process to block conductivity to prevent any growth around the frame, so they can fit smoothly together. Rubber is used because it is a good insulator and blocks the electrical current.

Figure 28. Panel connection detail.

Designer can really begin to play around with these modification and potentially try to enhance building performance. For instance, one could specify thicker walls for the areas that are going to be exposed to prevailing winds or that will not receive much daylight. Or one could specify a more permeable membrane to allow more light penetration for the areas that receive ample amounts of light. Another technique could consist of a series of smaller pockets on the exterior membrane that gradually grow larger towards the inside, which could help prevent heat from escaping. Once the panels have been fully accreted, they client also has the option to tailor their panels by sandblasting it, which can remove any impurities or engrave/contour any details.

Ecosystemic: is a community of organisms interacting with each other and with their environment such that energy is exchanged and system-level processes, such as the cycling of elements, emerge.

The HCF and biotope pavilions are designed to provide new habitats and shelter nodes for indigenous and migrating animals, in hopes of restoring ecological biodiversity at Red Head Marsh and Hazen Creek, refer to Figure 29. The master plan for this proposal also includes a new network of paths though the marsh lands that will provide locals with walking trails and viewing platforms. There will be a series of information hubs along these paths that will inform travelers of specific creatures on site, as well as Electrorock's contribute to the site.

CHAPTER 4: Design Proposal

Figure 29. Red Head Marsh, St. John. Image provided by google images.

*Generally, every modern development that interferes or disrupts any natural system is obligated to replace or to restore the systems after construction, in order to obtain a permit. Unfortunately, the restorations are rarely equivalent to the original and lack the complexity of **ecosystemic** interrelations.⁷¹ For instance, the Red Head Marsh area was once a very popular birding site in Saint John and was slowly dissolved with the implementation of man. However, it is now slowly beginning to come back over time with the removal of the dam. I believe “ecology and industry are not one-way streets, [but should in fact be] crossroads.”⁷² These strategies strive to revitalize the site by bringing back by repairing damaged habitats and degraded ecosystems.*

⁶⁴ CBC News, "Wildlife Returning to Red Head Marsh", CBC News, New Brunswick, Accessed March 20, 2016.

<http://www.cbc.ca/news/canada/new-brunswick/wildlife-returning-to-red-head-marsh-1.652451>

⁶⁵ Yuri Sorokin, *Ecological Studies: Coral Reef Ecology*, (Springer, 1995), 2.

⁶⁶ Paul Hebert, "Atlantic Ocean", *The Encyclopedia of Earth*, Accessed March 28, 2006.

<http://www.eoearth.org/view/article/150279/>

⁶⁷ Bay of Fundy Tourism Partnership, "The Phenomenal Bay of Fundy", Tantramar Interactive Inc., Accessed March 24, 2016. <http://bayoffundytourism.com/>

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⁶⁹ Stephano Mion, Personal Interview. October 23, 2015.

⁷⁰ Ibid.

⁷¹ *Environmental Restoration, ethics, theory, and practice*- p.128

⁷² William Throop, *Environmental Restoration: Ethics, Theory, and Practice*. (Humanity Books, 2000), 12.

Definitions provided by Merriam-Webster. <http://www.merriam-webster.com/dictionary/definition>

CONCLUSION

CONCLUSION

We should take this opportunity to learn from biology and mimic basic design strategies to enhance our current construction methods and materials, while preventing any further deconstruction of our landscapes and resources. Electrorock, is an organic building material that uses a synthetic procedure derived from marine organism that grow their own skeletal structures from dissolved minerals in seawater. This innovative design solution eliminates the need for aggregates and other raw materials, who have recently been overexploited and responsible for +/- 7 percent of global CO₂ emission.⁷³ By taking advantage of the plentiful minerals already available in seawater, we ultimately diminish the number of quarries and mining facilities and the negative connotation associated with them.

Crystallization of calcium carbonate (CC) has proven to not only match the strength and durability of current construction methods, such as concrete, but can supersede them under the right accretion conditions, expanded upon in Chapter Four. The crystalline structure analysis conducted by Wolf Hilbertz, in association with my research states that this CC is approximately three times stronger than regular Portland Cement Concrete.⁷⁴ Mineral accretion technology (MAT) allows one to determine which minerals are accreted, effecting its overall composition. Thus, clients will have the freedom to demand which level of porosity and degree of strength they would like.

Electrorock offers an array of modulated products which range from screens, architectural panels, insulated panels, reinforced panels, and slabs offered in many different dimensions. This technology can also be utilized for custom products, as any prefabricated scaffold can be built for the calcite minerals to adhere to. Some advantages of MAT are that it does not require any formwork on-site during the construction process because the products are grown at the factory and delivered to the site, where they are erected. The products have built in adjustable connection point and fastener clips to ease transportation and positioning. Another benefit of Electrorock technology is the opportunity to consistently and uniformly accrete solid minerals around any frame of all shapes and sizes. Where this product drastically stands out from other systems is its ability to harness and calcify naturally dissolved minerals in seawater, and be able to repair itself if damaged by simply running it through the same process again.

The Hazen Creek Facility (HCF) situated in Saint John, is Electrorock's headquarters and primary manufacturing plant that intends to run solely off of renewable energy collected on-site. The factory will incorporate a geothermal system, photovoltaic panels, wind turbines, and tidal turbines located in the Bay of Fundy. By creating an enclosed system to grow the products, the facility is able to collect the hydrogen gas that's emitted from

the electrolysis of water process to help generate electricity for the plant. This self-sustaining building will provide a template for future factories to strive for, refer to Figure 30.

CONCLUSION

Figure 30. Long section.

The design of HCF and its biotope pavilions aim to reactive the site and increase awareness on how are infrastructures effect local ecosystems. The sporadic structures provide new habitats and shelters for indigenous and migrating species to occupy and flourish. The deign hopes to be eventually overgrown completely with foliage, creating a symbiotic relationship between buildings and nature, as the structures are composed of 100% recyclable minerals. The new network of pants implemented will provide local residents with new trails and observation platforms to witness the natural beauty of Red Head Marsh.

MAT could apply to many different disciplines other than architecture, who are interested in alternative energy sources and zero emissions. Its application could be geared anywhere from commercial manufacturing, to marine building technology, to corrosion protection for off shore oil rigs, to reinforcing structural columns submerged in seawater, such as Venice's underwater structure. The ability to grow architecture provides designers with much more freedom in regards to the built form, ultimately having no restrictions. Electrorock will help us reconfigure and seamlessly integrate future infrastructure within the natural fabric, interlinking biology and technology.

⁷³ Kumar Mehta, *Concrete: Microstructure, Properties and Materials*, (McGraw-Hill, 2006), 638.

⁷⁴ Thomas Goreau, *Marine Electrolysis for Building Materials and Environmental Restoration*, (In-Tech, 2012), 275.

CONCLUSION
Works Cited

APPENDIX A

APPENDIX A

Iteration #01Materials:

- + Power supply with connection cables (Alligator clips)
- + Two coated copper wires
- + Zip ties
- + Anode: 6" copper pipe (0.6" diameter)
- + Cathode: 6" Rebar rod (steel/iron) (0.6" diameter)
- + 14 gallons of well water with 7 cups of Ocean Mix solution
- + 20 gallon aquarium tank
- + 10-20 gallon water pump and biobags
- + Fluorescent tube lighting with tank lid
- + Nikon D5100 on tripod with self-timer connected (every 30 minutes)
- + Kitchen scale

Abstract:

The purpose of this experiment was to successfully precipitate dissolved minerals present in seawater to a metal frame using mineral accretion technology. This process developed by Wolf Hilbertz is currently applied to enhancing the growth of aquatic organism and structures in the sea. The test was to determine if one could reproduce these results in an enclosed system. Although this trial only ran for four hours before being terminated, it provided much compulsory data for future explorations. The results indicated that the electrical parameters were set to high, ultimately leading to the production and off-gassing of hydrogen. These findings have important implication for the next iteration in regards to the power supply settings.

Experimental Procedure:

1. Collect and cut metal pieces to appropriate dimensions
2. Attach metal electrodes to connector cables
3. Fill tank with 14 gallons of well water
4. Insert new biobag in filter and the pump on
5. Take water sample
6. Add 7 cups of Ocean Mix solution into the solution (let sit for 24hrs)
7. Take water sample
8. Weigh electrodes with cable connectors and zip ties
9. Suspend electrodes into solution using the connector cables that hook onto the lid of the tank (keep connection above solution levels to avoid oxidation)
10. Connect alligator clips to top of connector cable (that are connected to the electrodes)
11. Align and focus camera viewport with electrodes in the solution
12. Turn on power supply on with all settings set at zero
13. Change settings to 12.0 Amps and 5.0 volts (average of research settings I found)
14. Set plug-in timer for camera to take a photo every 30 minutes
15. Check-in periodically on process
16. Turn power supply off, due to CO2 alarm being set off
17. Take out electrodes and hang to dry
18. Take water sample
19. Weigh electrodes after 48 hours after extracting from solution
20. Take water samples to be tested
21. Empty and disinfect tank

Results:

The activation of the gas alarm suggested that some gases were being produced though the chemical reaction. After further analysis of electrolysis of seawater, I discovered that hydrogen gas collects around the cathode and oxygen around the anode during the process. The amount of hydrogen produced is dependent on the electrical settings of the power supply. Proper ventilation was originally not accounted for because all of my precedent research took place at sea where the gases released are nearly impossible to account for with currents and wave surge.

Conclusion:

This iteration has proven that the electrical settings of five volts with a current of twelve amps was too high to effectively accrete calcium carbonate through electrodeposition of minerals in seawater within an enclosed system.

APPENDIX A

Iteration #02Materials:

- + Power supply with connection cables (Alligator clips)
- + Two coated copper wires
- + Zip ties
- + Anode: 6" copper pipe (0.6" diameter)
- + Cathode: 6" Rebar rod (steel/iron) (0.6" diameter)
- + 19 gallons of well water with 9.5 cups of Ocean Mix solution
- + 20 gallon aquarium tank
- + 10-20 gallon water pump and biobags
- + Fluorescent tube lighting with tank lid
- + Nikon D5100 on tripod with self-timer connected (every 30 minutes)
- + Kitchen scale

Abstract:

The objective of this experiment was to try and determine the optimal electrical parameters in order to successfully accrete calcium carbonate (limestone). The power supply settings were set much lower for this trial to try and reduce the amount of off-gassing produced. This test ran for twenty-five hours and had precipitated approximately one millimeter of solid mineral around the exposed cathode. Though this was a success, there were still many improvements made. One being that the copper anode was dissolving at a fast rate and staining the solution pale blue, making documentation of the process very difficult. Though extremely conductive and inexpensive, copper had proven itself to be a poor inert electrode for electrolysis of seawater.

Experimental Procedure:

1. Collect and cut metal pieces to appropriate dimensions
2. Attach metal electrodes to connector cables
3. Fill tank with 19 gallons of well water
4. Insert new biobag in filter and the pump on
5. Take water sample
6. Add 9.5 cups of Ocean Mix solution into the solution (let sit for 24hrs)
7. Take water sample
8. Weigh electrodes with cable connectors and zip ties
9. Suspend electrodes into solution using the connector cables that hook onto the lid of the tank (keep connection above solution levels to avoid oxidation)
10. Connect alligator clips to top of connector cable (that are connected to the electrodes)
11. Align and focus camera viewport with electrodes in the solution
12. Turn on power supply on with all settings set at zero
13. Change settings to 0.3 Amps and 2.0 volts
14. Set plug-in timer for camera to take a photo every 30 minutes
15. Turn off after 19 hours of running
16. Turn back on following day
17. Turn off after 6 hours
18. Take out electrodes and hang to dry
19. Take water sample
20. Weigh electrodes after 48 hours after extracting from solution
21. Take water samples to be tested
22. Empty and disinfect tank

Results:

I was able to precipitate approximately one millimeter of calcium carbonate (2 grams) around the steel piece of rebar within twenty-five hours, with the power supply set at 2.00 volts and 0.30 amps. However, throughout this operation the solution slowly began turning pale blue (cyan). I eventually discovered that this discoloration was caused by the copper ions being dissolved into the solution, who inherently absorb red light wavelengths. The copper tubing dissolved 10 grams of its total mass into the solution. This indicates that it is not a good electrode candidate because it would have to be periodically replaced throughout the process once completely diminished.

Conclusion:

This iteration has proven that it is possible to precipitate solid minerals in an enclosed systems with controlled variables. It has also revealed that copper is not an effective electrode for this process and that I must find a non-consumable metal that would resist electrolytic dissolution.

APPENDIX A

Iteration #03Materials:

- + Power supply with connection cables (Alligator clips)
- + Two coated copper wires
- + Zip ties
- + Anode: 6" Lead Bar (0.6" diameter)
- + Cathode: 6" Rebar rod (steel/iron) (0.6" diameter)
- + 18 gallons of well water with 9 cups of Ocean Mix solution
- + 20 gallon aquarium tank
- + 10-20 gallon water pump and biobags
- + Fluorescent tube lighting with tank lid
- + Nikon D5100 on tripod with self-timer connected (every 30 minutes)
- + Kitchen scale

Abstract:

This experiment examined the potential of using lead as the primary anode, as its compounds are not soluble. Lead was successful in maintaining its total mass, but began to oxidize when exposed to the saline solution and electrical current. This ultimately stained the solution a yellow-brown colour (lurid) that eventually cleared up through the filtration system. The lead anode proved itself superior to the copper as it provided the same accretion results but did not show any signs of structural depletion. The only metals that would outperform lead would be noble metals which are much more expensive and rare.

Experimental Procedure:

1. Collect and cut metal pieces to appropriate dimensions
2. Attach metal electrodes to connector cables
3. Fill tank with 18 gallons of well water
4. Insert new biobag in filter and the pump on
5. Take water sample
6. Add 9 cups of Ocean Mix solution into the solution (let sit for 24hrs)
7. Take water sample
8. Weigh electrodes with cable connectors and zip ties
9. Suspend electrodes into solution using the connector cables that hook onto the lid of the tank (keep connection above solution levels to avoid oxidation)
10. Connect alligator clips to top of connector cable (that are connected to the electrodes)
11. Align and focus camera viewport with electrodes in the solution
12. Turn on power supply on with all settings set at zero
13. Change settings to 0.2 Amps and 3.1 volts
14. Set plug-in timer for camera to take a photo every 30 minutes
15. Turn off after 11 hours of running
16. Turn back on following day
17. Turn off after 14 hours
18. Take out electrodes and hang to dry
19. Take water sample
20. Weigh electrodes after 48 hours after extracting from solution
21. Take water samples to be tested
22. Empty and disinfect tank

Results:

By using lead as the anode, I was able to effectively document the accretion process as it did not alter the translucency of the solution. The lead bar weighed the exact same after the entire process (81 grams), which means it did not experience any electrolytic dissolution, although it showed to be susceptible to corrosion. The rebar cathode precipitated 2 grams of calcium carbonate within the 25 hours of operation with the power supply settings at 3.1 volts and 0.20 amps.

Conclusion:

This trial verified that lead is a greater metal to be used for an anode, as it does not deteriorate in the solution like copper did. However, lead still oxidizes in the solution which can affect the electric field strength between the electrodes. Thus in order to avoid corrosion and oxidation I must use a noble metal such as platinum, silver, or gold. This one eliminate the need to replace the anode and would create a more powerful connection between the electrodes.

APPENDIX A

Iteration #04Materials:

- + Power supply with connection cables (Alligator clips)
- + Two coated copper wires
- + Zip ties
- + Anode: 6" Lead Bar (0.6" diameter)
- + Cathode: 6" X 1" Lead Bar
- + 18 gallons of well water with 9 cups of Ocean Mix solution (Reef & Crystals)
- + 20 gallon aquarium tank
- + 10-20 gallon water pump and biobags
- + Fluorescent tube lighting with tank lid
- + Nikon D5100 on tripod with self-timer connected (every 30 minutes)
- + Kitchen scale

Abstract:

The purpose of this test was to investigate if a higher concentration of calcium and magnesium in the electrolyte would increase growth rates. This experiment used an enriched ocean mix solution which contained higher mineral levels that ensure growth and survival of corals and other invertebrates. An important observations was that I was unable to match the electrical parameters set at the beginning when I went to turn on the power supply back on. Additionally, the electrical current began to slowly diminish as the cathode continued to precipitate calcium carbonate.

Experimental Procedure:

1. Collect and cut metal pieces to appropriate dimensions
2. Attach metal electrodes to connector cables
3. Fill tank with 18 gallons of well water
4. Insert new biobag in filter and the pump on
5. Take water sample
6. Add 9 cups of Ocean Mix (reef & crystals) solution into the solution (let sit for 24hrs)
7. Take water sample
8. Weigh electrodes with cable connectors and zip ties
9. Suspend electrodes into solution using the connector cables that hook onto the lid of the tank (keep connection above solution levels to avoid oxidation)
10. Connect alligator clips to top of connector cable (that are connected to the electrodes)
11. Align and focus camera viewport with electrodes in the solution
12. Turn on power supply on with all settings set at zero
13. Change settings to 0.20 Amps and 04.8 volts
14. Set plug-in timer for camera to take a photo every 30 minutes
15. Turn off after 16 hours of running (09.08.15)
16. Turn back on following day
17. Turn off after 6 hours (09.08.15)
18. Take out electrodes and hang to dry
19. Take water sample
20. Weigh electrodes after 48 hours after extracting from solution
21. Take water samples to be tested
22. Empty and disinfect tank

Results:

Throughout the 22 hours of its operation, the steel cathode managed to accrete a total of 2 grams of calcium carbonate while the lead anode remained the same. These results demonstrate that having a higher concentration of minerals within the solution does not increase the rate of accretion. Another observation worth discussing is that I was unable to maintain the same electrical parameters set forth at the beginning of the experiment. The power supply settings began at 4.80 volts and 0.20 amps and gradually changed to 11.0 volts and 0.06 amps. This suggest that the precipitated minerals on the cathode and the corrosion of the anode are diminishing the electrical field between the electrodes.

Conclusion:

Not a significant change with new solution. Accretion does effect electrical field strength. And electrical parameters control accretion and porosity. Can't match setting once turned off and back on. Need right amount of hydrogen to create channels through calcium to maintain electric field strength.

APPENDIX A

Iteration #05**Materials:**

- + Power supply with connection cables (Alligator clips)
- + Two coated copper wires
- + Zip ties
- + Anode: 6" Lead Bar (0.6" diameter)
- + Cathode: 4"X4" Nickel Mesh
- + 18 gallons of well water with 9 cups of Ocean Mix solution (Reef & Crystals)
- + 20 gallon aquarium tank
- + 10-20 gallon water pump and biobags
- + Fluorescent tube lighting with tank lid
- + Nikon D5100 on tripod with self-timer connected (every 30 minutes)
- + Kitchen scale

Abstract: Purpose,

The objective of this experiment was to explore the potential of the accretion process. I wanted to see if I could not only precipitate minerals around the perimeter of a metal element, but if I could grow enough fill a void. Thus Iteration 5 used a 4"X4" nickel wire mesh as the cathode with 1/2" spacing to see if we can accrete enough calcium carbonate to fill the openings. Nickel proved to be a poor electrode as the tips of the wire began to corrode, ultimately creating a weak surface for the minerals to adhere to. A key finding throughout this trial was that the solution had depleted nearly half of its original content before being terminated.

Experimental Procedure:

1. Collect and cut metal pieces to appropriate dimensions
2. Attach metal electrodes to connector cables
3. Fill tank with 18 gallons of well water
4. Insert new biobag in filter and the pump on
5. Take water sample
6. Add 9 cups of Ocean Mix (reef & crystals) solution into the solution (let sit for 24hrs)
7. Take water sample
8. Weigh electrodes with cable connectors and zip ties
9. Suspend electrodes into solution using the connector cables that hook onto the lid of the tank (keep connection above solution levels to avoid oxidation)
10. Connect alligator clips to top of connector cable (that are connected to the electrodes)
11. Align and focus camera viewport with electrodes in the solution
12. Turn on power supply on with all settings set at zero
13. Change settings to 0.20 Amps and 04.0 volts
14. Set plug-in timer for camera to take a photo every 30 minutes
15. Let system run for 190 hours
16. Take out electrodes and hang to dry
17. Take water sample
18. Weigh electrodes after 48 hours after extracting from solution
19. Take water samples to be tested
20. Empty and disinfect tank

Results:

The nickel based wire mesh was able to precipitate 3 grams within 190 hours of operation with the electrical parameters set at 4.00 volts and 0.20 amps. This was a very minimal transformation in comparison to previous trials where I successfully accreted 2 grams within 22 hours. Therefore there was at least one limiting factor present that caused the accretion rate to be diminished. An observation worth mentioning is that the minerals seem to be more attracted to connection points on the mesh where 2 bars intersect, possibly because there is a stronger electrical field present. This was the first experiment to self-terminate itself, as the current between the electrodes eventually stopped. I believe nickel was responsible for this, as it is not nearly as conductive as steel and began to corrode within the solution.

APPENDIX A

Iteration #06 & 07Materials:

- + Power supply with connection cables (Alligator clips)
- + Two coated copper wires
- + Zip ties
- + Anode: 6" Lead Bar (0.6" diameter)
- + Cathode: 4"X4" Aluminum Mesh
- + 18 gallons of fresh water with 9 cups of Ocean Mix solution (Reef & Crystals)
- + 20 gallon aquarium tank
- + 10-20 gallon water pump and biobags
- + Fluorescent tube lighting with tank lid
- + Nikon D5100 on tripod with self-timer connected (every 30 minutes)
- + Kitchen scale

Abstract:

The aim of these experiments was to try and simulate the exact same results for 2 separate test. This is crucial for the development of this technology because I would need to be able to guarantee consistent and uniform growth of these structural panels. Thus I ran the two trials under precisely the same conditions and was able to achieve identical results. One major change that I implemented was the use of purified water instead of well water because I needed to guarantee the same chemical formula for the electrolyte. Aluminum was the metal of choice for this iteration, although an additional electrical clamp was required to enhance the electrical field between the electrodes. Aluminum proved to be a poor electrode as it is an amphoteric oxide.

Experimental Procedure:

1. Collect and cut metal pieces to appropriate dimensions
2. Attach metal electrodes to connector cables
3. Fill tank with 18 gallons of well water
4. Insert new biobag in filter and the pump on
5. Take water sample
6. Add 9 cups of Ocean Mix (reef & crystals) solution into the solution (let sit for 24hrs)
7. Take water sample
8. Weigh electrodes with cable connectors and zip ties
9. Suspend electrodes into solution using the connector cables that hook onto the lid of the tank (keep connection above solution levels to avoid oxidation)
10. Connect alligator clips to top of connector cable (that are connected to the electrodes)
11. Align and focus camera viewport with electrodes in the solution
12. Turn on power supply on with all settings set at zero
13. Change settings to 0.20 Amps and 04.0 volts
14. Set plug-in timer for camera to take a photo every 30 minutes
15. Let system run for 50 hours
16. Take out electrodes and hang to dry
17. Take water sample
18. Weigh electrodes after 48 hours after extracting from solution
19. Take water samples to be tested
20. Empty and disinfect tank

Results:

These trials were successful in proving that it is possible to accrete the same amount of calcium carbonate if the same conditions are matched. In this case both aluminum meshes were able to precipitate 3 grams of solid minerals within 50 hours of operation with the power supply set at 4.00 volts and 0.20 amps. After further analysis and research I discover that aluminum is the only common metal that readily dissolves under both alkaline and acidic conditions, so it cannot be used as either an anode or a cathode. Another important finding was that I was accreting the mineral brucite, instead of aragonite, which is structurally weak and flakes off. The electrolysis process also increases the rate of evaporation which ends up being 0.02 litres per hour.

APPENDIX A

Iteration #08**Materials:**

- + Power supply with connection cables (Alligator clips)
- + Two coated copper wires
- + Zip ties
- + Anode: 6" Lead Bar (0.6" diameter)
- + Cathode: 4"X4" Steel Mesh with Corrugated steel plating
- + 18 gallons of well water with 9 cups of Ocean Mix solution (Reef & Crystals)
- + 20 gallon aquarium tank
- + 10-20 gallon water pump and biobags
- + Fluorescent tube lighting with tank lid
- + Nikon D5100 on tripod with self-timer connected (every 30 minutes)
- + Kitchen scale
- + Water Heater
- + Liquid Calcium

Abstract:

This experiment strived to achieve maximum accretion rate by trying to solve for the limiting factors. For instance I added a tank heater to the solution because it is proven that corals grow faster and harder in warm tropical waters. I also periodically mixed in additional liquid calcium to electrolyte to try and replenish what has already been accreted. The cathode was composed of a steel wire mesh that was enclosed with a perforated steel sheet, which provided a stronger electrical field connection between the electrodes. This iteration is the most successful so far as it has proven that it can fill in small voids within the panel.

Experimental Procedure:

1. Collect and cut metal pieces to appropriate dimensions
2. Attach metal electrodes to connector cables
3. Fill tank with 18 gallons of well water
4. Insert new biobag in filter and the pump on
5. Take water sample
6. Add 9 cups of Ocean Mix (reef & crystals) solution into the solution (let sit for 24hrs)
7. Take water sample
8. Weigh electrodes with cable connectors and zip ties
9. Heat water to 78 degrees Fahrenheit for 24 hours
10. Suspend electrodes into solution using the connector cables that hook onto the lid of the tank (keep connection above solution levels to avoid oxidation)
11. Connect alligator clips to top of connector cable (that are connected to the electrodes)
12. Align and focus camera viewport with electrodes in the solution
13. Turn on power supply on with all settings set at zero
14. Change settings to 0.20 Amps and 04.0 volts
15. Set plug-in timer for camera to take a photo every 30 minutes
16. Periodically add 100 milliliters of liquid calcium every 12 hours
17. Let system run for 159 hours
18. Take out electrodes and hang to dry
19. Take water sample
20. Weigh electrodes after 48 hours after extracting from solution
21. Take water samples to be tested
22. Empty and disinfect tank

Results:

By providing an ideal atmosphere for accretion I was able to precipitate 9 grams for calcium carbonate within 159 hours of operation. The majority of this growth occurred around the steel frame, especially near the intersecting areas then eventually cultivated over the perforated sheet. To avoid the precipitation of the mineral brucite I lowered the electrical settings to attract aragonite which is a carbonate mineral. The x-ray powder diffraction analysis provided by Carleton's University chemistry department confirmed the crystalline structure to be that of aragonite. A significant observation was that of the hydrogen pores that channel from the metal to the electrolyte. These pores are crucial for the continuous growth as they allow electrons to flow through them. Iteration 8 was terminated because the solution level was getting to low due to evaporation.

APPENDIX A

Iteration #09**Materials:**

- + Power supply with connection cables (Alligator clips)
- + Two coated copper wires
- + Zip ties
- + Anode: 6" Lead Bar (0.6" diameter)
- + Cathode: 4"X4" Steel Mesh with Corrugated steel plating
- + 18 gallons of well water with 9 cups of Ocean Mix solution (Reef & Crystals)
- + 20 gallon aquarium tank
- + 10-20 gallon water pump and biobags
- + Fluorescent tube lighting with tank lid
- + Nikon D5100 on tripod with self-timer connected (every 30 minutes)
- + Kitchen scale
- + Water Heater
- + Liquid Calcium

Abstract:

This final experiment endeavored to achieve maximum accretion rates over an undulating surface. Previous experiments have proven that it is possible to completely encase a flat steel frame panel with calcite minerals. However, I wanted to see if similar results could be attained over an irregular plane. Iteration 9 used a 4"X4" steel frame with corrugated steel sheets welded in-between. The form of the cathode did not seem to affect the uniform growth pattern.

Experimental Procedure:

1. Collect and cut metal pieces to appropriate dimensions
2. Attach metal electrodes to connector cables
3. Fill tank with 18 gallons of well water
4. Insert new biobag in filter and the pump on
5. Take water sample
6. Add 9 cups of Ocean Mix (reef & crystals) solution into the solution (let sit for 24hrs)
7. Take water sample
8. Weigh electrodes with cable connectors and zip ties
9. Heat water to 78 degrees Fahrenheit for 24 hours
10. Suspend electrodes into solution using the connector cables that hook onto the lid of the tank (keep connection above solution levels to avoid oxidation)
11. Connect alligator clips to top of connector cable (that are connected to the electrodes)
12. Align and focus camera viewport with electrodes in the solution
13. Turn on power supply on with all settings set at zero
14. **Change settings to 0.10 Amps and 01.3 volts**
15. Set plug-in timer for camera to take a photo every 30 minutes
16. Periodically add 100 milliliters of liquid calcium every 12 hours
17. **Let system run for 580 hours**
18. Take out electrodes and hang to dry
19. Take water sample
20. Weigh electrodes after 48 hours after extracting from solution
21. Take water samples to be tested
22. Empty and disinfect tank

Results:

This expedient ran for approximately 25 days with the power parameters set at 0.10 amps and 01.3 volts, and successfully precipitated over 26 grams of calcium carbonate. This was by far my most successful trial yet, and it proved that accretion rates would not be affected by the shape of the formwork. This iteration was also able to last much longer than the rest because I suspended the cathode near the bottom of the tank so the entire structure would be exposed for the same duration of time, and would not be affected by decreasing water levels caused from evaporation. This is great news, because it confirms that we can accrete panels of all shapes and sizes of any geometry and can guarantee uniform growth.

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