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An Examination of the Seawater Aquarium System at Scripps Institution of Oceanography

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An Examination of the Seawater Aquarium System at Scripps Institution of Oceanography

A thesis submitted in partial satisfaction of the requirements
for the degree Master of Science

in

Marine Biology

by

Daniel Akira Jio

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Professor Stuart Sandin

2022

The thesis of Daniel Akira Jio is approved, and it is acceptable in quality and form for publication on microfilm and electronically.

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ABSTRACT OF THE THESIS

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by

Daniel Akira Jio

Master of Science in Marine Biology

University of California San Diego, 2022

Professor Martin Tresguerres, Chair

Scripps Institution of Oceanography (Scripps Oceanography) utilizes a flow-through aquarium system to provide seawater to the various aquaria used to conduct research on campus; however, information on this system is not readily available. This thesis serves as a guide on how the Scripps Oceanography aquarium system works. Through facility tours and consultation with Scripps facilities staff, information was compiled on the aquarium system from the initial collection of seawater at Scripps Pier, the various filtering, piping, and seawater holding tanks, the aquaria that hold research organisms, and the final disposal of wastewater. This system also includes Birch Aquarium and the NOAA Southwest Fisheries Science Center. This thesis also describes several emergency responses that are available in the event of system failure or extreme seawater conditions, including “crash carts” that can be used as mobile life support systems. Additionally, information on a coral recirculating aquarium system (RAS) built in the Tresguerres laboratory is provided, which better reflects seawater conditions at natural coral reefs instead of California seawater. Finally, this thesis discusses some of the funding, staffing, and infrastructure challenges experienced at the Scripps Oceanography aquarium system, as well as potential measures to improve the aquarium system and lead to better research practices and facility knowledge.

Introduction

In our changing world, knowledge about marine life during current and future conditions is becoming increasingly important. There are numerous aquarium facilities around the world, and they play essential roles on ocean research and education. Although an experimental aquarium housing organisms for research differs in goals and necessities from a public aquarium that displays organisms for educational purposes, both rely on seawater. Whether the water is pumped in from the ocean or recycled in a closed loop, these systems have their own intricacies, advantages, disadvantages, and challenges. Seawater systems are fundamentally different from freshwater ones, as many intricacies can go into the complex water chemistry like salinity, alkalinity, or pH that all can affect research being done using them. Seawater may also have to be created from scratch in certain closed systems with various conditions needing to be perfected, while freshwater systems may be able to run from a tap. Seawater is also more corrosive to its surroundings and would require specialized equipment to run it as well as more frequent replacement.

Knowledge about the features and limitations of the aquarium system is essential for ensuring appropriate husbandry conditions and research practices, as well as for identifying areas for improvement. With recent increased research into the world's oceans such as warming, acidification, hypoxia, harmful algal blooms (popularly known as 'red tides'), and oil spills, seawater aquaria have become more important than ever.

The Scripps Institution of Oceanography (Scripps Oceanography) (University of California San Diego) possesses a system that supplies seawater from La Jolla shores (CA) to a series of flow-through experimental aquaria that house diverse marine organisms and research activities. Research topics include ecology, biology, physiology, and impacts of climate change, while organisms being studied or held include many species of fish, invertebrates like sea urchins or snails, and corals.

In addition, one branch of the system supplies seawater to Birch Aquarium at Scripps (https://aquarium.ucsd.edu/), an oceanographic museum that showcases marine organisms and Scripps cutting-edge research to the general public. However, information about the equipment, infrastructure, and technical details that are essential for the functioning of these aquarium operations are not readily available. Although the Scripps Experimental Aquarium manager and staff (currently Phil Zerofski and Christine Steinke) and the Building Operations superintendent (currently Larry Octon) are available for consultation, they are not always available on short notice, and they may not know all the details off-hand. Thus, the goal of my thesis is to help address this problem by providing an overview of the seawater flow-through system servicing the Scripps and Birch Aquaria. My hope is that my thesis serves as a resource for researchers, administrators, and facilities managers. My thesis provides technical details about the process of seawater distribution starting at the initial collection at Scripps Pier, continuing through various plumbing, seawater holding tanks, and aquarium tanks that house organisms, and ending with wastewater disposal at five outfalls on the beach. Finally, my thesis identifies current challenges, existing plans and equipment to mitigate the effects of extreme seawater conditions such as those experienced during typical spring red tide events, and suggestions for future improvements.

One of the major challenges of the Scripps and Birch Aquaria is that the quality of the source seawater is highly variably due to natural seasonal and oceanographic conditions. And while some degree of fluctuation is normal and inconsequential, larger events could affect the health of the organisms. For example, red tides can cause dangerous oxygen levels (hyperoxia, hypoxia or anoxia), extreme acidification, and produce harmful toxins. One recent example of a red tide near Scripps Oceanography occurred in the spring of 2020, when above-normal rain precipitation combined with warm temperatures facilitated conditions for a widespread algal bloom that lasted over a month. At the peak of the red tide, oxygen levels fluctuated greatly: the increased photosynthesis from the algal bloom raised oxygen to hyperoxic levels around April 26th and the decay of the algae resulted in a drop in oxygen to hypoxic and anoxic levels in May (Figure 1A). In addition, pH levels in the ocean reached a minimum of 7.0, which is much more acidic than normal conditions with pH ~8.1 (Figure 1B) and also much more acidic than the most extreme predicted scenarios of future ocean acidification, which estimate an average open ocean pH of ~ 7.70 by the year 2100 (Bernie et al. 2010).

Despite the great effort by the aquarium and facilities staff and the researchers, this extreme red tide event overwhelmed all the safety mechanisms that were available at the moment. And to make things even worse, this red tide event took place in the midst of the Covid-19 pandemic, imposing additional challenges due to the mandates for reducing personnel density on campus and for maintaining social distancing. As a result, the harmful seawater conditions present off of Scripps Pier were eventually translated to the flow-through aquaria leading to widespread stress and mortality of the organisms housed there (Figure 2). To mitigate similar damage during future red tides, additional safety measures have been put in place at Scripps, including additional filtering systems at the pier and “crash carts” that can be used to temporarily improve the seawater quality in the aquaria holding organisms.

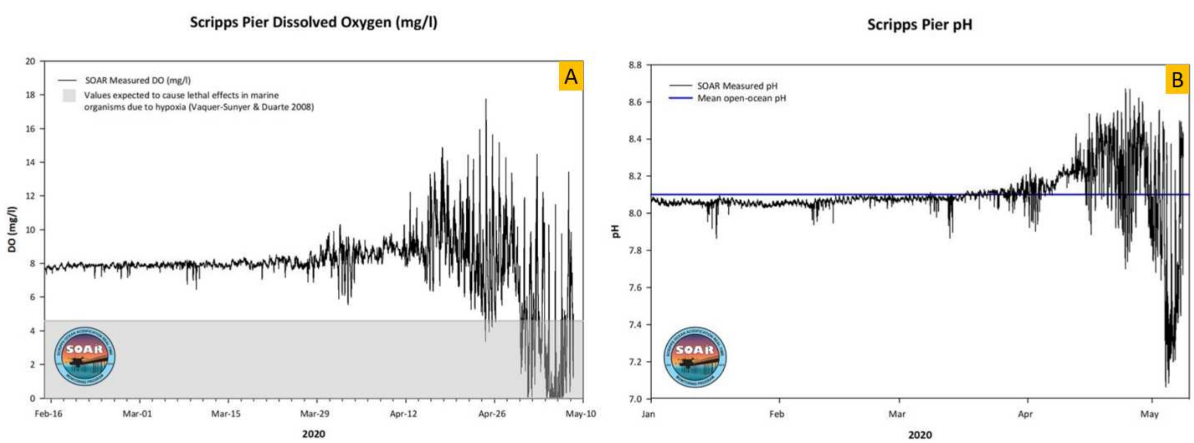

Figure 1: Oxygen and pH levels at Scripps Pier during a red tide in the spring of 2020. A) Oxygen levels. Notice the huge diurnal swings starting around March 29, with hyperoxia during the day due to phytoplankton photosynthesis and hypoxia and even anoxia at night due to phytoplankton and microbial respiration. B) pH levels followed a similar pattern as oxygen: very high pH levels during the day, very acidic pH levels at night, and more extreme values as the red tide progressed. Source: Jen Smith (UCSD/Scripps) and Sam Clements (Scripps Ocean Acidification Real-Time (SOAR) monitoring program Scripps-UCSD) https://coralreefecology.ucsd.edu/2020/05/20/soar-spring-2020-report-red-tide-edition/).

Figure 2: Consequences of the 2020 red tide. (A) Visually murky water conditions in tanks. (B) Mortality of coral held in the flow-through system. (C) Mortality of fish held in the flow-through system. Photo credits: Martin Tresguerres (UCSD/Scripps).

Experiments being done at Scripps require stable seawater conditions to ensure their welfare as well as replicability of the experiments. Seawater conditions can affect the biology of these organisms, which can in turn affect experimental results. For example, ocean acidification studies need careful and controlled water conditions as well as standardized holding conditions. Replication of results is important to science and knowing how conditions may vary and when is key to better research. Elaborate systems like the one at Scripps may be difficult to maintain or keep stable, affecting the science being done. Alternatives to the flow-through system are also in place at Scripps. In addition to the flow-through aquarium system, many research laboratories at Scripps Oceanography use recirculating aquarium systems (RAS) that continuously condition seawater within a closed loop. When experimental needs are not met by a flow-through system, it may be advantageous to utilize a closed RAS instead. The stability and degree of control is higher in a RAS, especially with the seawater within. Events like the 2020 are an incentive to building more closed systems which are not subject to environmental variability. I will discuss a RAS that I helped establish in the Tresguerres Laboratory, which is being used for experimental research on corals.

Methods

Most of the information about the Scripps Oceanography aquarium system was obtained through guided tours by Phil Zerofski, the Experimental Aquarium Manager at Scripps, who allowed me access to the different areas of the aquarium system and provided documentation and explanation of the various components. The pictures included in this thesis were taken during these tours. Additional information was provided by Larry Octon, the Building Operations Superintendent, through tours, facility blueprints and plans, and digital contact.

The information about the aquarium system at Birch Aquarium were provided by Fernando Nosratpour, an Associate Curator at Birch Aquarium, who also provided behind-the-scenes tours of the piping system outside the building and the quarantine and exhibit tanks inside the building. Other aspects of Birch Aquarium were deemed confidential and therefore could not be shared with me.

Details on and photos of the 2020 red tide were provided by Dr. Martin Tresguerres of the Tresguerres Laboratory, as I was not present during it.

Plans for a coral RAS in the Tresguerres Laboratory started in 2020. Originally, the system was to be built from scratch by myself and other members of the laboratory; however, UC San Diego Academic Senate and Scripps Oceanography Director's Office funding allowed to purchase a premade zebrafish RAS from Aquaneering, Inc. (San Diego, CA) (https://aquaneering.com/). The rack was assembled in Hubbs Hall (HH)3320A by an Aquaneering representative on July 14, 2021. Over the next eight months, myself and Angus Thies worked to modify the zebrafish system for the housing of coral, including setting up the system with conditions reflecting tropical seawater, light, and biological filters. Brian Zgliczynski from the Sandin laboratory provided essential coral aquarium advice as well as seawater from their own coral systems to seed the biological filter bed. After the seawater conditions stabilized, *Acropora yongei* and *Stylophora pistillata* coral fragments were introduced in March 2022 into the system and continue to be monitored. A CO_2 monitoring system was purchased from Qubit Systems Inc. (Kingston, ON Canada) (https://qubitsystems.com/), which I set up in the coral RAS.

Results

1. Scripps Institution of Oceanography Aquarium System

The Scripps Oceanography aquarium system extends throughout the 177 acres (over 700,000 m2) of the Scripps campus, and includes the Ellen Browning Scripps Memorial Pier, multiple pumps and seawater holding tanks, 11 buildings containing many aquaria and extensive piping both between buildings and within each of them. The buildings on campus that have seawater connections are Kaplan Experimental Aquarium, Hubbs Hall, Scholander Hall, the Hydraulics lab, the new Marine Conservation and Technology Facility (MCTF), the NOAA Southwest Fisheries Science Center, Birch Aquarium, the Electromagnetic Research Facility (EMRF), and outside spigots or piping at MESOM, Keck, and Nierenberg/Spiess Hall. The Scripps aquaria are mainly used for research purposes, and hold a variety of organisms including kelp, coral, crustaceans, and fish. Birch Aquarium is the public outreach center for Scripps Oceanography and features exhibits that include coral reef, Pacific Northwest, and local La Jolla environments.

For the Scripps Oceanography aquarium system overall, the volume of water pumped from the pier is between 650,000 and 750,000 gallons (2,400,000-2,800,000 liters) per day, or ~250,000,000 gallons (946,000,000 liters) per year, with an annual average electricity cost of ~$112,000 between 2021-2022 and yearly maintenance costs in excess of $800,000. Supplying seawater to the future MCTF would add an estimated 100,000 gallons (378,000 liters) per day and ~$16,000 in annual electricity cost.

Figure 3: Map of aquarium systems described in this thesis, as well as seawater flow direction. Imagery ©2022 Data CSUMB SFML, CA OPC, Maxar Technologies, U.S. Geological Survey, USDA/FPAC/GEO, Map data ©2022 Google.

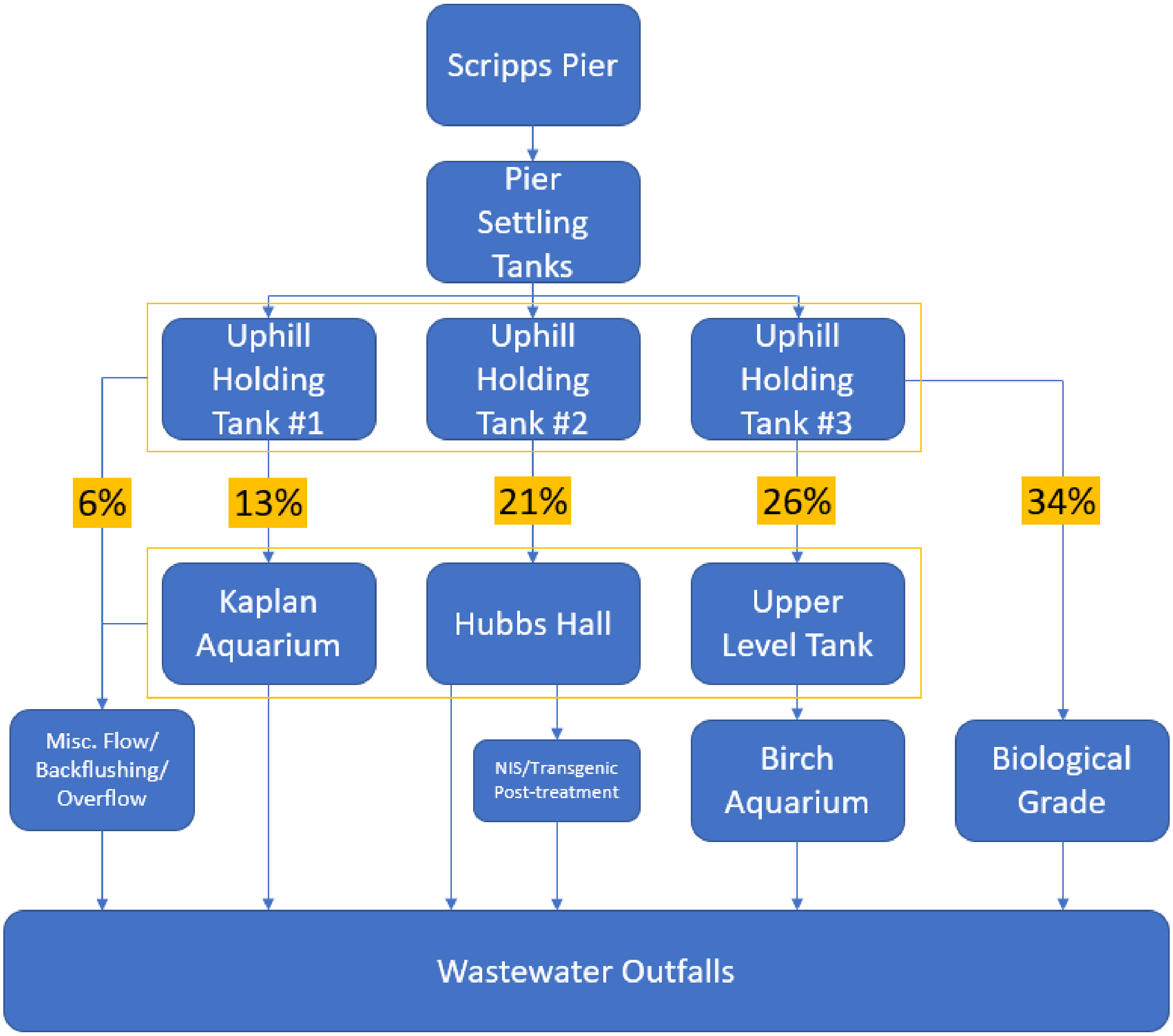

Figure 4: Flowchart showing the flow of seawater from initial collection at the pier and continuing through the Scripps Oceanography aquarium system, including approximate allocation percentage of total seawater flow.

2. Scripps Pier (Pump Station 1 and 2)

The seawater that circulates through the Scripps Oceanography campus, Birch aquarium, and the NOAA Southwest Fisheries Science Center (SWFSC) is collected at the end of Scripps Pier (Figure 5). Collection begins from three gray PVC intake pipes that extend from the pump room at the end of the pier into the ocean (Figure 5A). The distance from the end of these pipes to the seafloor depends on sand buildup and retreat and varies from about 1-3 meters. The ends of the pipes are fitted with cages to prevent swimmers, surfers, and divers from accidentally getting caught in the intake. The inlet pipes

(Figure 5B) are each connected to one of three 40 horsepower (hp) Main Seawater pumps (Worthington 8 CNG 104, stainless steel) which are rated at 1200 gallons per minute (gpm). These are alternated for equal use which suction seawater from the ocean; only one intake pump is running at a time and are alternated weekly at minimum. The suction of the pump closest to shore can often become too close to the sand and have portions of its exclusion cage buried, so overall it runs less. The pump room features two floors: the bottom floor contains pump suction and discharge piping and valves, as well as the Main Seawater pumps, all of which can receive seawater from the intake pipes (Figure 5C), depending on which one is running. Through valve manipulation, the flow-through the piping can be made into a closed loop to backflush water from out of one pump's discharge to another pump's intake pipe and clear any clogs due to sand and kelp. The top floor features control panels for pumps, valves and motors in the pump room, discharge piping, hoists for removing pumps from the lower level, an IT cabinet with network switch, an electrical distribution center for electrical power at the pier, and two vacuum pumps which alternate to help maintain a 21"Hg vacuum on the inlet piping, keeping the suction of the Main Seawater pumps flooded to counter the self-priming problems common with centrifugal-style pumps. From there, the seawater is directed into a detritus filter box (parabolic screen) located on the pier, which removes remaining large materials greater than 2 mm in size like kelp blades, organisms, and inorganic material (Figure 5D). The seawater flow then continues into a spinning drum filter fitted with a poly mesh screen (Figure 5E) that filters the incoming seawater and is constantly self-cleaned off with seawater spray nozzles. The spinning drum can be fitted with mesh of different sizes (18µm, 20µm, 60µm, or 120µm) depending on the seawater conditions. For example, during normal conditions a 60 µm mesh size is used, but during an algal bloom, a smaller mesh of 18 or 20 µm may be used to filter out phytoplankton more efficiently. The waste product (filtrate) from the drum filter flows separately out to a small sandbox/settling tank (Figure 5F) that allows sand and other sediment to be separated out for disposal to landfill, while the cleaned and filtered seawater flows into the trough or "flume" (Figure 5G) along the side of the pier. This flume is slightly inclined towards the base of the pier, which allows the seawater to flow towards the land based on gravity. The pier has a seam near the middle, which allows it to move slightly to prevent cracking due to natural pier movement from waves, tides, and pier operations and expansion and contraction due to seasonal variations in temperature. Similarly, the flume features a flexible connection at that point for the same purpose.

The pump area at the base of the pier is designated "Pump Station 2", where at the end of the flume an additional filter screen made from a layer of 1 mm wedgewire and another layer of ½" mesh stainless steel screen provide backup coarse filtration when the drum and parabolic screen are down for maintenance, and catches small detritus still present in the seawater, before flowing into one of two 19,000-gallon (72,000 liter) settling tanks (Figure 5H) at the base of the pier. Both settling tanks are currently used simultaneously but can be split out and operated separately when necessary to take each individual tank down for maintenance. The tanks are currently operated together to avoid a particular cavitation issue observed due to piping inadequacies which should be resolved in the future. Future plans will include an isolation valve between pumps number 2 and number 3 to allow separation and individual use of the tanks. A water level sensor in the settling tanks controls the pumps at the end of the pier: if a settling tank is running low, the sensor will signal the Main Seawater pumps on the pier to begin water collection, and once a threshold is reached in the tanks, the sensor will then signal to shut off the pumps. On average, the pumps alternate on a 20 min on / 40 min off cycle. Downstream of the settling tanks are four, 600 gpm 40 hp stainless steel pumps (Figure 5I) arranged in parallel, which push the seawater from the settling tanks through the sand filters (Figure 5J) and then direct the water to subsequent holding tanks located uphill at Pump Station 3 near the Old Director's House. The pumps at pump station 2 run in pairs in a LEAD / LAG scheme to match pumping capacity with system load. No more than two of the four pumps will ever operate at one time. Each of the pumps can be individually connected or switched out as needed, and feature rubber connections between the pump and piping to buffer the rigid piping from pump vibrations and as a safety measure that will allow some movement during earthquakes. All of the equipment at Pump Station 2 and the pier settling tanks are monitored by gauges and displays onsite. The system currently operates on pneumatic controls for water level and pump signaling but will be upgraded to solid state controls by the end of 2023.

Figure 5: Scripps Pier area (Pump Stations 1 and 2). (A) Seawater inlet pipes at the end of the pier. (B) Inlet pipe connected to vacuum pump line. (C) Water piping inside the pump room. (D) Parabolic screen that newly collected water passes through. (E) Rotating drum filter. (F) Sediment settling tank. (G) Flume used to transport seawater up the pier. (H) Seawater settling tanks at base of pier. (I) Pumps used to transport seawater uphill to the holding tanks. (J) Sand filters at base of pier.

3. Uphill Holding Tanks (Pump Station 3)

From the Pump Station 2 at the base of the pier, the water is pumped uphill to Pump Station 3 and directed into one of three 60,000-gallon (227,000 liter) holding tanks (Figure 6). These tanks can be cross connected to each other for redundancy when needed, but in general use each serves a different area of the Scripps campus: Tank #1 (South) (Figure 6A) supplies the Kaplan aquarium, the ring tank, and Scholander Hall. Tank #2 (Middle) (Figure 6B) supplies water to Hubbs Hall. Tank #3 (North) (Figure 6C) is generally used to support the north and east parts of campus via the pump array at Pump Station 3, the BFC tank on La Jolla Shore Lane, and the Upper Level Tank near EMRF north of Birch Aquarium. The Upper Level tank services the buildings along Biological Grade including NOAA-SWFSC, the hydraulics lab, MESOM, MCTF, and Birch Aquarium.

Each of these tanks at Pump Station 3 is equipped with an exterior level site glass for visual indication, and an ultrasonic level sensor (Figure 6F) that controls the pumps at the settling tanks (Pump Station 2) at the end of the pier via a combination of pneumatic switches and solid-state controllers that ensure adequate seawater supply and prevent emptying or overflow. Degassers (Figure 6E) on top of each tank serve to remove potentially harmful microbubbles from the water flow before it enters the tank for storage. All of the seawater piping from Pump Station 2 and beyond consists of two separate piping lines which are used alternately (Figure 6G) to provide 100% redundancy. These lines are denoted as “red” or “green” and their use is alternated (approximately) monthly or quarterly to control and minimize growth of biological organisms. Typical use has one line on service while the other is opened to atmosphere to allow time for the organisms to die off before the line is put back in service during the next rotation. The tanks feature a variety of piping (Figure 6H) that can allow for flow control, specifically allowing each tank to be operated separately or cross-connected to any other tank as needed.

Pumping from Pump Station 3 to the Upper Level and BCF tanks is accomplished by four, 250 gpm, 30 hp pumps operating in pairs in a LEAD / LAG operational scheme as determined by the level in the 60,000-gallon Upper Level Tank situated above Birch Aquarium. An ultrasonic level sensor on the Upper Level tank sends real time level signals to a Johnson Controls "Metasys" CGM controller in the pump shed at Pump Station 3 and the controller determines when pumping is necessary. The Metasys controller will start, stop and stage up (start a second pump) based on software setpoints in the Metasys automation system. No more than 2 pumps will ever operate at any given time. The level in the 14,000 gallon-Bureau of Commercial Fisheries (BCF) tank is controlled by an ultrasonic level sensor driving its own local control valve, without any direct communication to the rest of the system.

Figure 6: Uphill holding tanks at Pump Station 3. (A) Holding tank #1. (B) Holding tank #2. (C) Holding tank #3. (D) Side view of holding tank #3. (E) Degassers located on top of the tanks. (F) Water level marker (site glass). (G) Dual seawater intake and output lines. (H) Series of pumps and piping serving the holding tanks.

4. Kaplan Experimental Aquarium

The seawater from holding tank #1 feeds into the Kaplan Experimental Aquarium just down the hill (Figure 7). Upon entering the utility room in the Kaplan Aquarium space, the piping splits, where one branch continues untreated (ambient temperature) while the second branch is cooled by a separate cooling loop to provide approximately 8°C chilled seawater in the experimental aquarium. Cooling for the chilled seawater loop is provided by a McQuay 40-ton air-cooled water chiller (Figure 7C) located behind the Kaplan building via an ethylene glycol loop. The McQuay chiller cools the glycol loop and a 500-gallon insulated glycol storage tank to approximately 28°F which is used through a plate type heat exchanger to generate the supply of colder seawater at 8 °C. Alternative or backup cooling can be provided by another heat exchanger either in parallel or in series with the main glycol/seawater heat exchanger. The second heat exchanger is cooled by "house" chilled water at approximately 45°F from the lower campus chilled water loop and the main chiller in Sverdrup Hall. It is notable that differences in operating temperature between the glycol loop and the "house" loop will limit the effectiveness of the "House" heat exchanger to create chilled seawater at the desired temperature, thus this heat exchanger is not used except to provide pre-cooling of the seawater. When future plans remove cold water species from the Kaplan Aquarium and allow the chilled seawater temperature to be raised to about 12°C (similar to that of Hubbs Hall), this heat exchanger will become an effective, independent means of providing chilled seawater. Currently, both the glycol heat exchanger and the chilled water heat exchanger are used in series to minimize the load on the McQuay chiller. Motive force for the seawater through the heat exchangers is driven by a jacuzzi pump located in the mechanical space, distributes the water to the heat exchangers (Figure 7B), and then into the aquarium space throughout Kaplan. Lines carrying ambient seawater flow directly into the aquarium and service tanks or racks holding organisms (Figure 7E). Currently there is no warm water line, however a placeholder pipe and a small heat exchanger for warm water (currently not in use) are present in anticipation for a future installation. The Kaplan aquarium building features three separate side rooms (Figure 7A) of about 2.5 meters by 4.5 meters, which contain air lines and ambient and chilled water lines and allow for experiments in an enclosed space where aspects like light, or pH can be controlled. The main floor of Kaplan contains 10 open floor tanks as well as three aquarium racks (Figure 7D) that can be served by the seawater flow. These racks feature a modular design to allow for expansion and customization and can also be converted into recirculating systems as well.

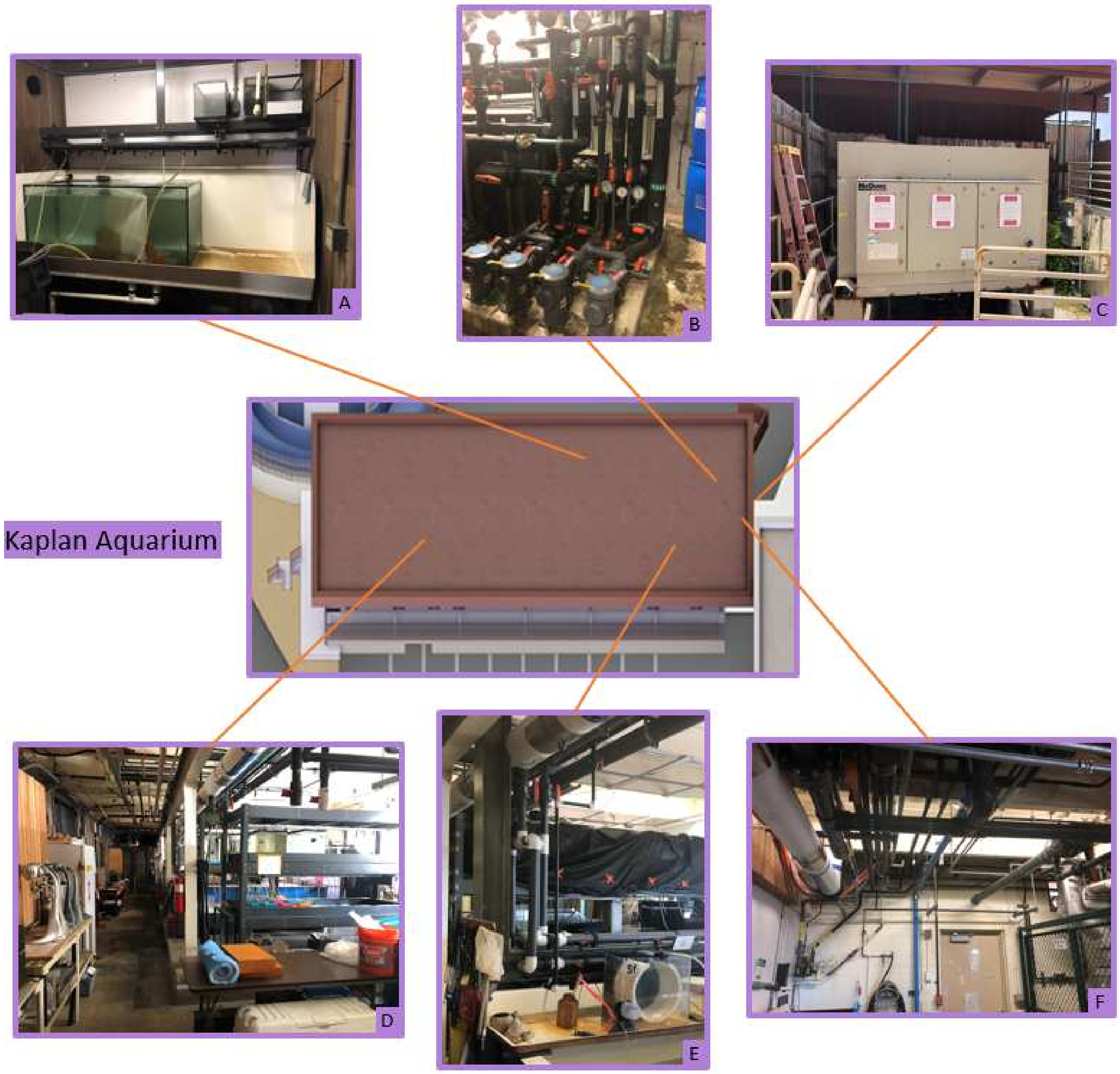

Figure 7: Kaplan Aquarium. (A) Contents of side rooms in Kaplan (B) Heat exchangers and filters. (C) McQuay water chiller. (D) Kaplan interior showing modular racks and seawater plumbing. (E) Example of piping output into a tank. (F) Seawater piping entering the building. The dark gray piping represents ambient seawater and the white piping carries chilled seawater.

5. Hubbs Hall

The seawater from holding tank #2 at Pump Station 3 flows via gravity to Hubbs Hall (Figure 8). The water enters a pump room located on the 2nd floor (HH2460) (Figure 8A), where it is split into various treatments and usages (Figure 8D). Ambient water flows throughout the building to rooms that need ambient water and can be used directly. Some of that ambient water splits off into an ArctiChill 30-ton water-cooled chiller (Figure 8C), which cools a glycol loop in a similar fashion to the glycol loop in the Kaplan Experimental Aquarium. The glycol system is cooled to approximately -2°C and then cools a "Very Cold Seawater (VCW) Loop to between 4°C and 6°C. The VCW is then mixed with ambient seawater via a three-way mixing valve and separate controller to maintain a temperature of 12°C. This serves as the cold seawater line in the building. The chiller has a backup channel for cooling via a separate heat exchanger using "house" chilled water at approximately 42°F. Using the backup heat exchanger, normal 12°C temperature can be maintained even when the Arctic Chill chiller is offline. Certain labs require water that is even colder, as low as 4°C. For those labs (currently only the Rouse Lab), a small heat exchanger is dedicated to strictly to producing a separate RLVCSW (Rouse Lab Very Cold Seawater) loop by the same methods used to create the chilled seawater for the rest of the building. For generating warm seawater, part of the ambient seawater is diverted through a heat exchanger that is warmed by the house heating hot water system via a boiler on the roof of the building to 25-27°C. The warm, cold, and ambient lines branch off as needed throughout the building, including through the core of Hubbs Hall, the experimental aquarium (HH1300) (Figure 8F), and various laboratories or common wetlabs (Figure 8E) used for holding or experiments.

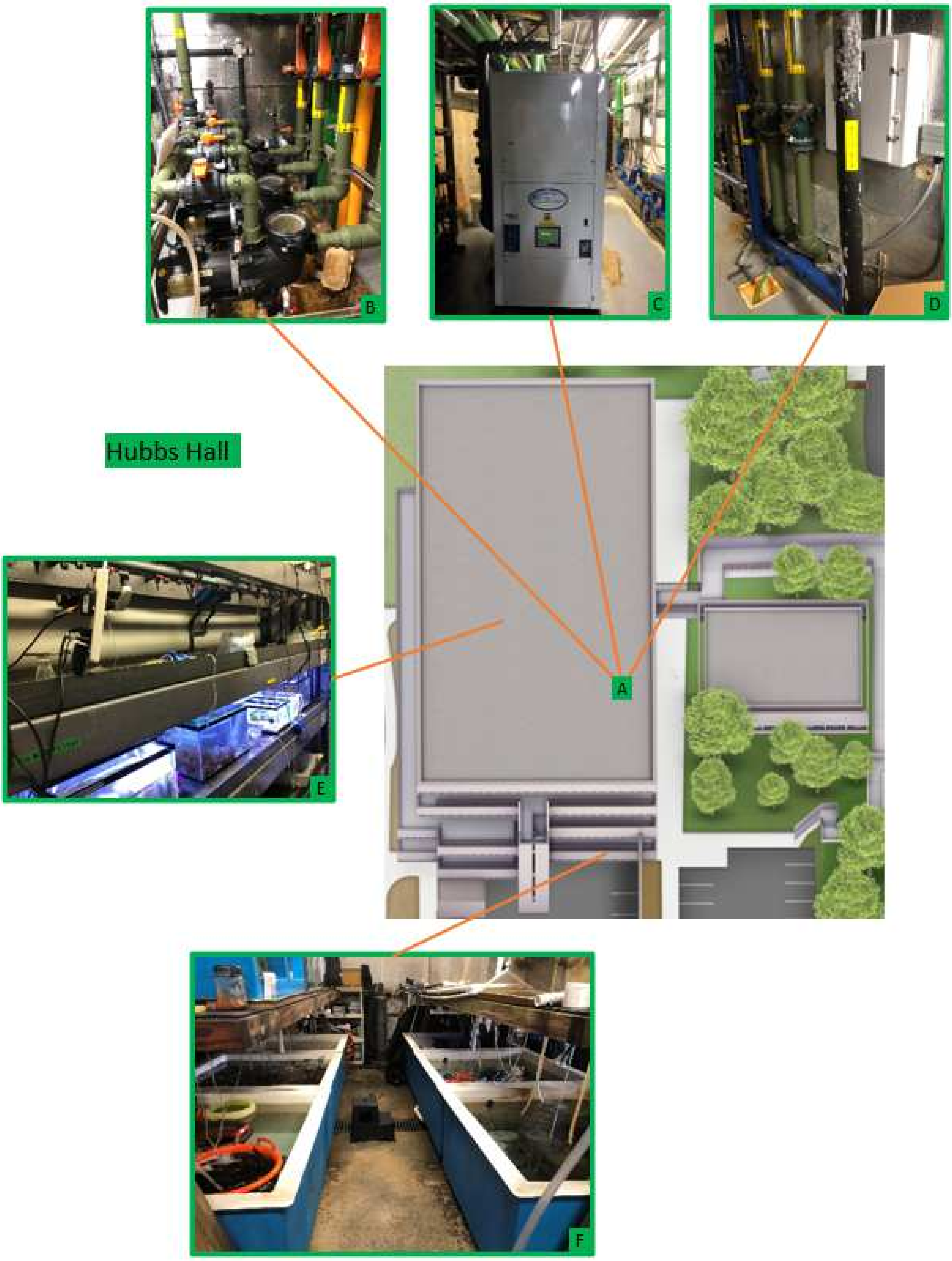

Figure 8: Hubbs Hall. (A) 2nd floor pump room. (B) Pumps controlling water flow in the building. (C) Chiller used to cool water for chilled lines. (D) Chilled, ambient, and warm seawater lines used throughout the building. (E) Seawater usage in wet lab aquarium racks. (F) Larger tanks served by the aquarium system.

6. Birch Aquarium at Scripps

Birch Aquarium is focused on public outreach rather than research; however, it also receives seawater from Scripps pier. Seawater is pumped from the uphill holding tank #3 further uphill to a 60,000-gallon reservoir located north of Birch Aquarium and near the EMRF (Figure 3). This tank has separate distribution piping that supplies seawater by gravity to Birch Aquarium. The Upper Level tank is actually split internally into two separate 30,000 gallon tanks and can be used as individual tanks to provide redundancy in supply for Birch Aquarium. Additionally, the Upper Level tank provides a pressure head back down its own supply/fill lines to the distribution piping installed up the Biological Grade. This piping connects Pump Station 3 and the Upper Level tank with all buildings along Biological Grade, namely NOAA-SWFSC, MCTF, Hydraulics Lab, and Birch Aquarium and additionally serves outdoor spigots located at MESOM, Keck 1 and Nierenberg Hall. At Birch Aquarium, the water enters a booster pump located at a pump and filter pad which splits it into several lines. In addition to the ambient water line, two different heated lines flow into tropical exhibits - one for fish only and the other for live coral exhibits. A chilled line services the Pacific Northwest exhibits, and a local water line flows to the La Jolla exhibits. Additional chillers and heat exchangers located outside the building are used to cool water down during the summer and heat water up if the weather is too cold, respectively. The La Jolla and Gulf Systems have their own sumps/reservoirs with their own sand filters, and these are recirculating systems which receive heated or cooled water (from the booster pump) respectively. Sensors installed in each of the lines can track the water flow running throughout the aquarium. On average, Birch Aquarium uses up about 144,000 gallons (545,000 liters) of water per day and features an alternating red/green line system that is similar to Scripps Oceanography's main campus. In addition to the tanks that are displayed to the public, these lines service quarantine tanks behind the scenes. The amount of water coming into the system is logged three times daily, and flow rates are monitored continuously. Rarely or in case of an emergency (for example, during a red tide event), the incoming seawater flow can be shut off and the system can run exclusively on recirculating water. This recirculation can also be useful in aquaria with colder water, as the chiller would not need to work as hard.

7. Wastewater

The majority of the wastewater from the Scripps Oceanography aquarium system flows out through untreated pipes that open into five outfalls along the beach. Most of the wastewater flows out of two of these outfalls (Figure 9). The main outfall is located north of Scripps Pier, and releases water from Birch Aquarium, Hubbs Hall, and NOAA-SWFSC. The water discharge through this main outfall (Figure 9A) amounts from 470,000 to 700,000 gallons (1,800,000-2,600,000 liters) a day. The secondary outfall for Scripps (Figure 9B) is located underneath the pier and releases water from the Kaplan Experimental Aquarium as well as several seawater holding tanks when they are drained for maintenance. Flow through this outfall can vary from 80,000 to 360,000 gallons (300,000-1,400,000 liters) a day. The discharge from the other three outfalls varies, depending on conditions like storms or settling tank switching/draining, around 10,000-19,000 gallons (38,000-72,000 liters). However, some components of the flow-through aquarium systems do require post-treatment, including those housing non-indigenous species in floors 2-4 of Hubbs Hall, and including those housing transgenic organisms in Hubbs 1300. Water from the systems housing non-indigenous species (NIS) first flows through 25 μm mesh particle filtration and UV sterilization, which is tested at least quarterly to ensure at least a 99.5% bacteria kill rate. Water from the transgenic systems run through 1 μm particle filtration, followed by UV sterilization (with a higher bacteria kill rate than the non-indigenous species water) and an ozone-infused protein fractionator.

The wastewater system at Birch Aquarium is similar to that of the Scripps main campus- most water is returned to the ocean through the same outfall as Hubbs Hall, with some exhibits requiring pretreatment of wastewater before being disposed. Water flowing out of exhibits featuring non-indigenous species pass through a hub that includes several water treatments, such as a 25 μm filter, ozone sterilization/foam fractionation, and UV sterilization. Bacteria levels are checked quarterly by an outside lab to ensure a 99% kill rate before the wastewater is sent back out to the ocean. In addition, water outflow from some tanks is sometimes disposed into the sewer instead; for example, when a tank is treated with chemicals for veterinary purposes.

The MCTF will also house post-treatment for wastewater, including 20 µm filtration for non-indigenous species, UV sterilization, and ozone-infused protein fractionation. After these treatments all this wastewater can rejoin with the normal wastewater at the outfalls.

Figure 9: The two main wastewater outfalls, and their locations on the beach. (A) The outfall serving Birch Aquarium, Hubbs Hall, and NOAA-SWFSC. (B) The outfall serving Kaplan Aquarium and holding tanks.

8. Emergency Systems

Variable oceanic conditions and equipment malfunction can lead to emergencies within the Scripps Oceanography aquarium system and jeopardize the welfare of the organisms as well as ongoing experiments. Several large-scale responses can be utilized during these emergencies. Backup pumps are available to transfer water around and can even be lowered into the ocean at the end of the pier to collect fresh seawater. The air systems can be connected to scuba tanks to provide air into the aquaria but will burn through the oxygen supply quickly. Backup generators for pumps, heaters, and chillers are also in place, however the entire Scripps campus is also placed on an electrical backup system. The Scripps campus utilizes a Metasys automation system to monitor conditions of the water which is able to notify staff automatically when conditions change or if there is an emergency. Emails and text messages are sent out to facilitate a quick response.

Following the 2020 red tide, the Scripps Institution of Oceanography Experimental Aquarium committee formed a “Life Support System” (LSS) subcommittee to develop strategies to deal with emergencies such as red tides, heat waves, and oil spills. The LSS subcommittee was chaired by Jennifer Moffat (Birch Aquarium) and attended by Jenni Lewis and Fernando Nosratpour (Birch Aquarium), Phil Zerofski, Larry Octon, Martin Tresguerres, and Greg Rouse (Scripps Oceanography). At the onset of a red tide in the Spring of 2021, the LSS requested funds to urgently build mobile “LSS crash carts” (Figure 10) to maintain water quality in the Scripps Oceanography aquarium system and the health of the organisms housed within. Scripps responded immediately and provided $14,000 that were used to purchase life support aquarium equipment by Phil Zerofski and Jenni Lewis, who also installed it on mobile carts. Most of these crash carts are stored on the first floor of Hubbs Hall, in a hallway next to the experimental aquarium.

One type of LSS crash cart is set up with an Iwaki magnet water pump, a Nu-Clear modular canister filter, and optional UV sterilizer (Figure 10A). Currently there are two of these carts available, both stored in Hubbs Hall. This cart can be deployed at tanks where the water is shut off and needs to be initially cleaned. After this cart is used, a simpler filter can be set up in the tank and the cart can be moved onto the next tank. An example of a simple filter system is a Newa Maxi powerhead submerged and recirculating water through a 25 μm filter bag (Figure 10B). Another simple cleaning option is an Eheim Ecco Pro canister filter that can be enhanced with activated carbon or bio balls (stored on-site) (Figure 10C). These cartridge filters may be washed between uses but cannot be used interchangeably on normal and transgenic systems. There are approximately 40 of the Newa Maxi powerheads and six of the canister filters stored in Hubbs Hall. In addition, around 200 new bag filters are available, with some used to filter the wastewater from systems housing non-indigenous species.

The carts also carry portable chillers (Figure 10D), which can be placed in the water to keep a cooler temperature, adjustable to fit the necessary temperature of the system. It is worth noticing that the cooling unit release warm air as it runs, which can warm up the room in proportional manner to the degree of cooling achieved and duration of the operation. Nonetheless, these portable chillers can provide an efficient first response in the event of a failure in the Scripps Oceanography aquarium system temperature regulation. Three of these chillers are stored in Hubbs Hall and two are stored in Kaplan Aquarium.

Additional measures include eight 5-gallon (23 liter) buckets with frozen seawater stored in one of the -20°C freezer rooms in Ritter Hall. This backup frozen seawater can be added directly into tanks housing organisms in the event of an emergency affecting the power system or the chillers and provide a temporary solution until the problem is resolved. Birch Aquarium can also provide extra space for organisms during emergencies.

Birch Aquarium’s emergency systems include a generator to run life-support systems, as well as oxygen bottles and battery-operated air pumps.

Figure 10: Crash carts and emergency maintenance equipment. (A) Water pump connected to both a canister filter and UV sterilizer. (B) Emergency filter setup with small powerhead flowing water through a filter bag. (C) Canister filter. (D) Water cooler with arm to be submerged in tank.

9. Coral Recirculating Aquarium System (RAS) in Tresguerres Laboratory

While a flow-through system like the Scripps Oceanography aquarium system can provide water to much of the Scripps campus, it is highly variable and reflects the water conditions off of Scripps Pier. When stricter control over experimental seawater is needed, a recirculating aquarium system (RAS) may be needed. For this purpose, an RAS focusing on housing corals was assembled in the Tresguerres laboratory. The goal of this RAS is to provide a highly controlled environment mimicking the seawater conditions on a natural coral reef, and that can additionally be manipulated to simulate environmentally relevant fluctuations in light, pH/CO_2, ammonia, and food availability, among other factors. This RAS would greatly improve our ability to conduct research on coral, as the seawater supplied by the flow-through system does not match typical conditions of tropical oceans. For example, the seawater off the coast of La Jolla is richer in micronutrients and contains more abundant and different plankton species than tropical seawater. Thus, corals exposed to Californian seawater cannot be expected to reflect the biology seen on their natural reefs, and therefore the results from experiments might be not entirely relevant for the "real world". Moreover, smaller fluctuations in seawater quality may go unnoticed but still affect coral biology leading to the erroneous interpretation of experiments, further highlighting the need for aquarium systems that supply seawater with known and stable chemistry. The 2020 red tide also resulted in the total die-off of corals held in the flow-through aquarium system by the Tresguerres Laboratory, presenting an opportunity to build an RAS system.

The RAS in the Tresguerres Laboratory is a modified Aquaneering ZT250-C zebrafish housing rack (Figures 11 and 12). Two racks hold independent recirculating systems of 25 gallons (95 liters) each, which are served by two separate sumps and sets of components. Each system has five 2.5-gallon (9.5 liter) tanks, which drain into channels that lead to the sumps. Airlines are connected to each tank via airline splitters and air pumps. Above each row of tanks are four Aqua Illumination Hydra 64 HD LED aquarium light fixtures that provide adjustable light conditions. Each sump contains a carbon filter with filter sock (Figure 11A), a fluidized bed biological filter (Figure 11B), a protein skimmer (Figure 11C), a heater, and a pump which pushes the water through an 8-watt Aqua Ultraviolet UV sterilizer and into the tanks on the rack. In addition, Tunze Osmolator 3155 auto top-off systems (Figure 11D) were installed in each of the sumps to counteract evaporation. Both sump auto top-offs are connected to a central carboy filled with deionized water, which needs to be topped off at least every three days. The entire coral RAS is housed on top of a spill tray that also contains an emergency sump pump in case of seawater overflow.

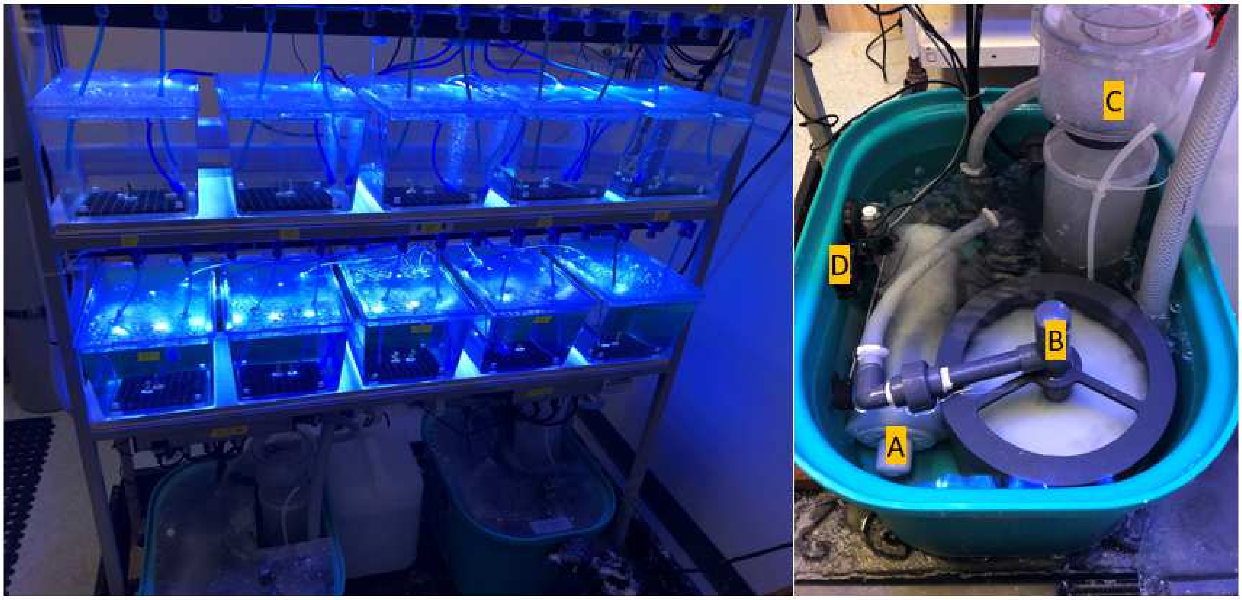

Figure 11: Recirculating coral system at the Tresguerres Laboratory (A) Carbon filter. (B) Fluidized bed biological filter. (C) Protein skimmer. (D) Tunze Osmolator 3155 auto-top off sensors.

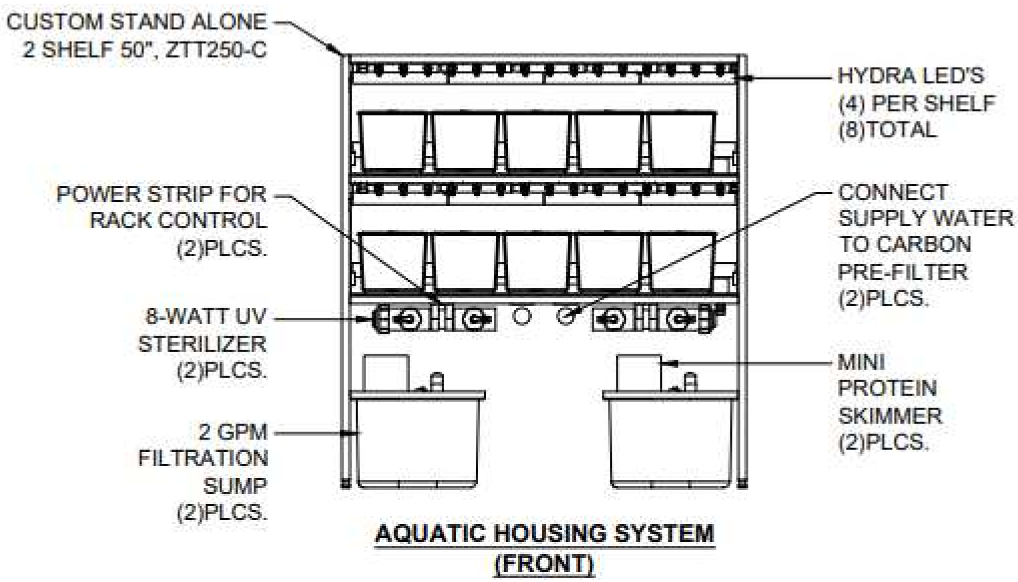

Figure 12: Drawn plans for the coral RAS system. (Aquaneering Incorporated).

Currently the rack is being used to house coral fragments of *A. yongei* and *S. pistillata* as well as the jellyfish *C. xamachana*. Maintenance of the system includes changing ~20% of the total water volume twice a week, as well as testing of seawater pH, alkalinity, salinity, ammonia, calcium, and magnesium levels and feeding the corals and jellyfish with live *Artemia* shrimp nauplii. This feeding and water change consists of bleaching, rinsing, and placing the *Artemia* eggs in a hatchery cylinder, letting them hatch over a 24-hour period. The next day the live nauplii are poured out into a beaker and coerced into gathering towards a flashlight, then collected with a turkey baster. After tank flow is shut off in the RAS, the nauplii are then poured into the tanks and allowed to disperse to feed the corals and jellyfish for about an hour. While they are feeding, samples of the system seawater are taken from the sump and the water chemistry is tested using test strips and a titration kit. The tanks and racks are cleaned and wiped off to remove any growth. Afterwards, a water change is done by siphoning out approximately 2.5 gallons (9.5 liters) from the tanks containing the organisms. Water flow is resumed, and new makeup seawater is poured into the sump.

A Qubit Systems Rapid Dissolved CO2 System (Figure 13) is used to monitor CO_2 levels. This Qubit system is comprised of a water pump (Figure 13D), a S400 DCO_2 sampler (Figure 13B), a S157-P CO_2 analyzer (Figure 13A), as well as gas and water tubing connecting the individual components (Figure 13E and F).

After setting up the system, it must be calibrated by using both a zero CO_2 level and a known CO_2 level. To obtain a zero, small stream of nitrogen gas was connected to the intake line of the S157-P CO_2 analyzer and the display was adjusted with dials until it read a CO_2 level of zero. For the known level, a stream of CO_2 with concentration of 1000 parts per million (ppm) was connected, and the dials were adjusted until the display read 1000 ppm. CO_2 levels are calculated and corrected by connecting temperature and salinity sensors, which are then placed in the water being monitored. The water pump pushes a stream of water into the DCO_2 sampler, in the opposite direction of a closed gas loop that is also flowing in the analyzer. A gas-permeable membrane separates these flows, where CO_2 from the water is allowed to pass into the gas loop and equilibrate brought into the CO_2 analyzer. The signals from the water pump, CO_2 analyzer, and temperature probe are converted to data by a LabQuest Mini data interface (Figure 13C). This interface is then connected to a computer and paired with Logger Pro software (Figure 13H), where usage of the system allows for constant or spot monitoring of CO_2 levels in an aquarium system. The salinity sensor is connected directly to the computer and can be detected by Logger Pro as well.

Figure 13: The Qubit Systems Rapid Dissolved CO_2 System set up and connected to both the coral RAS system and laptop with Logger Pro software. (A) S157-P CO_2 analyzer. (B) S400 DCO_2 Sampler. (C) LabQuest Mini data interface. (D) PL175 water pump. (E) Water intake line. (F) Water output line. (G) Salinity and temperature probes. (H) Laptop with Logger Pro software.

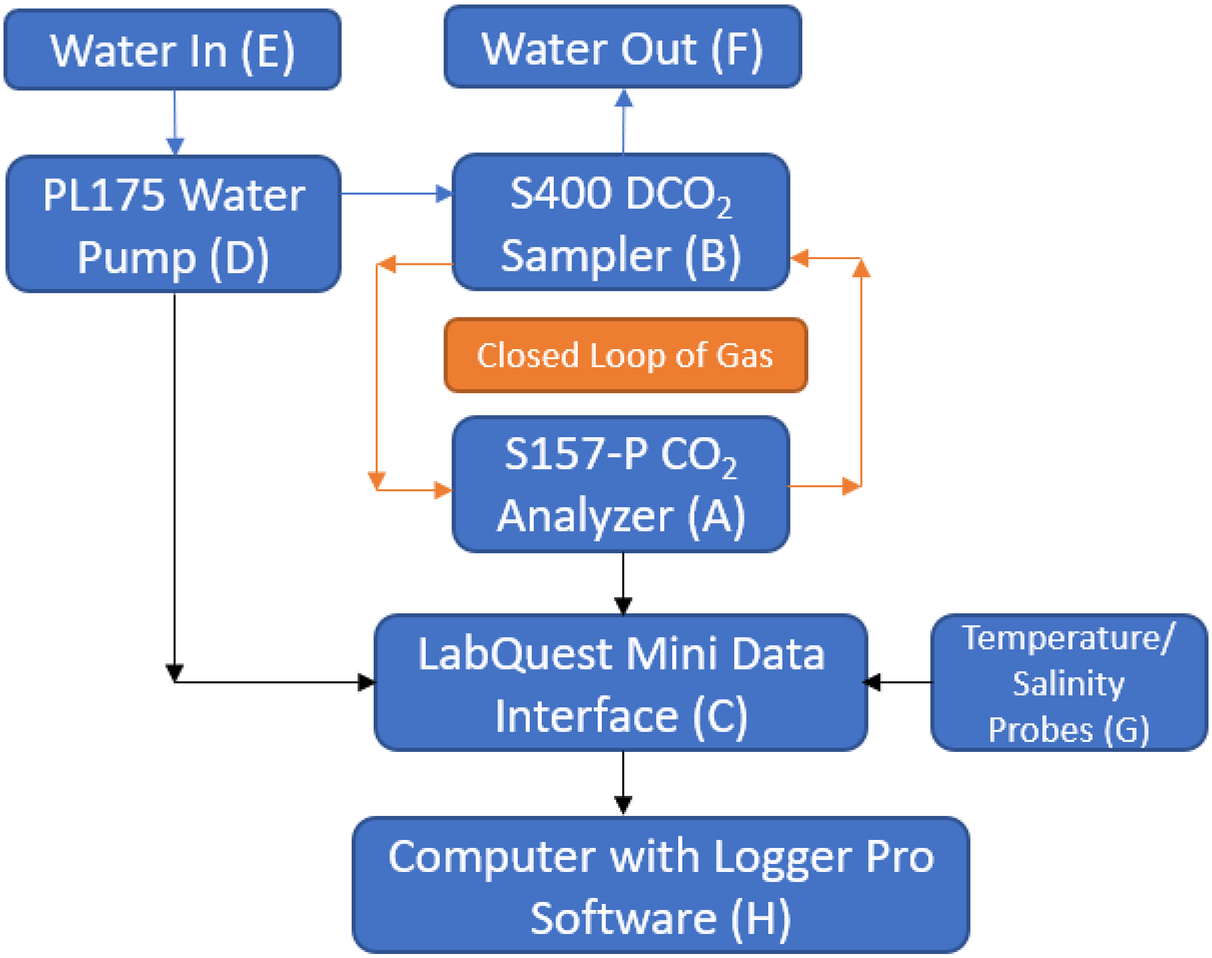

Figure 14: Simplified diagram of the Qubit Systems Rapid Dissolved CO_2 System based on the diagram from the instruction manual (Qubit Systems Incorporated). The letters correspond to the components shown in Figure 12.

The Qubit system was used for continuously measuring and recording CO_2 levels in the coral RAS over one week (November 2-10, 2021) (Figure 15). The data showed a day-night cycle of CO_2 levels within the RAS system during weekdays, with CO_2 peaks between 470-490 ppm around 5:00 pm and lower CO_2 levels around 450 ppm at night. These results are counterintuitive, as coral photosynthesis may be expected to decrease CO_2 levels during the day (Jiang et al. 2019) i.e., the opposite of what was observed. However, the CO_2 day-night fluctuations disappeared during the weekend (with levels hovering around 430 ppm) and appeared again on the following Monday. These patterns suggest that human activity and the ensuing CO_2 from respiration can affect CO_2 levels in the building (or in the Tresguerres laboratory), ultimately raising CO_2 levels in the coral RAS during the weekdays (when more people come to work). This has some implications for potential research using the RAS system, as it seems like the CO_2 conditions on the building are very dependent on human activity. The CO_2 levels in the tanks may not reflect desired values due to the ventilation and lead to erroneous experimental results. Increased ventilation may be a potential solution, to attempt to counteract CO_2 buildup in the RAS room and in the seawater.

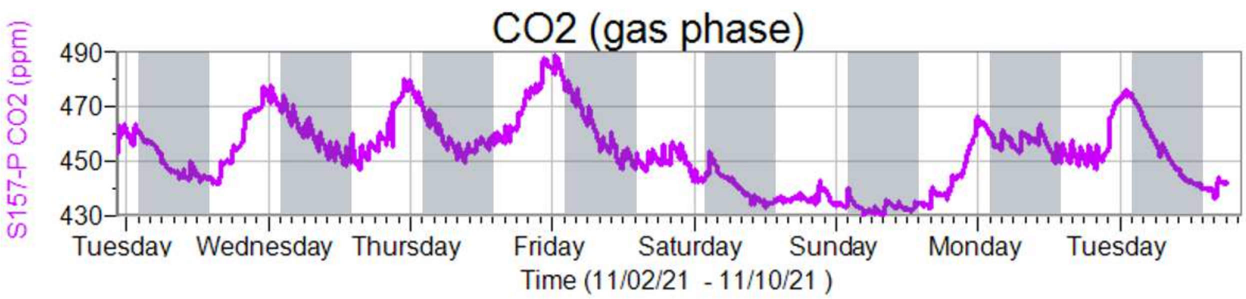

Figure 15: Logger Pro graph of CO_2 levels in the coral RAS collected over one week. CO_2 units are in parts per million (ppm), and the shaded portions represent the hours of 7:00 PM to 7:00 AM. Each peak occurred at around 5:00 PM each weekday.

Discussion

The Scripps Oceanography aquarium system has been used to provide seawater for on-campus aquaria for many years and has sustained productive research programs. With facilities as expansive as these, there is no wonder that new discoveries are constantly taking place. Ease of access to not only fresh seawater, but different temperatures and all over campus cannot be understated. However, it is not without its share of problems. One major ongoing challenge is personnel shortage as the entire Scripps Oceanography aquarium system (including facilities, equipment, and piping) is monitored and maintained by a small group of people. While there are 13 employees in Larry Octon's shop, their primary concern is aquarium system maintenance. In addition, 5600 person-hours were spent on maintenance on the system alone during the 2020-2021 fiscal year. Phil Zerofski and Christine Steinke are also involved with aquarium maintenance but depend on volunteers to assist them in their tasks. When staff or volunteers are scarce, their share of the maintenance work increases. Few available staff combined with constant reprioritization of tasks leads to aquarium maintenance never truly being completed. Additional people are urgently needed to lighten the load for the existing crew to ensure the welfare of organisms and high quality of the research during normal times as well as during emergencies. Importantly, many aquarium tasks are performed by the investigators; for example, aquarium checks, cleaning, and maintenance at the Tresguerres Laboratory currently takes combined at least 15 person-hours weekly that could otherwise be used to conduct research. Indeed, the aquaria from other leading research institutions typically relies on specialized staff for these tasks.

Since the Scripps Oceanography aquarium system sources water off of La Jolla shores, oceanographic and environmental conditions such as upwelling, red tides, rain run-offs and oil spills will be reflected in the seawater that flows through the aquaria holding organisms. To prevent harming or killing off organisms, several measures have recently been put in place including finer mesh at key filter points along the aquarium system and the use of LSS crash carts. A future plan includes installing seawater recirculation systems at the Kaplan and Hubbs aquaria, similar to that already present in Birch

Aquarium and that planned for the new MCTF. This would require capturing the wastewater leaving Kaplan and Hubbs Hall aquaria, possibly at a sump to be built in the parking lot and pumping it back to the uphill holding tank where it could be reconditioned or mixed with fresh seawater and sent back. The new MCTF will have this feature in place, as all output will be filtered. This water could additionally pass-through chiller or heater systems and be mixed as needed to be reused within the building. Being able to design and develop these systems from scratch at MCTF is a huge advantage; however, is much more complicated for the rest of the Scripps campus as the current plumbing has been in place for a long time, and thus significant alterations would need to be done to redirect flow and ensure the water would not be exposed to contaminants like oil from cars, dirt, or chemicals seeping into the ground. Wastewater flows also join up at certain locations and would need to be intercepted early to ensure the recycling of water only within the same buildings or areas.

Many of the systems and aquaria present at Scripps are aging or are outdated. Various parts of the underground piping have been in place since the 1970s. Some of the tanks holding fish have square corners, which are not ideal for housing aquatic animals (based on IACUC guidelines), and some piping material and organization could use improvement. In addition, some metal portions of the buildings are rusting and at risk of falling into the tanks. Replacing these aging portions with modern designs could alleviate some of these problems but would require bulk purchases and installation. Plans are already in place for replacing a few systems, like the monitoring system for the settling tanks at the base of the pier.

The high cost of running, maintaining, and improving the aquarium system could prove problematic. As mentioned before, maintenance alone can cost $700,000 to $900,000 yearly, and the electricity cost to run the pumps adds >$100,000 yearly. Gathering funding for the aquarium system is challenging, in part because research aquaria are not as accessible to the public eye which limits public outreach. Facility tours are a common method of outreach, but regular public tours may affect the health of the organisms or disrupt ongoing studies. In response, separate sections of the aquaria could be designated as accessible to the public for education purposes. While this outreach does not directly help fund the system, it does spread awareness on the research being done, and could result in grants or more funding directly from UC San Diego.

Birch Aquarium is focused heavily on education and features some key differences to the rest of the Scripps Oceanography aquarium system; prominently, the Birch Aquarium provides ideal conditions to the organisms which might not always reflect those found in the environment. In addition, replication is not needed within the tanks like in experimental conditions. Single tanks may have mixed conditions as well as groups of organisms where healthy living is the focus. Birch Aquarium is also better staffed and can receive monetary resources separate from the rest of the Scripps campus in the form of revenue from ticket sales, memberships, and venue rentals as well as philanthropy.

An RAS like the one in the Tresguerres Laboratory also differs from the main flow-through Scripps Oceanography aquarium system. The highly controlled nature of an RAS allows for a level of manipulation that is not possible with just flow-through seawater. Water conditions can be stable or controlled as needed for an experiment. However, getting an RAS system fully functioning can come with several challenges. For the Aquaneering system, the seawater chemistry needs to match conditions found on a coral reef, which requires using commercially available salt mixes and continuously monitoring and adjusting various parameters. Additionally, the organisms in the system may alter the seawater chemistry. Photosynthesis, calcification, and waste all can alter the water conditions, and require periodic adjustment, for example with alkalinity and calcium dosing. An auto-top off unit is required to ensure the volume of water stays stable even with evaporation, paired with consistent water changes to maintain the salinity level. While light can be controlled to sustain the corals' photosynthetic algae, food needs to be added to the RAS as a supplementary food source. This is unlike the flow-through system, which naturally can bring food to the corals. Coral diet and feeding schedule need to be evaluated to see what works best. Even the conditions in the room and building need to be considered, as CO_2, room temperature, and ventilation can affect the water conditions and health of the organisms. Surrounding human activity may alter CO_2 levels throughout the day, which may need to be monitored by a CO_2

measurement system. Many oceanic studies do not monitor or include CO_2 data during their experiments, so establishing this practice could lead to better reproducibility of results or understanding of the outcomes of a study. A closed and poorly ventilated room can also cause temperature fluctuations. All of these factors compound into requiring checks every day to ensure all components in the system are working properly and the conditions are stable.

Table 1: Table highlighting some flaws in the Scripps Oceanography Aquarium System and possible solutions or improvements that could be made.

Summary of Aquarium System Challenges	
Challenge	Possible Solution
Personnel shortage	Additional dedicated staff for aquarium maintenance to assist both facility staff and researchers
Collected seawater is subject to oceanographic conditions- Red tide, oil spills, etc.	Adding some degree of seawater recirculation to both reduce wastewater and add the ability to sustain systems during an emergency event
Aging/outdated systems, plumbing, infrastructure	Upgrading to modern monitoring systems and plumbing, adding the ability to update systems in the future, reviewing animal care guidelines to update facilities
High cost of maintenance, improvements, and daily use	Improved outreach to inform the public of the research facilities and their use, dedicated sections of research aquariums for outreach, additional funding or grants to address shortcomings

Conclusion

Facility knowledge is important when conducting research, and I hope that this thesis can serve as an aid in learning how the Scripps Oceanography aquarium system functions, its emergency response, flaws, and potential improvements. This system is intricate and expansive, so knowing its capabilities can aid in research and replication of that research. This extends to recirculating aquarium systems, where the higher control can contribute to better science practices. Both flow-through and closed systems should be assessed to determine which fits best for the purposes of research. Conditions within the seawater system may not be tailored to animal health like at Birch or perfectly align with true conditions at oceanic sites. Instead, these facilities provide a middle ground in learning how the oceans work both in the present and in the future.

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