Greening Aquarium of the Bay:

Recommendations for Reduced Environmental Impact

A 2012 Group Project Final Report Draft

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Environmental Impact & Recommendations for Reduction

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The mission of the Bren School of Environmental Science & Management is to produce professionals with unrivaled training in environmental science and management who will devote their unique skills to the diagnosis, assessment, mitigation, prevention, and remedy of the environmental problems of today and the future. A guiding principle of the School is that the analysis of environmental problems requires quantitative training in more than one discipline and an awareness of the physical, biological, social, political, and economic consequences that arise from scientific or technological decisions.

The Group Project is required of all students in the Master‘s of Environmental Science and Management (MESM) Program. It is a three academic quarter activity in which small groups of students conduct focused, interdisciplinary research on the scientific, management, and policy dimensions of a specific environmental issue. This Final Group Project Report is authored by MESM students and has been reviewed and approved by:

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Hunter Lenihan, PhD
June 2012

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1. Abstract

As a certified San Francisco Green Business, Aquarium of the Bay (AOTB) is in search of new ways to improve its environmental performance. The major objective of an aquarium is to provide life-support for aquatic organisms, and for AOTB this means maintaining over 20,000 marine animals. Animal care is highly energy intensive, and AOTB expends 89% of its electricity consumption maintaining appropriate water temperatures for exhibits, and pumping 100,000 gallons of water per day through its multi-tank facility. We addressed the question of how AOTB might reduce its electrical costs and carbon footprint while meeting animal care needs. By analyzing pumping and cooling operations, exploring alternative technologies, and conducting a cost-benefit analysis, we formulated a set of recommendations designed to maximize energy efficiency and minimize the aquarium's costs and carbon emissions. Our results indicate that over a 20-year period, AOTB can substantially reduce energy consumption by installing low-cost cooling fans, insulating pipes, implementing variable speed pumps, decreasing system head, using energy saving power conditioners, and removing three species of temperature sensitive rockfish. On an annual basis, this plan would save the aquarium $48,000, reduce carbon dioxide emissions by 10,000 lbs, and reduce temperature-related mortality. Our multidisciplinary research approach balanced environmental performance, cost, and animal welfare to help foster AOTB's mission in an environmentally sustainable way.

2. Executive Summary

In 2011, Master's students from UC Santa Barbara's Bren School undertook a project designed to enhance Aquarium of the Bay's (AOTB) environmental performance, with a focus on improving energy efficiency within the life support system that maintains over 20,000 marine organisms. The project's specific goal was to provide recommendations for reducing energy consumption related to water flow and temperature control, processes which are critical for animal welfare but that account for about 89% of the aquarium's annual energy expenditures.

Methods for improving the Aquarium's environmental performance were identified and analyzed based on their ability to reduce carbon dioxide emissions, improve cost-effectiveness, and maintain animal welfare. A cost-benefit analysis was performed for each recommendation, and Scope 2 carbon dioxide emissions were calculated to determine the carbon footprint from electricity consumption. Both the net present value and carbon footprint were calculated using a 20-year time horizon.

2.1 Pumping

Maintaining animal welfare and high water quality requires adequate water flow through a complex network of displays, and cooling and filtration systems. AOTB uses a total of 35 pumps to move water through their facility, which represent 67% of the Aquarium's energy expenditures. The following improvement options were assessed:

- Motor replacement: Each pump is paired with a motor, and replacing 16 of the motors with more efficient models would save the Aquarium an estimated $49,552 and 280,663 lbs of CO_2 over 20 years.
- Variable Frequency Drives (VFD): If a pump is running below its maximum load, a VFD can save energy by adjusting the speed of the motor. The Team proposed replacing filtering material in the Aquarium's sand filtration system, and replacing high-resistance meters to increase flow and decrease head. Combining these changes with a VFD would save the Aquarium an estimated $328,489 and 1,906,740 lbs of CO_2.
- Demand Response Plan (DRP): The price of electricity and associated CO_2 vary during the day, increasing with demand. By shifting operating times for equipment such as the raw water pump to off-peak hours when the demand is low, the Aquarium can save $37,639 and 501,180 lbs of CO_2.
- Power Conditioners: A motor's power factor (PF) describes its ability to convert electricity into work. Power conditioners correct the PF by storing electricity and discharging it to the pump motor, as needed. Installing a power conditioner would improve the PF of pumps by about 8%, which will save $285,024 and 1,344,280 lbs of CO_2.

2.2 Temperature Control

When water temperatures exceed 14°C, fish mortality and disease increase significantly. Water temperature is maintained by a main chiller, which consumes 29% of the energy spent on life support.

- Insulation: By insulating the pipes in the system, heat gain can be reduced in water transferred from the chiller to the aquarium tanks. Insulation will save energy by reducing the load on the chiller. Installation costs are high and will generate a negative net present value (NPV) of -$195,073, but also could save 191,861 lbs of CO_2 annually.

- Fan: Installing a fan above the main tanks will generate heat loss through evaporation, which is a more energy efficient means of cooling the water than chilling. The fan saves energy by reducing the load on the chiller, and would generate a positive NPV of $193,589 and save 1,033,433 lbs of CO_2 emissions.

- New chiller: An additional main chiller would also cool water effectively but would be very costly, generating a NPV of -$18,635,742, and increasing AOTB's carbon footprint by 87,323,355 lbs.

2.3 Animal Care

- Remove sensitive fish species: Three species of rockfish (black, brown, and grass) account for 25% of total mortality in Tank 1. Most of that morality (72%) occurred when water temperatures rose above 14°C. AOTB can decrease mortality without increasing chilling capacity by removing these three highly sensitive species.

2.4 Renewable Energy

- CleanPowerSF: A new local electricity provider, CleanPowerSF, expected by mid-2012, will provide electricity from 100% renewable sources but cost an additional 2 cents/kWh. Switching to this provider will cost AOTB an additional $658,361, but save 22,387,460 lbs of CO_2, an amount equal to their entire Scope 2 emissions.

The Team's analyses were incorporated into three scenarios. Scenario 1 focused on reducing carbon emissions to the least possible extent. Scenario 2 emphasized improving animal welfare with the minimum carbon emissions increase. Finally, Scenario 3 balanced the reduction of carbon emissions, cost savings, and improved animal welfare.

The three scenarios presented a range of options that the Aquarium can evaluate based on their needs. The Team recommends that AOTB adopt Scenario 3, which saves money, enhances animal welfare, and increases environmental performance. This greening strategy will increase flow through the main exhibits by upgrading equipment and removing sensitive fish species to decrease temperature-related mortality. At the same time, Scenario 3 would decrease costs by $671,000 and CO_2 emissions by 3,967,510 lbs over 20 years.

3. Background

3.1 About the Aquarium

Aquarium of the Bay (“AOTB” or “Aquarium”) is a popular marine animal center located on San Francisco’s Pier 39, drawing 600,000 visitors per year. It opened in 1995 and was purchased in 2009 by The Bay Institute, a non-profit organization dedicated to the conservation of San Francisco Bay and its watershed. A key goal of the Aquarium is to educate the public about the local marine populations and important related environmental issues. The operation includes two gift shops, administrative offices, life support facilities and exhibits displaying over 20,000 aquatic animals. The central features of the facility are two underwater tunnels, which total 300 feet in length and sit beneath large tanks containing 740,000 gallons of sea water.

In 2005, the Aquarium was certified as a San Francisco Green Business, an effort which included diverting 80% of their waste and making energy efficiency improvements. To build upon these achievements, AOTB approached the Bren School of Environmental Science & Management about taking the next step in their sustainability efforts.

Though substantial accomplishments were realized through the Green Business certification process, it only applied to the retail side of the Aquarium, neglecting impacts from the life support systems. It turns out that approximately 89% of the facility’s energy is expended on the latter, so the Bren School team (Team) decided to focus on alleviating environmental impacts from life support systems.

From the preliminary analysis, the Team concluded that the Aquarium’s water impact was negligible. Although AOTB draws in up to 50,000 gallons of salt water per day from the San Francisco Bay, they send it to sewage to be treated and returned to the ocean. Conversely, energy consumption by the life support system represents a significant carbon impact, releasing over 1.2 million pounds of CO_2 per year. Water pumping and water cooling are the main sources of this consumption, both which are necessary to maintain animal well-being. A major challenge faced by the Team was to balance the often-conflicting sustainability objectives of improving biological health and decreasing environmental impact.

3.2 Research Question

The Team formulated a research question to guide the project analysis and outcomes:

> How can the Aquarium improve its environmental performance in a cost-effective way while still maintaining excellent animal care standards?

3.3 Project Objectives

There were three main objectives of the project. First, the Team had to establish a baseline for energy use, Scope 2 carbon dioxide emissions, and biological health to have a means of comparing results. Second, the Team had to identify new methods and processes that will reduce environmental impacts and improve animal welfare. Thirdly, the financial feasibility of the proposed methods and processes needed to be analyzed in order to determine whether each suggestion would be viable for the Aquarium.

3.4 Research Focus

3.4.1 Energy

Motivating the project is the growing global and national demand for energy. According to the U.S. Energy Information Administration (EIA), 505 quadrillion Btu of energy were consumed throughout the world in 2007 (EIA, 2011a). More importantly, the United States accounted for 21% of world energy consumption. With approximately 4.5% of the world's population, the U.S. is using energy at a per capita rate much higher than many of its peers. U.S. electricity demand in 2009 was 3,745 billion kilowatt hours (EIA, 2011). Of this, about 3% is used for water and wastewater systems (EPRI, 1994).

The implications of this energy consumption pattern are serious because of the associated environmental problems arising from energy production, consumption, and pollution. Most prominent among these issues are greenhouse gas emissions (GHG) and global warming effects. In the U.S., buildings account for 42% of electricity usage (IEA, 2011). Moreover, Aquarium facilities likely use more energy per square foot than the average building due to the energy intensive nature of life support systems (LSS).

Furthermore, the City of San Francisco set a goal to reduce carbon emissions and energy consumption by 20% below 1990 levels, or by about 3.6 million tons of carbon dioxide (SF DOE, 2004). To meet this goal, businesses will need to become more energy efficient. To maintain its reputation as an environmental leader, the Aquarium must build upon their previous improvements to help the City of San Francisco reach its environmental benchmarks.

The Team determined that approximately 89% of electricity is being used for marine animal life support, while only 11% is being used for all other facility systems, including lighting, heating, and cooling. Life support systems include water pumps, chillers, ozone filtration and other minor systems. Of the LSS consumption, 60% is due to pumping and 29% to the remaining equipment (Figure 1). The bulk of the latter category can be attributed to the facility's main water chiller.

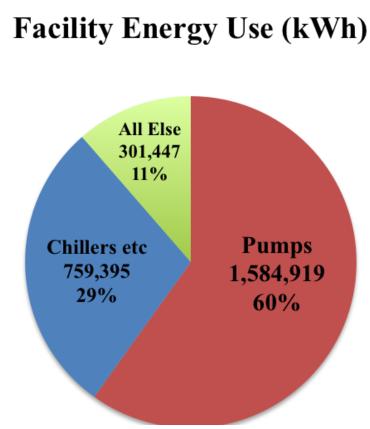

Figure 1: Facility Energy Consumption Breakdown

Aquarium of the Bay's life support system consists of three major hydraulic systems: the raw water pump, the main system, and the side loop systems. The raw water pump brings in sea water from the nearby pier into the facility and is served by a 7.5 horsepower (hp) pump that operates only when make-up sea water is needed.

The main life support system serves the aquarium's two large tanks, Tank 1 and Tank 2 or "T1" and "T2." Each tank has its own pumping infrastructure, with three 25 hp pumps, which are designed to operate at 900 gallons per minute (gpm) each. This system also includes side loops to deliver water to the water chiller and ozone filters. The ozone filters have two 10 hp booster pumps for each tank.

3.4.2 Animal Care

The Aquarium houses more than 20,000 marine animals that are displayed in a variety of exhibits. The goal of the aquarium is to educate visitors about the San Francisco Bay and adjacent Pacific Ocean species and habitats. Achieving this goal requires that AOTB maintain environmental conditions within exhibits that adequately mimic those of the natural environment. The LSS does this primarily by controlling the water flow rate that in turn regulates temperature, oxygen concentration, and water clarity, factors that are also influenced by the system's filtration process.

Aquarium of the Bay's main exhibit, Under the Bay, features two large tanks, T1 and T2, which provide visitors a unique underwater Bay experience. T1 is contains mostly near shore species indigenous to the San Francisco Bay and the adjacent Pacific Ocean, including anchovies and a variety of rockfish species. Tank 2 is made up of the larger deeper-water species such as seven-gill sharks, sturgeons, and rays. Not only are the two tanks comprised of both near-shore and deeper-water species from different locations (San Francisco Bay and the Pacific Ocean), they also receive the same water supply. Therefore, it is important that water characteristics are suitable for a variety of species.

3.4.2.1 Temperature

The San Francisco Bay has a seasonal temperature range of 10.5°C – 18.9°C (NODC 2012), with warmest temperatures occurring in the summer and coldest temperatures in the winter. The Aquarium's staff strives to keep water temperatures within the range of 9-14°C. Although temperatures in this range are suitable for a wide variety of species, one key reason for the selected range is the presence of rockfish in the Aquarium. Most of the rockfish live in T1, with 21 species of rockfish, totaling over 400 individuals.

Although some rockfish species can be found at shallower depths, most rockfish species are typically found in deeper, colder water (Green and Starr 2011), making them more sensitive to temperature fluctuations than other species.

3.4.2.2 Mortality

Mortality in aquarium exhibits are caused by natural factors, including predation and complications with reproduction, but also by factors associated with the LSS. In particular, animals can be threatened when the water sees low dissolved oxygen levels, variability in salinity, or erratic temperature fluctuations. Over the past two years (2010-2011), Aquarium animal care staff have documented mortality and health issues, including an ailment affecting rockfish called exophthalmia, also known as "pop-eye", which is caused by a bacterial or fungal infection (Seng et al., 2006). Pop-eye is also caused by the build-up of gas in tissues that eventually enters the eye cavity causing the eye to bulge (Dehadrai, 1966). Due to the possible spread of the disease to other animals, and undesirable appearance for visitors, rockfish suffering from exophthalmia are relocated to a quarantine tank where they recover or, eventually, are euthanized. Aquarium staff have noted that rockfish mortality appears to increase when water temperature exceeds 14^{o}C.

3.4.2.3 Metabolism

The temperature of the water within each exhibit also affects the metabolism of the animals. Although some species found within AOTB are endotherms, meaning they are able to regulate their internal heat, the majority of the animals in Tank 1 are ectothermic and rely on surrounding temperatures for thermoregulation (Levinton, 2001). For ectothermic animals, their metabolic rates vary depending on the surrounding temperature (Clarke and Johnston, 1999). As water becomes warmer, metabolic rates increase. This can lead to an increase in predation among species, as well as an increase in feed needed to satisfy animal needs.

3.4.2.4 Flow Rate

The rate at which water circulates through each exhibit is also important to maintaining animal health. Flow reduces turbidity, and the probability of unwanted parasites and bacteria settling in the exhibit (Hallett et al, 2008). It is important to maintain a flow rate that is suitable for all animals. A low flow rate can contribute to poor water quality, while a flow rate that is too high can also be harmful to the animals, by impacting swimming and feeding abilities (Webb and Cotel, 2011). A higher flow rate also increases clarity of the water, which is an important factor in visitor viewing experience. It is also important to regulate other factors such as salinity levels, dissolved oxygen and nutrient concentrations in order to maintain animal health.

3.4.3 Pumping

In total, Aquarium of the Bay's hydraulic system contains close to one million gallons. At 377,000 gallons and 363,000 gallons, respectively, most of the water is held in T1 and T2. The combined volume from the Discover the Bay exhibits is 4,500 gal; Touch the Bay exhibit holds 6,000 gallons; and the other tanks, including those for quarantine, hold another 3,125 gallons. Remaining water reservoirs include pipes and filters. (C. Low, pers. comm., 2012).

A centrifugal pump uses mechanical energy to increase the velocity of a liquid. The mechanical force is created by electricity from a motor, which turns an impeller (Figure 2). Energy is imparted to the water by centrifugal force by speeding it up and pushing it outward from the center of the impeller; the energy is transformed into kinetic, pressure, and potential energy in the system.

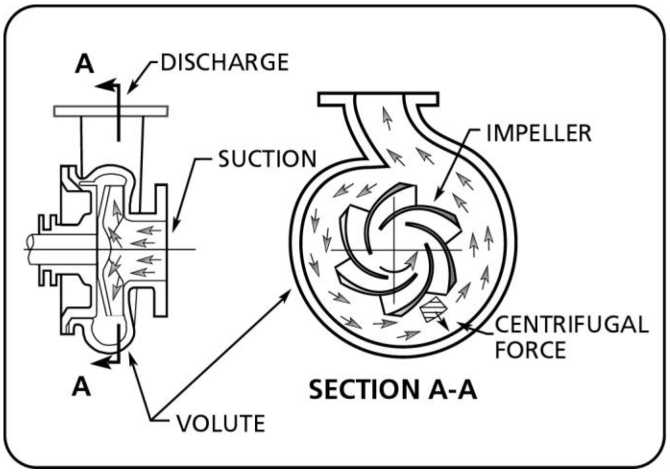

Figure 2 Centrifugal Pump (Chaurette, 2002)

When using multiple pumps in parallel (feeding into the same pipe), flow is additive, but head is not. For example, two 100 gallon per minute (gpm) pumps with 75 feet of head capacity will pump 200 gpm at 75 feet in parallel.

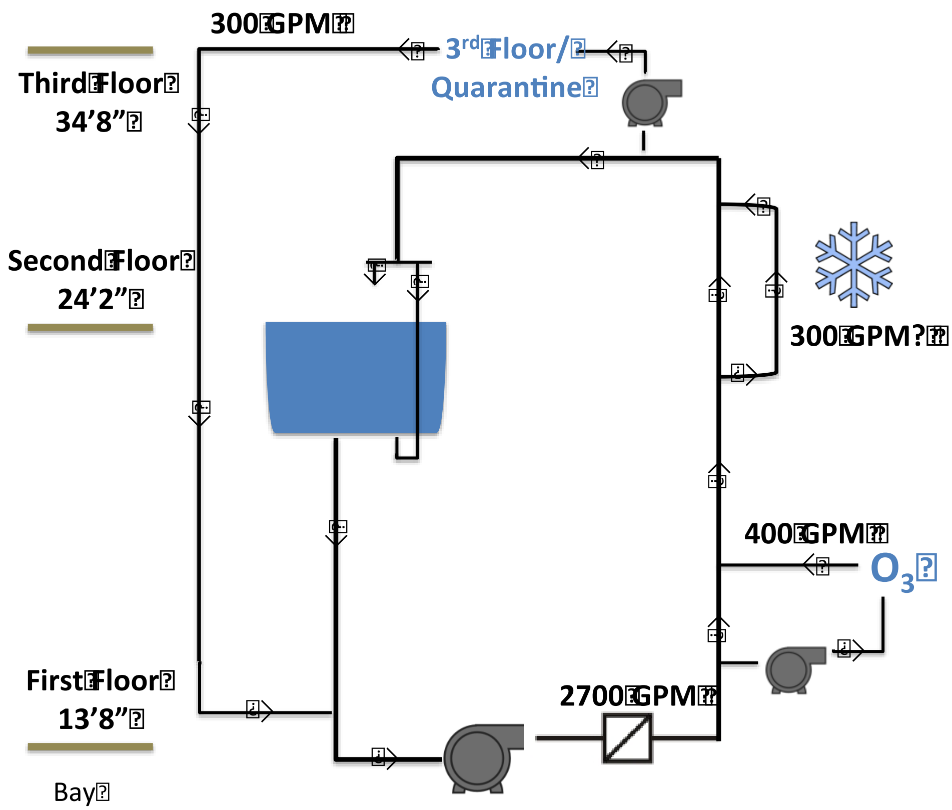

Figure 3. Pumping System Layout

The side loop is fed by water from the main LSS and uses a 10 hp pump to bring water to the 3rd floor Touch the Bay and quarantine tanks. This pump operates at 300 gpm (Figure 3).

3.4.3.1 Pumping Schedule

Water is pumped into the aquarium when tides in the bay are at or above +2 feet. At this level, water is cleaner and has higher salinity content. Salinity levels should be above 28 parts per thousand (ppt) and ideally between 32-34 ppt (Jensen pers. Comm., 2011b). In the spring, engineers must be more cautious about when they draw raw water because snow melt brings more fresh water into the bay and salinity levels fall. Pulling in water under these tidal conditions also ensures an influx of water free from the pollutants originating from nearby industry. According to Aquarium pumping records, raw water is pumped for an average of 14 hours per day.

Water in the system is lost through three main activities: overflow, vacuuming, and backwashing. Overflow occurs when T1 and T2 are filled to capacity. At this point, additional water exits through a drain that leads directly back to the bay. Two underwater vacuum pumps are used to clean T1 and T2. They operate for about 6 hours per week at 150 gpm each (Jensen pers. comm. 2011). When the main LSS filters become clogged with sediment and other filtered particles, the system experiences pressure loss. This is corrected through backwashing, a process in which water flow through the filters is reversed in order to clean them. Backwashing takes about 20 minutes, results in the loss of 25,000 gallons, and takes place once a day for each system (Jensen pers. comm. 2012a). Water lost from backwashing and vacuuming is directed to the municipal sewage system for treatment. Local regulations require that the Aquarium send this lost water to sewage rather than to the Bay because of possible contaminants.

3.4.3.2 Filters

There are six sand filters for the main LSS system (model: Stark SB-120S). They are comprised of a stack of two filters, each of which has 35 square feet of filtration area and 45.5 cubic feet of filtration media. The media is made of 3/8" pea gravel with a #20 silica bed (Jensen pers. comm. 2012a). Bacteria collect in the filters where they detoxify the water by converting ammonia to nitrate and nitrite (Moe 1982).

The filtration media has not been replaced since the filters were first installed at the opening of the aquarium in 1995. Over time, the sand and gravel grain have become rounded and less effective, increasing resistance through the filters. Whereas a new filter has a pressure differential of 1.5 pounds per square inch (psi) when clean, the current system has a 9 psi pressure differential, increasing to 17 psi when dirty. The manufacturer of the filters recommends backwashing when pressure drop reaches 10 psi (Edler, pers. comm., 2012).

3.4.3.3 Centrifugal Pumps

Altogether, the Aquarium has 35 centrifugal pumps which consume 422,100 kWh per year at a cost of $217,700. The largest energy draws are the six 25 horsepower main life support system pumps, consuming 40% of pumping electricity. All larger pumps, including the six 25 hp main pumps and the four 10 hp ozone pumps are original and have never been rewound (Jensen, pers. comm. 2012a).

3.4.4 Water Cooling

AOTB's water cooling system consists of five chillers serving various Aquarium systems. Four of the chillers are small, used primarily for individual exhibits or behind-the-scenes tanks (such as the nettle jellies and quarantine tanks). The main chiller is responsible for cooling the majority of the aquarium's 1,000,000 gallons of seawater, and is situated on a side loop in the water circulating system, as illustrated in Figure 4. It consumes about 95% of the Aquarium's electricity for chilling.

Although water is pumped directly from San Francisco Bay, it must be cooled, especially from April to November (NODC 2012), before reaching the animals for several reasons:

- Certain fish species, particularly rockfish, are found in the Pacific Ocean, are adapted to cooler and deeper waters. The Aquarium cannot easily replicate the temperature at these depths and such species are particularly affected by temperature fluctuations. Impacts include declining animal health and increasing mortality for rockfish species.

  Exothermic animals, including some fish species, experience higher metabolic rates in warmer environments. When ambient water temperatures in the Aquarium increase, metabolism also goes up, along with animal feeding requirements.

- Pumping sea water directly from the near-shore bay means incoming water temperatures fluctuate significantly. According to the National Oceanic Atmospheric Administration (NOAA), bay water temperature typically ranges from 10.5°C – 18.9°C (NODC 2012), while the optimum range for the exhibit fish is 9°C – 14°C.

In addition to incoming seawater, there are three other potential sources of added heat:

1) Presently, the Aquarium has no insulation on its approximately 2300 feet of piping. Average monthly air temperatures within the AOTB are 2.7°C warmer than outside air temperatures (Jensen pers. comm. 2011a) which range between 13.6°C – 19.7°C (The Weather Channel 2012). Since ambient air temperatures are higher than the water in the pipes, heat is transferred via convection and conduction into the circulating sea water through the system's schedule-80 polyvinylchloride (PVC) pipes.

2) T1 and T2 are exposed to the ambient air inside the Aquarium. Heat is transferred through long wave radiation and sensible heat into the tank sea water (Dozier and Dunne, 2010; Incropera, 2007; Aeschbach-Hertig, 2010).

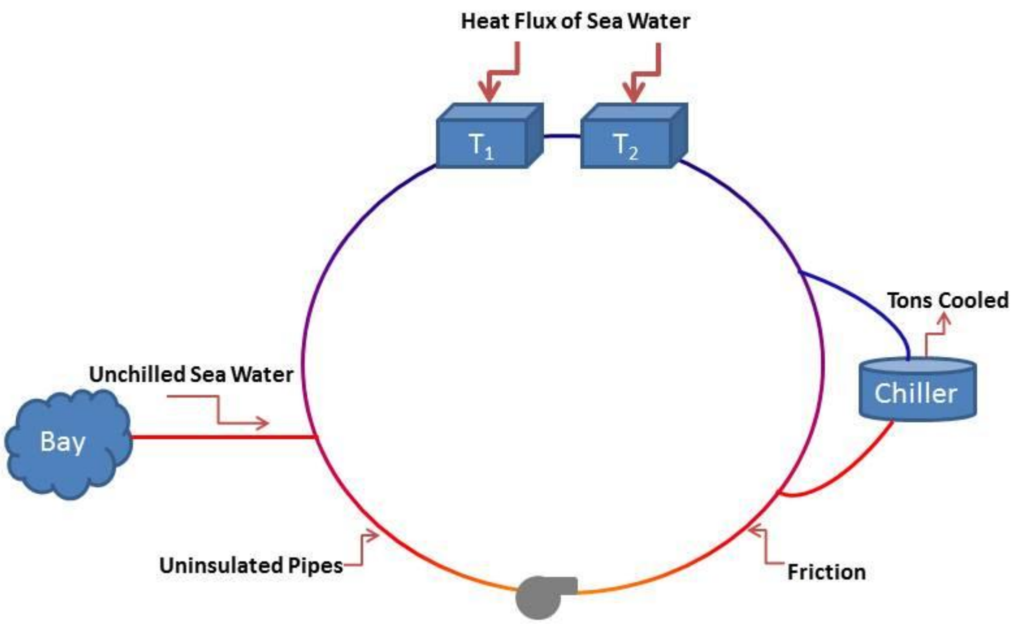

Figure 4: Sources of heat transfer into Aquarium of the Bay's system

All inputs of heat must be counterbalanced by the main chiller. The chiller takes in water from a side loop (Figure 4) that must receive highly regulated water flow in order to maximize heat transfer. The chiller removes 83.2 tons of heat per hour and operates at a flow rate of 253 gallons per minute (gpm). At this flow rate, the main chiller is chilling 364,320 gallons a day, or only 45% of the main system's water.

One of the water cooling objectives is to reduce the inputs of heat, thereby minimizing the need for cooling by the energy-intensive chiller. To achieve this goal, the Team researched the following solutions:

1) Installing 2,300ft of insulation on the exposed pipes.
2) Placing a cover over the exposed T1 and T2 tanks.
3) Relocating of the raw sea water inlet to cooler, deeper waters.
4) Adding a second chiller to achieve optimal animal welfare.
5) Replacing the current chiller with innovative chilling technology such as implementing a cooling tower or a geothermal cooling system.
6) Installing a fan to increase evaporation over T1 and T2, thereby increasing water cooling.

4. Methods

4.1 Animal Care

The Team used data obtained from Aquarium animal care staff to evaluate the relationship between biological health and the life support system. This data spanned 2010 and 2011 and included information on feeding, mortality, and water quality.

4.1.1 Mortality

The Team plotted total mortality data to determine the distribution of mortality in Tank 1 and Tank 2. The Team also analyzed the correlation between sensitive species and ambient water temperature.

4.1.2 Feed Cost

To determine the relationship between temperature and feed cost, the Team obtained an estimated cost per pound of each feed type used in T1 and T2 for 2011(Grassmann pers. comm. 2012) (Table 1)

Feed Type	Price Per Pound
Silversides	$3.75
Superb Krill	$1.95
Squid	$1.53
Pacifica Krill	$1.50
Sardines	$0.90
Mackerel	$0.90
Capelin	$0.80
Herring	$0.75

Table 1: Estimated Cost per pound of each feed type (2011).

Using Aquarium feed data for 2010 and 2011, the Team then determined the total amount of feed (in pounds) given to animals in each tank per month. This was used to estimate the monthly cost to purchase feed. Price per pound was calculated using the following equation:

Equation 1

$$average\ price\ per\ pound = (total\ cost)/(total\ feed)$$

Once the average price per pound was determined, the Team calculated the average daily feed cost per month using the equation below:

Equation 2

$$\text{average daily feed cost} = (\text{average daily feed}) \times (\text{average price per pound})$$

Missing feed dates from June 2011, possibly, June 2010 were excluded from the data set (Grassmann pers. comm., 2012).

As a means of testing how feed costs were influenced by water temperature, a linear regression analysis was performed that estimated the statistical relationship between average daily temperature and the cost of daily feed. Reported on the x-axis are increasing values of average daily temperature per month, in degree Celsius, and on the y-axis are average daily feed costs per month. This means that feed cost are expected to depend on the water temperature. The linear regression analysis determines the R^2 value and best-fit equation. The R^2 value represents how much of the actual data is explained by the best-fit linear equation. A low R^2 values signifies little linear correlation between the x and y-axis, whereas a high R^2 signifies a strong correlation between each axis. R^2 values ranges between 0 and 1, and can be interpreted as a percentage. For example an R^2 value of 0.5 means 50% of the data can be explained by the best-fit linear equation.

4.2 Pumping

The Team evaluated several options for increasing water flow and reducing CO_2 emissions. Each pump has a curve, along which it is capable of operating. The axes of the curve are head and flow. On the x-axis of the pump curve is head, which is a measure of the system resistance the pump is capable of pumping against. Along the y-axis is flow, which is measured in gallons per minute and describes the rate at which a pump can deliver water. The best efficiency point (BEP) is the point along the curve at which the pump is most efficient. Ideally, a pump will be sized to be at BEP under the system's normal operating conditions. (Chaurette, 2002)

Figure 5 shows the pump curve for Aquarium of the Bay's main life support pumps. They were initially planned to operate at 900 gpm and 75 feet of head each. Peak efficiency is at just under 1000 gpm.

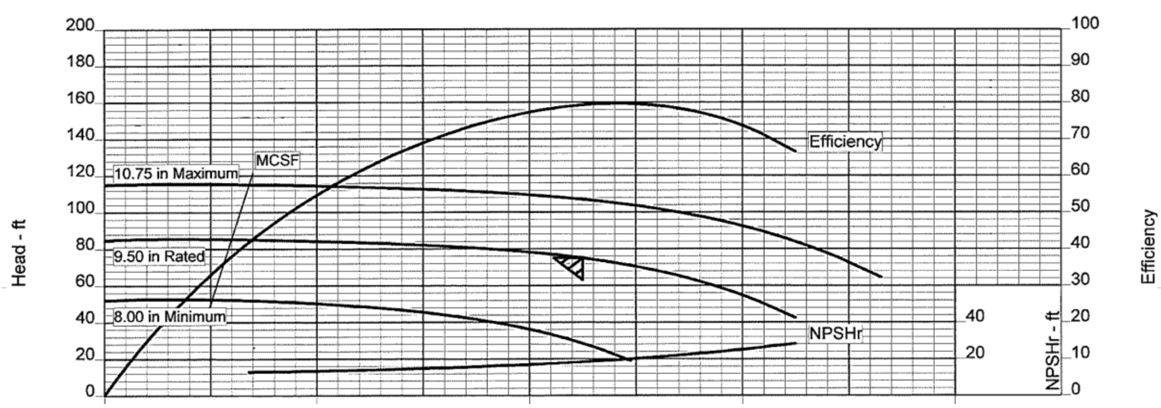

Figure 5: Main Life Support Pump Curve (Source: Flowserve Corp.)

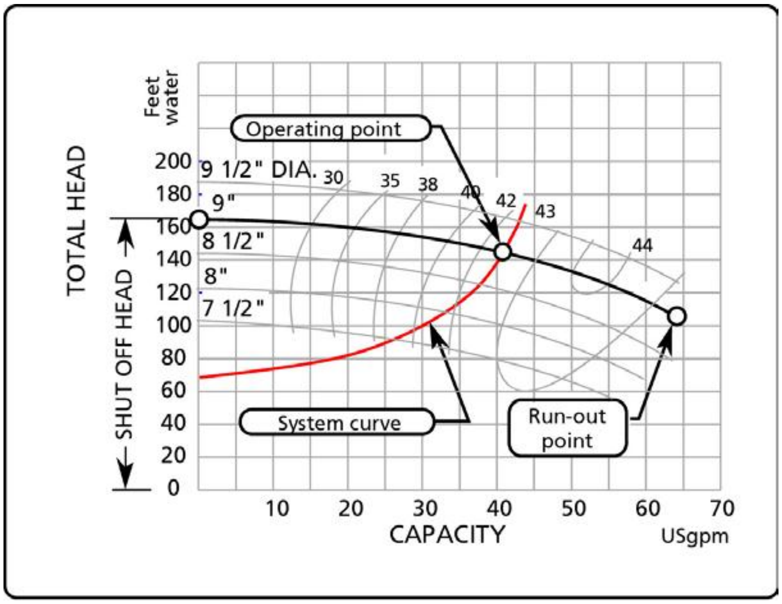

Figure 6: Run-out Point and Shut-off Head (Chaurette 2002)

4.2.1 Hydraulic System Analysis

Conservation of energy states that, for an incompressible fluid, the sum of all forms of energy must be the same anywhere in a system. This leads to Bernoulli's equation, which can describe the relationship between potential energy (*z*), pressure energy (*p/y*), and kinetic energy ($v^2/2g$) in a pumping system. Because the total amount of energy stays constant, a decrease in one form of energy must be compensated by an increase in another form of energy. For example, when the passage through which a fluid is moving decreases in size, the fluid increases in kinetic energy at the expense of pressure energy (Brater, 1976; Chaurette, 2002).

Bernoulli's Equation

Equation 3

$$z + \frac{p}{\gamma} + \frac{v^2}{2g} = \overline{E} = CONSTANT$$

g = gravity, *z* = height, *p* = pressure, ν = velocity, *y* = specific gravity

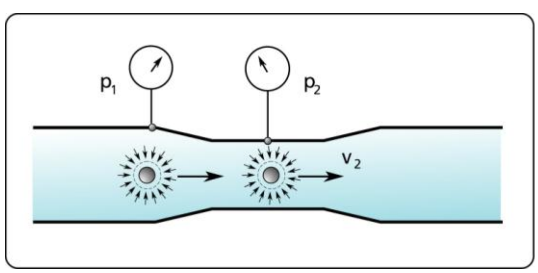

Figure 7: Relationship Between Pressure and Velocity (Chaurette, 2002)

The specific gravity of a fluid (its density in relation to water) allows pressure energy to be converted to feet of fluid column height, also known as "head". The purpose of a centrifugal pump is to move fluid through a system by increasing the internal energy of that system. Total system head is calculated by summing the various forms of head:

Total Head = pipe friction head + equipment friction head + velocity head + static head

From these equations and principles, the equation for total head is the following:

Equation 4

$$\Delta H_P(ft\ fluid) = (\Delta H_{F1-2} + \Delta H_{EQ1-2}) + \frac{1}{2g}(v_2^{\,2} - v_1^{\,2}) + z_2 + H_2 - (z_1 + H_1)$$

In this equation, the subscripted "1" refers to the suction tank and "2" to the discharge tank.

ΔH_{F1-2} = friction from pipes and fittings

ΔH_{EQ1-2} = equipment head

$\frac{1}{2g}(v_2^{\,2} - v_1^{\,2})$ = velocity head

$z_2 + H_2 - (z_1 + H_1)$ = pressure and static head

Figure 8 shows the relationships between different sources of head. Z_1 and Z_2 represent static head (height, in feet) between the surfaces of the suction and discharge tanks. H is pressure head in the tanks and the value can be positive or negative, depending on whether the system has positive pressure or a vacuum. If the tanks are open to the atmosphere, or unpressurized, these values are zero. V_1 and V_2 refer to the velocity at which the tanks are being emptied or filled. In many situations, the V values are so similar that they can be ignored (Chaurette, 2002).

At Aquarium of the Bay, the tanks are open to the atmosphere, so H_1 and H_2 are zero. Likewise, V_1 and V_2 are zero in this situation, because neither tank is changing height in relation to the other. Velocity was determined using on-site measurements and construction blueprints.

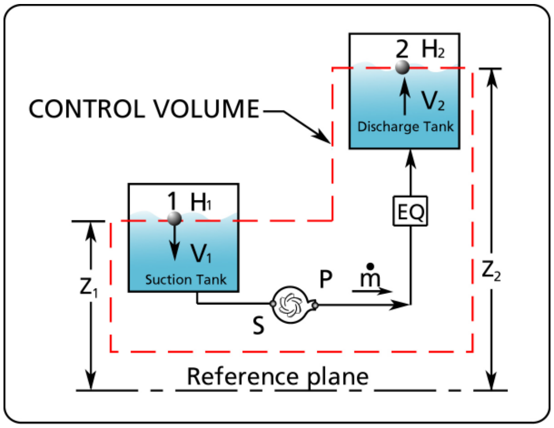

Figure 8: Relationship between sources of system head (Chaurette, 2002)

Friction head was calculated using facility blueprints to find pipe diameter and length. Friction loss tables were then consulted to find the appropriate losses. Pipe friction losses are most often expressed in feet of head per 100 feet of pipe. Resistances for fittings such as valves and pipe elbows are expressed in k values. These are then used in the equation below, where v^2 is velocity squared and $2g$ is gravity multiplied by two:

$$HF = K(v^2/2g)$$

Equipment head was determined through interviews with aquarium staff and on-site observations. From these calculations, head was estimated for current flow (2700 gpm) and for a high flow (3600 gpm) condition. Microsoft Excel was used to input and calculate the head properties of the system.

4.2.2 Filters

From on-site measurements and interviews of Aquarium staff, the Team determined current pressure drop through the biological sand filters. Documents provided by the manufacturer of the filters were used to estimate pressure drop expected from new filtration media.

4.2.3 Operating Point

Operating point is where the system curve meets the pump curve. At Aquarium of the Bay, the operating point moves up the pump curve as the filters clog and head in the system increases. The Team found the operating point for the Aquarium by overlaying the system curve on the pump curve.

At Aquarium of the Bay, the system is frequently operated in a closed system, with the main exception being when raw seawater is brought into the facility from the bay. Therefore, the total head equations can be applied and a control volume defined by the internal pumping system.

4.2.4 Motor Calculations

Pump nameplate information gathered during site visits included power needs, efficiency, and load. These statistics enabled the Team to identify more efficient replacement motors and to make other recommendations for efficiency upgrades. Replacement motors were found through company catalogues and use of the MotorMaster+ software program.

Motor replacement has the advantage of being cheaper and simpler than replacing entire pumps. To ensure compatibility, new motors must have the same power output, RPM, and frame size as the old motors.

Power consumption for a given pump can be determined using the following equation:

[(hp x 0.746 kW/hp x % load) / (efficiency)] x [# hours operated]

4.2.5 Affinity Laws

The relationships between head, flow, motor speed and power follow the affinity laws. In short, these laws state that as motor speed increases, flow increases linearly, pressure (or head) increases as a square, and power increases as a cube (Figure 9). As a result, small decreases in motor speed result in significant energy savings (“Variable Frequency Drives” 2000). Variable frequency drives (VFDs) allow an operator to change the speed of a motor depending on the system load and to capture the savings from decreased RPM.

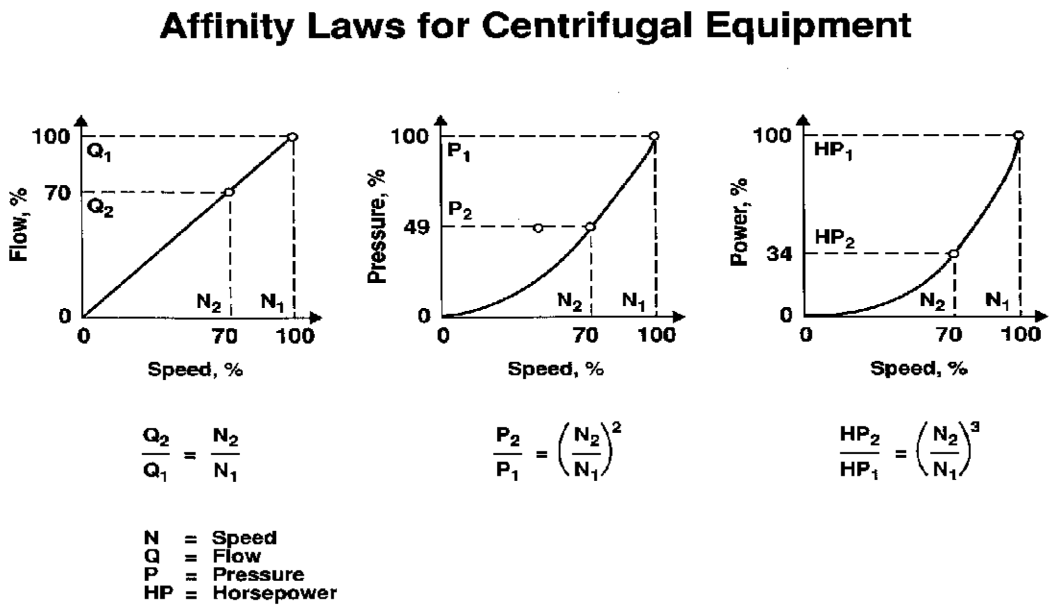

Figure 9: ("Variable Frequency Drives" 2000)

4.2.6 Power Conditioners

Power conditioners regulate the flow of electricity to a motor by correcting its power factor (the ratio of electricity drawn from the grid to that used by the motor). Motors run on inductive loads, meaning that they operate by converting electricity into a magnetic field that produces work. Inductive loads have three classes of associated power: real, reactive, and apparent. The first, real power, is what the motor converts from electricity into useful work. The unit of measure for real power is kilowatts (kW). The second, reactive power, is the non-working power that comes from the magnetization of the current, measured in kilovars (kVAR). Together, these two make up the third power class, apparent power, which is the total power drawn from the grid. The unit for apparent power is kilovolt amps (kVA). Altogether, power factor is the real power divided by apparent power (DOE):

Equation 5

$$Power\ Factor = \frac{Real\ Power\ (kW)}{Apparent\ Power\ (kVA)}$$

Power factor (PF) is depicted as a ranging from 0 to 1. At its maximum of 1, the machine is drawing no additional reactive power, meaning that all incoming apparent power is converted into work. This is known as "unity power." Oftentimes, motors lose energy by inefficiently drawing reactive power. For instance, the main life support system motors are rated with a power factor of 85.5, meaning that the percentage of apparent power that is converted into real power is 85.5%. Power conditioners can be utilized as an intermediary between the grid and the motors.

They receive electricity from the grid and store it until the motor demands power, which can potentially increase the power factor by several percentage points.

The Team assessed two models of power conditioners: the Power Save 3400 and the Green Choice PF600C. The Power Save 3400 has the voltage capacity to manage the six main 25 hp LSS pump motors at a cost of $1,690. The Green Choice PF600C has the capacity to manage the six main LSS motors and the four 10 hp ozone booster pumps with a cost of $2,328. Installation would add $200 to the cost of each option.

Energy consumption was calculated using the following equation:

$$kW = Volts * Amps * 1.73 * Power\ Factor/1000$$

With a power factor of 85.5, the LSS motors have an apparent power of 24.03 kW and real power of 20.55 kW. With a power factor of 88.5, the ozone booster motors have an apparent power of 9.71 kW and real power of 8.59 kW.

Power conditioner savings were determined by reducing apparent power and leaving real power constant. Therefore, for the main LSS pumps, real power would remain 20.55 kW while apparent power would improve to 22 kVA, increasing the power factor from 0.855 to 0.935.

A conservative power factor improvement of 8% was chosen, but improvements of 11.5-14.5% are possible. For comparison, the Team used a sensitivity analysis to demonstrate the potential savings from a 1% improvement and a maximum improvement (14.5% for the six main LSS motors and 11.5% for the four ozone booster motors).

Table 2: Power Factor specifications of the main aquarium pumps.

Pumps	Power Factor	Real Power (kW)	Apparent Power (kVa)	8% PF increase (kVa)
Main LSS	85.5	20.55	24.03	22.11
Ozone Booster	88.5	8.59	9.71	8.59

The difference in pre-and post-power conditioner energy consumption is the accrued savings. This is converted into a monetary savings by multiplying kWh by the cost of electricity ($0.14/kWh), and carbon dioxide savings by 0.524 to get pounds of CO_2 conserved.

4.2.7 Demand Response Plan

Peak energy refers to the variation in daily demand for energy. Energy consumption varies throughout the day as a function of processes such as heating, air conditioning, and lighting. The fluctuations are both daily and seasonal, with demand being highest midday and in the summer months (NPCC 2010) (Figure 10). This demand cycle creates extra costs for utility companies because they must have “peaker plants” which operate only when demand is high. (Denholm & Short, 2006). In response, many electricity companies, including PG&E, create a time-of-use (TOU) pricing structure to encourage consumers not to use electricity during peak periods.

Aquarium of the Bay experiences average electricity prices that range between 8 and 15 cents per kilowatt hour between off-peak and peak hours, respectively. A more detailed breakdown of energy prices can be seen in Table 3.

There is also an environmental component to peak energy demand. During peak hours, natural gas plants are used because they can be quickly brought online as needed. In contrast, hydroelectric dams are used for baseload power because they produce as long as it has enough water. As a result, peak power generation is more carbon intensive, with 0.73 pounds of CO_2e emitted per kWh of baseload electricity and 1.08 pounds of CO_2e are emitted per kWh of peak load electricity in California[1] (EPA eGrid, 2010). Using this knowledge, the Aquarium has the opportunity to reduce their electricity costs and carbon footprint by simply shifting operation of their raw water pump to off-peak hours via a demand response plan.

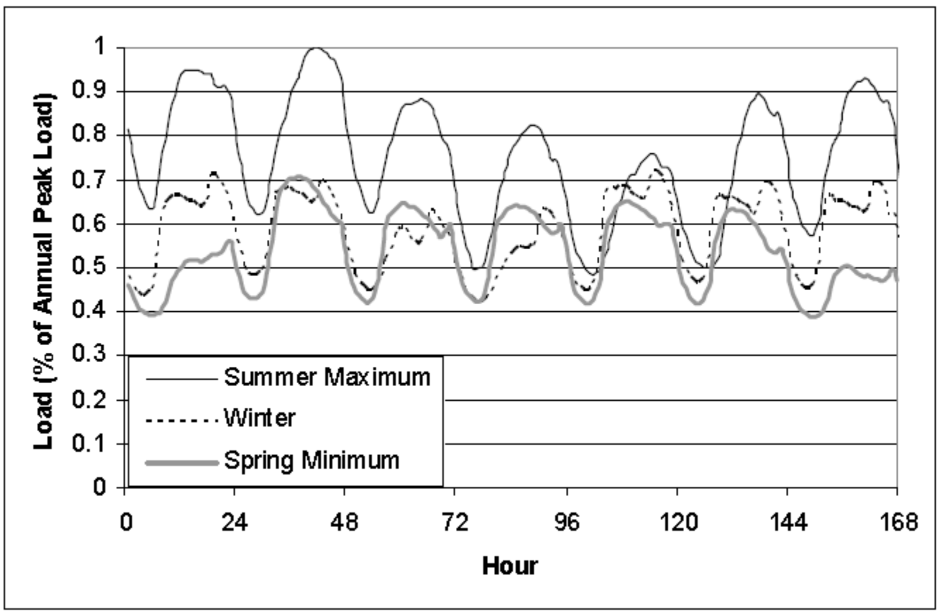

Figure 10: Variation in electricity demand by day and season. (Denholm & Short 2006)

Table 3: Time of use pricing schedule as set by PG&E (2012).

	Peak Demand Schedule		
	Off Peak	**Park Peak**	**Peak**
Summer Weekdays	9PM-10AM	10AM-1PM, 7PM-9PM	1PM-7PM
Summer Weekends	8PM-5PM	5PM-8PM	--

[1] The EPA's estimate of CO2/kWh emissions is greater than PG&E's estimate of 0.524 lbs/kWh for two reasons. First, the EPA uses the unit CO2e. This means they are measuring other greenhouse gases (CO2, CH4, and N20) and accounting for their cumulative contribution to the greenhouse effect. PG&E merely accounts for CO2. Second, in estimating CO2e emissions, the EPA groups all of California into one region (WECC California), so the results incorporate data from other utilities, including Southern California Edison and San Diego Gas & Electric (EPA 2010).

Winter (Everyday)	9PM-6PM	6PM-9PM	--
Price	$0.09/kWh	$0.10/kWh	$0.15/KWh
CO_2 Emissions	0.73 lbs/kWh	1.08 lbs/kWh	1.08 lbs/kWh

The Team calculated the savings from a demand response plan using Aquarium pumping records and estimates of pump operation cost. Costs were calculated by multiplying the hours in which the pump is in operation in each pricing tier by the cost of electricity at that level by the energy consumed by the pump (equation 6).

Equation 6

$$Daily\ cost\ of\ pumping = kW * \left(\left(h * \frac{cost_{off\ peak}}{kW}\right) + \left(h * \frac{cost_{part\ peak}}{kW}\right) + \left(h * \frac{cost_{peak}}{kW}\right)\right)$$

Equation 7

$$Daily\ CO2e\ Emissions = kWh_{off\ peak} * 0.73\ lbs\ CO2e + kWh_{part\ peak} * 1.08\ lbs\ CO2e + kWh_{peak} * 1.08\ lbs\ CO2e$$

The raw water pump was the only pump analyzed for demand response because all other pumps run 24 hours per day, making them inflexible to demand. The raw water pump operates an average 14 hours per day, so pump hours of operation can be tailored to off-peak hours, constrained by tidal conditions.

4.2.8 Renewable Energy Purchase Option

The San Francisco Public Utilities Commission is launching an effort, called CleanPowerSF, to provide renewable electricity to San Francisco residents and businesses. Set to commence in mid-2012, the program is based on community choice aggregation (CCA), in which electricity is purchased by local cities or counties for their electricity customers through an investor-owned-utility. Pacific Gas & Electric (PG&E) will still be responsible for transmission and distribution (PG&E 2012).

CleanPowerSF is unique because of its goal to generate electricity from a 100% renewable fuel mix (CleanPowerSF.org, n.d.), far exceeding California's current renewable portfolio standard of 20% in 2010 and 33% in 2020. Moreover, it also exceeds the 16% renewable energy mix that PG&E provides its customers (PG&E 2010).

Although electricity rates have not yet been released, the program is estimated to increase residential electricity bills by $7-$55 per month (Matier & Ross, 2011). The Aquarium currently purchases power from PG&E at an average rate of $0.138/kWh (including demand charges), which totals approximately $365,000 per year. To estimate the premium for CleanPowerSF electricity the Team reviewed similar renewable energy programs. In California, the average premium from programs that supply at least 50% renewable power comes out to 1.8 cents per kilowatt-hour (DOE, 2010). Added to the standard rate of $0.138/kWh from PG&E, the aquarium should expect to pay approximately $0.156/kWh for CleanPowerSF electricity.

Because the CleanPowerSF program is still in development, its electric power mix is yet to be determined. However, carbon savings will be calculated under the assumption that CleanPowerSF electricity is carbon neutral. In contrast, PG&E's 2010 power mix 20% fossil fuels (mostly from natural gas), 23.8% nuclear power, and 15.6% renewable energy with associated carbon emissions of 0.524 lbs per kWh delivered (PG&E, 2010)(Figure 11).

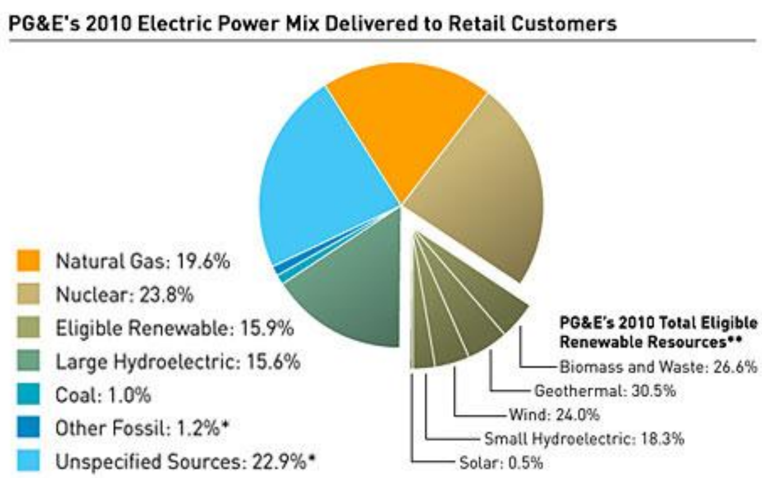

Figure 11: PG&E's 2010 Electric Power Mix

4.3 Water Cooling

Various innovative methods for improving the sustainability of water cooling processes at AOTB, beginning with an assessment of the Aquarium's associated energy usage and costs. Energy and carbon footprint reduction potential was analyzed through cost-benefit analysis (CBA). The methods used fall into three categories: heat sources, chilling capacity, and alternative solutions.

4.3.1 Heat Sources

Methods to determine the energy usage of the current cooling processes focused on the four possible sources of heat input into the system: exposed pipes, friction, exposed aquarium tanks, and incoming raw seawater.

4.3.1.1 Exposed Pipes

Presently, AOTB has no insulation on its schedule-80 PVC piping. Therefore, heat can enter the cold water system from the warmer ambient air through the pipe walls (Baylosis, 2007; Energy

Efficiency & Renewable Energy [1a] 2011). Using Aquarium blueprints, the total length of the facility's major pipes (those greater than eight inches in diameter) was estimated:

Pipe Diameter (inches)	Length (ft (m))
16	277 (84.43)
14	1154 (351.74)
10	588 (179.22)
8	258 (78.64)

In total, there are roughly 2,300 feet of exposed pipes, providing a large surface area for heat transfer. Quantifying the amount of heat entering the system required the following data:

- Pipe size (diameter, length, and thickness)
- Pipe composition (PVC; and its thermal conductivity or how much energy/heat is transferred through the pipe wall)
- Monthly temperatures of circulating sea water and ambient air

Much of the heat is transferred from the air to the water through convection. In convection, heat is transferred between two fluids (in this case, water and air) across a solid surface (the pipe wall) and is calculated using the heat transfer equation for convection (Baylosis, 2007; Normand and Peleg, 2012):

Equation 8

$$q = \left(\frac{1}{\frac{1}{h} + \frac{t}{k}} \right) \cdot A \cdot \Delta T \quad \text{where,} \quad h_{wall} = \frac{2k}{d_i \ln(d_o/d_i)}$$

Definition of variables and units:

q= heat transfer (W)
h= heat transfer coefficient of the pipe
k= pipe conductivity (W/mK)
A= surface area of the pipes (m; for a cylinder: $2\pi r^2 + 2\pi rx$)
x = length of the pipe (m)
d_o= outer diameter of pipe (m)
d_i= inner diameter of pipe (m)
T= temperature difference between water and air (K)

The pipe material – Polyvinyl chloride (PVC) - is already one of the most efficient materials available in terms of heat conductivity, durability and friction generation (Jensen pers. comm. 2011a; Open Electric 2011). Therefore, the Team did not consider replacing existing PVC pipes with another material. Smaller pipes were ignored because they transfer negligible amounts of heat.

Table 4 below illustrates monthly averages for ambient air temperature and water temperature in the facility. Aquarium staff estimate indoor air temperatures are generally 5^{o}F warmer than the outside air temperature (The Weather Channel, 2012; NODC, 2012).

Table 4: Average monthly temperatures for seawater and air circulating inside AOTB

Month	Indoor Water Temperature (Kelvin)	Indoor Air Temperature (Kelvin)
January	287.8331597	286.761111
February	286.6675	288.15
March	286.8104464	288.983333
April	287.1476042	289.261111
May	286.8817857	291.094444
June	287.9924554	291.483333
July	288.9146875	292.038889
August	289.0555556	292.316667
September	289.2692857	292.872222
October	288.840625	292.316667
November	287.5733333	289.538889
December	286.759375	286.761111

Using monthly indoor and outdoor temperature averages, the Team calculated the average amount of heat or energy (in watts) transferred through the exposed pipes during each month. This data was then used for further analysis in evaluating alternative scenarios to reduce this incoming heat (see "Alternative Methods: Exposed Pipes" section under Methods).

4.3.1.2 *Friction*

According to Moody and Princeton (1944), thermal heat is generated from friction when water flows through PVC pipes. However, after industry wide surveys and interviews with engineering experts, it appears thermal heat generated from friction is negligible (Holden, P. pers. comm. 2012; Bennett, T. pers. comm. 2012) As a result, heat from friction was not used in the water cooling calculations.

4.3.1.3 *Raw Water*

Average temperatures for the sea water entering the Aquarium (at an average rate of 168,000 gallons per day) are shown in Table 5.

Table 5: Average monthly water temperatures for San Francisco Bay (NODC, 2012).

Month	Average Outside Water Temperature (Kelvin)
January	283.70556
February	285.372222
March	286.483333
April	287.872222

May	290.094444
June	291.205556
July	292.038889
August	292.038889
September	291.761111
October	290.094444
November	287.59444
December	284.816667

Using the specific heat of seawater (3.93 kJ/(kg*K)), the heat input from raw seawater into the system was determined.

4.3.1.4 *Heat Flux*

AOTB's two main tanks – T1and T2 – together hold an estimated 800,000 gallons (Jensen pers. comm. 2012). Though they are located indoors, their surfaces are exposed to warmer ambient air. The net heat flux from the air into the two tanks occurs via infrared radiation and sensible heat exchange (Dozier and Dunne 2010; Incropera 2007; Aeschbach-Hertig 2010). Infrared radiation enters the water from the ambient warm air (IR_{air}) and ceiling above. Sensible heat (H) is created from the mixing of warm air with the cooler water. These heat sources are then offset by infrared radiation leaving the cooler water towards the ceiling (IR_{water}), and latent heat of evaporation (L), which cools the water (Figure 12).

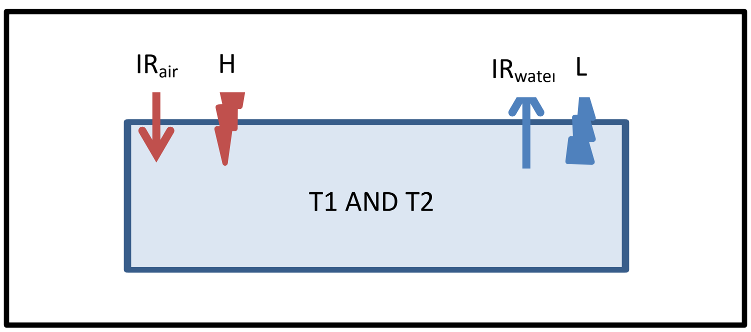

Figure 12: Concept model for factors affecting heat flux into T1 and T2

The net heat flux would then be the balance between these four factors, which is calculated by using the following formula (Dozier and Dunne, 2010; Incropera, 2007; Aeschbach-Hertig, 2010):

Equation 9

$$\text{Net Heat Flux (W/m}^2\text{)} = IR_{air} - IR_{water} + L + H$$

where:

$$IR_{air}\ (W/m^2) = [\sigma*\varepsilon_a*(-(1-p_{LW}))*(T_a)^4]$$

$$IR_{water}\ (W/m^2) = [\varepsilon_w*\sigma*T_w^4]$$

$$L\ (W/m^2) = [(IR_{air} - IR_{water}) - \text{Chiller}]/(1+B)$$

$$= [(\sigma*\varepsilon_a*(-(1-p_{LW}))*(T_a)^4) - (\varepsilon_w*\sigma*T_w^4)) - \text{Chiller}]/(1+B)$$

H (W/m^2) = LB

Definition of variables and units:

Chiller = amount of energy that is removed from the system's main chiller (see Chilling under Methods for procedures in determining the amount of heat removed)
σ = Stefan Boltzmann constant (5.67*10^{-8} W/(m^{2}K^4))
ε_a = emissivity of air (1.24*(e_a/T_a)$^{1/7}$*1.17)
p_{LW} = reflectivity of water (0.97)
T_a and T_w = temperature of air and water (Kelvin)
B = Bowen's Ratio[2] ($\gamma \left[\frac{T_w - T_a}{e^*(T_w) - e_a}\right]$)

γ= psychrometric constant[3] ($\gamma = \frac{m_a C_p P}{m_w \lambda_v}$) (in kPa/ K)

m_a= molecular weight of air (0.02897 kg/mole)

m_w= molecular weight of water (0.18015 kg/mole)

C_p= specific heat of air at constant pressure[4] (0.715 J/kgK)

L_v= latent heat (enthalpy) of vaporization[5] (2.3799 J/kg)

P= air Pressure (101.35 kPa)

e_a = RH*e*(T_a)

RH= relative humidity[6] (0.73)

e*(T_a)= saturation vapor pressure at T_a [$e^{\left(6808*\left(\frac{1}{To}-\frac{1}{T}\right)-5.09\ln\left(\frac{T}{To}\right)\right)} * (e^*(To))$]

e*(T_O)= saturation vapor pressure at 0^{o}C (0.611 kPa)
T= saturation vapor pressure at T_a[7] (2.31kPa)
T_o= -273.15K

Note: the factors that account for sunlight, cloud cover, and wind velocity were not incorporated since the tanks are located indoors. As a result, the sensible heat flux "H" can be calculated following Bowen's Ratio (Sellers et al. 1997, Dozier pers. comm. 2012).

4.3.2 Existing Chiller

After configuring the heat inputs from the four sources (exposed pipes, thermal heat from friction, raw water, and heat flux from the exposed tanks), it was then necessary to calculate the amount of heat the five chillers in the system remove. This information would be used to determine the optimal needs of the Aquarium in terms of water cooling (see "Alternative Methods: Chiller" under Methods). Methods to determine current chilling power were first developed for the system's main chiller. Figure 13 illustrates how the main chilling system operates:

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[2] Sellers et al. 1997
[3] Bohren and Albrecht, 1998
[4] Benson, 2010
[5] Mostafa et al. 2010
[6] NCDC, 2008
[7] Engineering Toolbox [1a], 2012

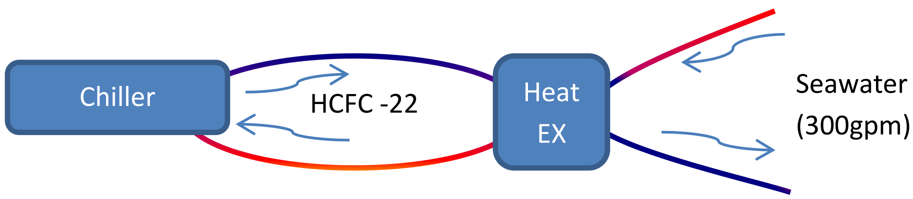

Figure 13: Concept model depicting main system chiller for AOTB and heat exchange between refrigerant HCFC-22 and circulating seawater.

Using the main chiller's operating manual, the following parameters were needed to configure how much heat is being removed by the chilling system:

- Desired Leaving Water Temperature (LWT ~ 40^{o}F)
- Incoming aquarium water and air temperatures (see Table X1 above)
- Set tonnage removed by the chiller (83.2 tons)[8]
- Incoming flow rate into the heat exchanger (252 gpm)[9]

Using these parameters, the flow rate of heat exchange between the sea water and the (HCFC-22) was estimated using the following equations:

Equation 10

$$h=(c_p p q \Delta T)/12000)$$

(Source: The Trane Company 1999; T.J. Snow Company 2011; The Engineering Toolbox [1b] 2011)

Equation 11

$$q=(12000h)/c_p p \Delta T$$

Definition of variables and units:

q= flow rate of the water (gpm)
h = heat load (83.2 tons)
c_p = coefficient (1 BTU/lb^{o}F)
p = density of seawater (8.556lb/gal)
ΔT = temperature difference of incoming water and outgoing water (^{o}F)

Tonnage is defined as the amount of heat needed to melt one ton of ice in 24 hours (SMB, 2011). One "ton" of heat removed is equivalent to 12,000 British Thermal Units (BTU's) per hour, or

[8] Matt Jensen pers. comm., 2012
[9] This was determined by looking at the Trane Chiller Manual performance data (see Table P-15) (The Trane Company, 1999) using a LWT of 40^{o}F and using the formula $h=c_p pq\Delta T$ as explained below.

12,660 kilojoules (kJ) per hour. This metric was used in the Team's calculations because this is the standard for chillers in the United States. Using the above information, the Team was able to estimate how much heat – in tons – the main chiller was removing from the water. More importantly, the Team was able to determine how much more heat needed to be removed in order to keep the system's water temperatures within the optimal range of 10^{o}C- 14^{o}C.

Collectively, the four smaller chillers remove only 3.23 tons per hour. Since these chillers are not part of the main chilling system because their energy requirements are insignificant compared to the main chiller, the Team focused its efforts on the main system chiller only.

4.3.3 Alternative Scenarios

Once the baseline heat flux was determined, the team explored ways to impede the most prominent sources of heat.

4.3.3.1 Insulation

The Team evaluated the multiple types of insulation based on their cost-effectiveness and ability to prevent the transfer of heat. Once heat transfer rates of exposed pipes were determined, the Team calculated how effectively each insulation material reduced the heat transfer rate. The Team identified three materials for evaluation: vinyl covered neoprene, elastomeric rubber, and polyethylene foam (Quamen pers. comm. 2011, Express Insulation, 2011).

To calculate the heat energy saved by each, a modified heat transfer equation for convection incorporating conduction between two walls (the pipe wall and the insulation layer) was used (Baylosis, 2007; Normand and Peleg, 2012):

Equation 12

$$q = \frac{A * \Delta T}{\left(\left(\frac{1}{hi}\right)+\left(\frac{di}{ki}\right)+\left(\frac{1}{hp}\right)+\left(\frac{dp}{kp}\right)\right)} \text{ where, } \quad hx = \frac{2k}{di\left(\ln\left(\frac{di}{do}\right)\right)}$$

<u>Definition of variables and units:</u>

q= heat transfer (W)
h= heat transfer coefficient of the pipe
k= pipe conductivity (W/mK)
A= surface area of the pipes (m; for a cylinder: $2\pi r^2 + 2\pi rx$)
x = length of the pipe
d_o= outer diameter of pipe (m)
d_i= inner diameter of pipe (m)
T= temperature difference between water and air (K)

Note: Assumptions were the same as for exposed pipes (see "Heat Sources: Exposed Pipes" section under Methods).

The above equations were used to determine the amount of energy (in watts) that passes through the PVC pipes with each material across the four different pipe sizes (8, 10, 14, and 16 inch diameters). A CBA was then conducted to compare each type of insulation. Metrics used in the

CBA were Net Present Value (NPV), Cost Benefit Ratio (CB Ratio), and Return on Investment (ROI) (Watkins 2012; Libecap 2011).

<u>Definition of variables and units:</u>

r= discount rate (set at 0.02)
t= amount of time benefits and costs are incurred (the Team decided to compute the costs and benefits over seven years and then twenty years as instructed by AOTB management).

To determine the cost-effectiveness of purchasing, installing, and maintaining the insulation, the Team calculated the amount of energy saved (watts or joules per second) with each material. Because water circulates constantly and chilling operates 24 hours a day (Jensen pers. comm. 2011a), the joules saved per second were multiplied across the entire year to find annual energy savings. The annual kilojoule saving were converted to BTUs (one kilojoule equals 0.947 BTU) and ultimately into tons saved. Using the efficiency of the current chiller (kWh input per tonnage output), the energy savings (in kWh) from insulation were multiplied by the average monthly electricity rates. Finally, these annual savings were discounted for the life expectancy of each insulation material with a discount rate equaling the mortgage loan interest rate of 2%. The annual carbon emissions saved were based on PG&E's ratio of 0.524 pounds of carbon dioxide derived for every kilowatt-hour delivered (PG&E 2012).

The capital costs of insulation were estimated based on estimates provided by various insulation suppliers and installation cost was based on industry averages, roughly $\$105.22/m^2$ (Semm 2011). However, the cost of installation is very sensitive to the positions and sizes of the pipes as well as local contractor prices. Life expectancy of the insulation was based on the materials' susceptibility to corrosion from condensation on the PVC pipes. Elastomeric rubber and vinyl covered neoprene are both estimated to have ten year life expectancies (Semm 2011; Adams 2011; Grainger 2012), while literature review suggests that polyethylene foam has no known limit on lifespan (ICC Flowtech 2012). Benefits to animal welfare resulting from reduced heat input were not included in the CBA due to the lack of data. A second CBA was conducted for a scenario in which water temperatures were maintained in the optimal 10^{o}C -14^{o}C range. The calculated heat transfer rates and CBA analyses are presented in the Results section of this document.

4.3.3.2 Extension of Raw Seawater Inlet

Interviews conducted by the Team suggested that extending the inlet for the raw water pump could allow the Aquarium to access colder Bay water and reduce the chilling need. Presently the inlet pipe is located near the surface. With average depths in the Bay of 25 meters (Baylosis et al. 1997) a deeper pipe might have temperature advantages. However, further research revealed that temperature gradients are tool small (<1^{o}C) for this strategy to be effective (Baylosis et al. 1997) (Figure 14).

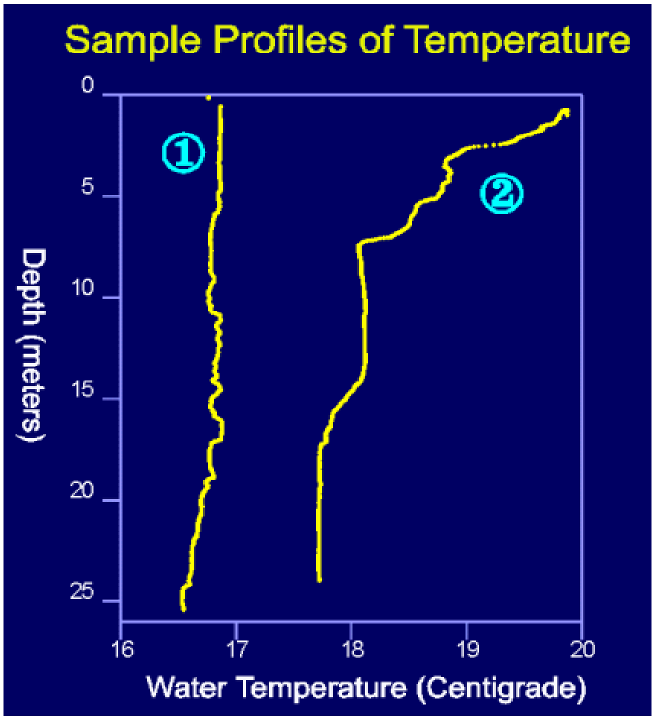

Figure 14: Temperature-depth profiles in July, 1996 for 1) Central Bay and 2) San Pablo Bay in San Francisco Bay. *Note: profile #1 showcases the temperature variation across depths in Central Bay of San Francisco Bay. AOTB is located on the coast of Central Bay (Baylosis et al. 1997).

4.3.3.3 Pool Cover

Sensible heat is mainly driven by the heat flux of infrared radiation from the ceiling and the heat in the ambient air above the tanks (Dozier and Dunne 2010; Incropera 2007; Aeschbach-Hertig 2010). To reduce the sensible heat, the Team researched pool covers that can be placed over the tanks. The Team assumed a pool cover would cover roughly 90% of the tanks (Figure 15).

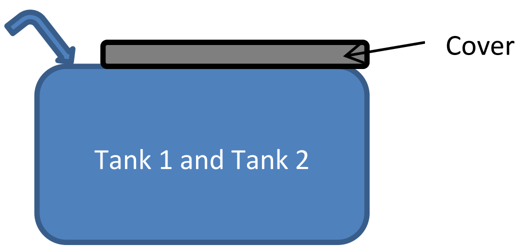

Figure 15: Theoretical cover for reducing contact of cooler water in T1 and T2 with warmer area

4.3.3.4 Fan

Latent heat flux of the exposed tanks was minimal, partially due to a lack of air currents. Because wind speed greatly affects the amount of water evaporated and heat removed, the Team analyzed the effects of installing an industrial fan near the tanks.

After estimating the volume of air in this part of the building, the Team identified a proper fan size of approximately 9,000 cubic feet per minute. The Team then converted these values into wind speed (m/s) before incorporating this value into the following mass-transfer to evaporation formula (Dunne and Leopald, 1978):

Equation 13

$$E_a = (0.013+0.00016u_2)(e_{sa}-e_a)$$

Definition of variables and units:

E_a = evapotranspiration rate (cm/day)
u_2= wind speed (9.13 km/day)
e_{sa}= saturation vapor pressure at set temperatures (mb)
e_a= atmospheric vapor pressure at set temperatures (mb)

Latent heat was determined by converting the evapotranspiration rate to meters per second and using the follow latent energy formula (Dozier and Dunne, 2010):

$$L = p_w \lambda E_a$$

Definition of variables and units:

L = latent heat flux (W/m^2)
p_w= density of seawater (1020 kg/m^3)
λ= latent heat of evaporation ($2.5x10^6$ J/kg)
E_a = evapotranspiration rate (m/s)

Wind speed also affects the amount of heat that enters the exposed tanks, so the following equation was used to determine how much heat in the form of sensible heat "H" would enter T1 and T2 (Dozier and Dunne, 2010; Incropera, 2007; Aeschbach-Hertig, 2010).

Equation 14

$$H = \rho_{air} * c_p * c_s * (T_w - T_a)$$

Definition of variables and units:

H = sensible heat flux (W/m^2)
p_{air}= density of air (1.25 kg/m^3)
c_a = specific heat of air at 20^oC[10] (1.005 kJ/kgK)
c_s = sensible heat transfer coefficient[11] (0.001)
T_w & T_a = Temperature of water and air (Kelvin)

These new values for latent heat flux "L" and sensible heat flux "H" were incorporated into the heat flux equation in the Methods section. By comparing these results to the original amount of

[10] The Engineering Toolbox [1c], 2011
[11] Aeschlbach-Hertig, 2010

net heat flux out of T1 and T2, the Team was able to estimate how much net heat the fan removes from the system as well as CO_2 savings.

The Team performed a CBA to compare the benefits from the savings of reduced chilling due to more heat being removed via evaporation to the costs. Costs considered were the costs to run the fan (calculated by converting the running horsepower to kilowatt demand), costs to install the fan (roughly estimated by literature reviews [Industrial Fans Direct 2012; Improvements and More 2010]), as well as the life expectancy of the fan (estimated to be three years [Industrial Fans Direct 2012]). The cost to install the fan highly affects the NPV of the CBA, and so the values derived for the NPV reflect an industry average. In addition, the Team calculated the efficiency of the fan in terms of amount of heat removed versus how much energy input is required by the fan. These efficiencies were then compared to the main chiller's efficiency.

4.3.3.5 Additional Chiller

The Team estimated the excess heat in the water by totaling heat amounts (kilojoules) from all heat sources and subtracting the amount of heat (in kilojoules) the current chiller removed. Using the specific heat of seawater [(3.93 kJ/(kg*K)] and average, monthly seawater temperatures within AOTB, the Team was able to evaluate how often and by how much the system water temperature still rose above the 14^{o}C threshold. Then, by calculating how much extra heat (in kilojoules) was still in the system, the Team was able to determine (using the ratio of BTU to kilojoules and then ratio of BTU/hr to tons) the average tons of heat was needed to be removed. The heat load equation from the "Chilling" section in Methods was repeated to estimate the tonnage from an additional chiller that would be necessary to keep AOTB's system seawater temperatures within the 10^{o}C- 14^{o}C range.

The Team then researched high-efficiency chillers available in the market that operated at these optimal heat loads. In addition, in an attempt to find the most sustainable chillers available, the Team researched chillers with more eco-friendly refrigerants. The Aquarium's current chiller uses HCFC-22 as the refrigerant, which has a global warming potential of 3100 CO_2e over twenty years (Lorentzen, 1995). Other refrigerants such as ammonia and pressurized carbon dioxide offer the same if not better heat cooling capacities than HCFC-22 with less global warming potentials (Lorentzen, 1995). However, carbon dioxide must remain under pressure (Lorentzen 1995) and ammonia is poisonous and flammable, all of which could pose a safety hazard. For these reasons, the Team decided not to pursue these refrigerants further.

Some of these more natural refrigerants and their global warming potentials as well as their refrigeration capacities illustrated in Appendix 4.

The Team then selected an upgraded Trane chiller because it not only had the capacity to chill the extra tonnage in the AOTB system, but it also had the highest efficiency of the chillers researched. In addition, the Team determined how many pounds of CO_2 this additional chiller would emit for every kilowatt-hour input.

A CBA was conducted to assess the cost-effectiveness of this option. The costs of operating both large chillers, and installation of the second chiller were evaluated (Aqualogic, 2012), and the life expectancy of the both chillers (estimated to be twenty years [Aqualogic, 2012]). Qualitative benefits not included in the CBA were improved animal welfare and reduced animal metabolism as it was beyond the scope of the project to determine willingness to pay of tourists to see healthy animals.

4.3.3.6 Cooling Towers

Cooling towers utilize the power of evaporation to cool water (Cooling Technology Inc. [1a] 2008). Compared to air compressed chillers such as the current Trane chiller that AOTB has cooling their main system, cooling towers require little energy inputs to operate (Cooling Technology Inc. [1a] 2008). However, cooling towers rely on the ambient air conditions to evaporate and cool the water. In areas such as San Francisco, where humidity is high, these systems work much less efficiently. In the end, the Team determined this was not a feasible option.

4.3.3.7 Geothermal Cooling

Another alternative to a chiller is to utilize geothermal principles. In many applications, buried pipes use the more stable underground temperatures as a heat source during cold weather. At the Aquarium, it would be possible to install pipes in the water beneath the pier the facility is located on. However, after calculating the heat transfer required and resulting pipe lengths needed, the Team found this option to be infeasible.

4.4 Cost-Benefit Analysis

To determine the cost effectiveness of different projects, the Team conducted a cost-benefit analysis (CBA) for each recommendation. The function of a CBA is to use a monetary value to put all costs and benefits into a common metric (Watkins, 2012). Although this approach has limitations, it is useful for weighing tradeoffs.

Two parameters must be defined in any CBA:

- Discount Rate: The discount rate for this project is 2% (r=0.02). This number is based on the Aquarium's opportunity cost, which is associated with their main loan. The discount rate is used to calculate the annual depreciation of money (i.e. $100 today is worth $98 in one year). It should be noted that the 2% discount rate is lower than the normal 5%, meaning that it more heavily weighs future values.
- Time Horizon: The time horizon is the length of time in which the accrued costs and benefits of a project are accounted for in the CBA. There are two time horizons selected for this project: 7 years and 20 years. The Team originally chose 20 years because it is the length of the warranty for much of the machinery that is being recommended. However, the Aquarium typically uses 7 years. Therefore, the Team chose to calculate CBAs based on both time horizons to meet the academic and professional needs of the project.

Multiple tools are used to quantify the costs and benefits of a project. These include:

Return-on-Investment (ROI): This is the point in time in which the savings from a project equal the upfront costs. For instance, if a motor costs $100 to install, but saves $50 in energy costs every year, the ROI would be two years ([cost] $100 = 2 * $50 [benefit]).

Equation 15

$$ROI = \frac{Upfront\ Costs}{Annual\ Benefits - Annual\ Costs}$$

Net Present Value (NPV): NPV is calculated by subtracting present value costs from present value benefits. The project is financially justifiable if the NPV is positive, indicating that the benefits are greater than the costs. This metric makes projects easy to compare by showing the net benefit that each offers.

Equation 16

$$\text{NPV} = \sum_{k=t} \frac{Benefits}{(1+r)^t} - \frac{Costs}{(1+r)^t}$$

r=discount rate
t=time in years

Benefit-Cost Ratio: This is simply the ratio of benefits to costs. For a project to be a worthy investment, its B:C ratio should be above 1 (where the benefits outweigh the costs). The simplicity of this tool is useful for comparing projects of different scales.

Equation17

$$\text{BC Ratio} = \frac{\sum \frac{Benefits}{(1+r)^t}}{\sum \frac{Costs}{(1+r)^t}}$$

5. Results

5.1 Animal Care

As of summer 2011, Aquarium of the Bay had over 5,000 animals in Tanks 1 and 2. Of those animals, there are roughly 400 rockfish, with over 20 species represented (Appendix 5). The highest mortality rates occur in Tank 1, where the majority of rockfish are.

5.1.1 Total Mortality

In T1, which contains near-shore species of marine animals, rockfish represent over 50 percent of total mortality for both 2010 and 2011 (Figure 16). Of the 65 animals that died in 2010, 33 of them were rockfish species (Figure 16). In 2011, 27 of 44 animals that died were rockfish

(Figure 16). AOTB staff believes these issues are a result of fluctuations in temperature within the tanks.

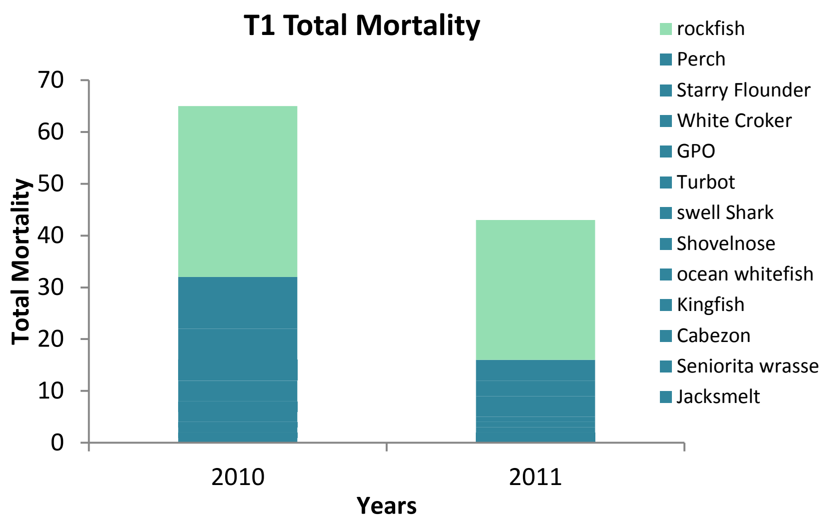

Figure 16: Total animal mortality in Tank 1

Further investigation of T1 mortality revealed that black, brown, and grass rockfish represented almost 50% of rockfish mortality in both 2010 and 2011 (Figure 17). These three species have the highest mortality of all species in T1 and T2, though they represent only 20% of the rockfish population (Appendix 5). Data shows that seven of the twenty rockfish species have not experienced mortality within the past two years. These species represent over 17% of the total rockfish population (Appendix 5).

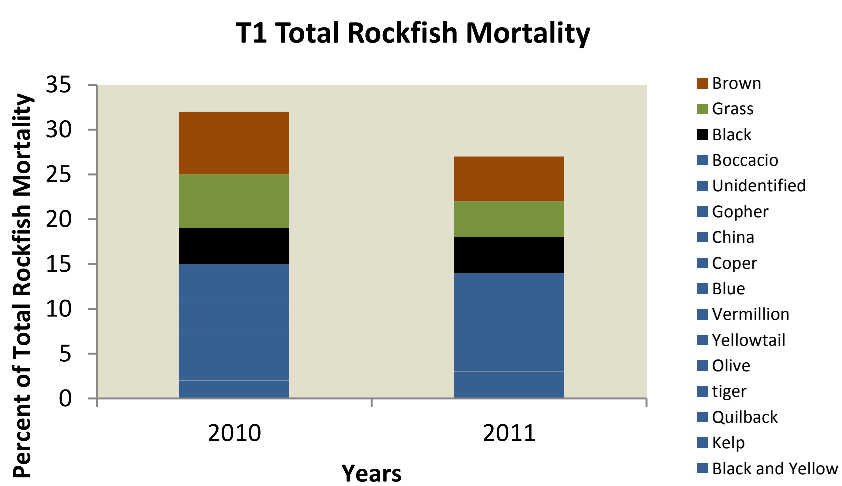

Figure 17: Total rockfish mortality in tank 1

In T2, which contains deeper water species, the species with the highest mortality varies from year to year, unlike the rockfish in T1. In 2010, chub and spiny dogfish had the highest mortality with six and five deaths, respectively (Figure 18). However, in 2011 mortality for those species decreased and mortality for seabass and yellowtail jack increased (Figure 18). This shows that unlike mortality in T1, the species death varies depending on a variety of factors. Aquarium records show that the causes of death in T2 are commonly reported as predation by seven-gill shark, as well as birthing complications for some species.

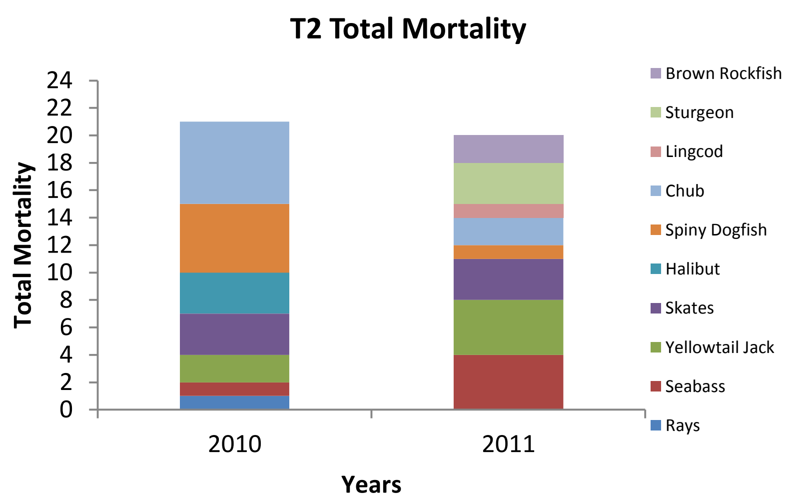

Figure 18: Total animal mortality in Tank 2

5.1.2 Rockfish and Temperature

After analyzing the relationship between rockfish mortality and temperature, the Team determined that the number of deaths is significantly higher when the water temperature is above the 14 °C threshold (Figure 19). In 2010, mortalities that occurred above 14°C were almost double the deaths that occurred within optimal temperatures (Figure 19). In 2011, mortalities that occurred above 14°C were more than four times that of mortalities within optimal temperature ranges (Figure 19). This relationship supports the Aquarium's speculation about the effects of temperature fluctuations on rockfish mortality. Although overall mortality in T1 has decrease from 2010 to 2011, the amount of deaths occurring when water temperature exceed 14°C are slightly higher in 2011 (Figure 19). This shows that although mortality has decreased, temperature related deaths are still an issue for rockfish.

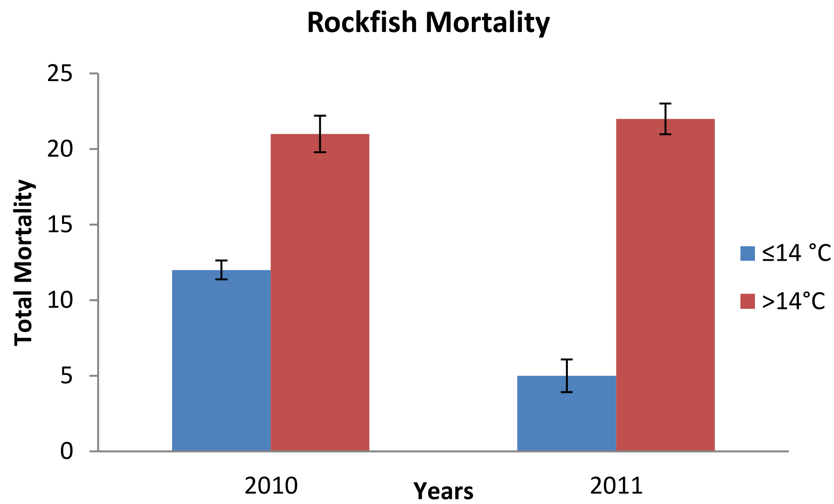

Figure 19: Rockfish mortality with different above and below 14°C

5.1.3 Rockfish and Temperature without sensitive species

As previously shown (Figure 17), black, brown and grass rockfish have the highest mortality of all rockfish species. Since this three species represent only 20% of the total rockfish population, we examined the relationship between the other 17 rockfish species and water temperature. If the three species are removed from the rockfish mortality data set, the relationship between temperature and mortality changes significantly for 2010 data (Appendix 6). In 2010, the number of deaths that occurred within the optimal temperature range is equal to the number that occurred above the optimal range (Appendix 6). Based on this finding, without those three species, we can no longer assume rockfish mortality is a result of temperature related death.

In 2011, however, after the removal of the three temperature-sensitive species, mortality above 14°C did decrease by nearly half, but was still greater than the number of deaths within the optimal range. This difference is largely due to the low number of overall rockfish mortality that occurred below 14°C. It is important to note that 25% of mortality occurring above 14°C is unidentified rockfish, which could in fact be black, brown, or grass rockfish (Appendix 6). In addition, of the identified species, all except copper and gopher rockfish experienced the death of only one individual.

These findings show that, although a variety of rockfish species may be susceptible to temperature related mortality, black, brown, and grass rockfish appear to be the most sensitive.

5.1.4 Feed and Temperature

After analyzing the relationship between animal feed and temperature in T1, the Team found a very weak positive correlation between average daily feed cost and average monthly temperature for 2010-2011 (Figure 20). The trend shows that daily feed cost increases slightly with temperature (Figure 20). The results from our linear regression analysis show a R^2 value of

0.1198, meaning the best-fit line explains over 11 percent of the data (Figure 20). These results imply that any other factors besides temperature contribute to feed cost, including tank densities, animal maturity and reproductions stage, as well as the types of animal present.

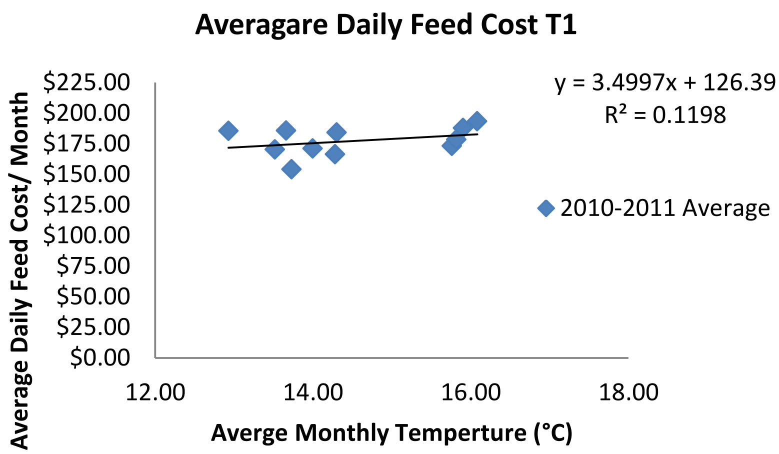

Figure 20: Average Daily Feed Cost per month as temperature increase in T1

The Team found a different result for Tank 2, in which average daily feed cost declined with monthly temperature (Figure 24). Regression analysis produced an R^2 value of 0.4471, implying that temperature has a much more important impact on feed cost in T2 than in T1. Although the results for T2 were statistically significant and implied a stronger relationship than in T1, factors other than temperature are important in controlling feed cost.

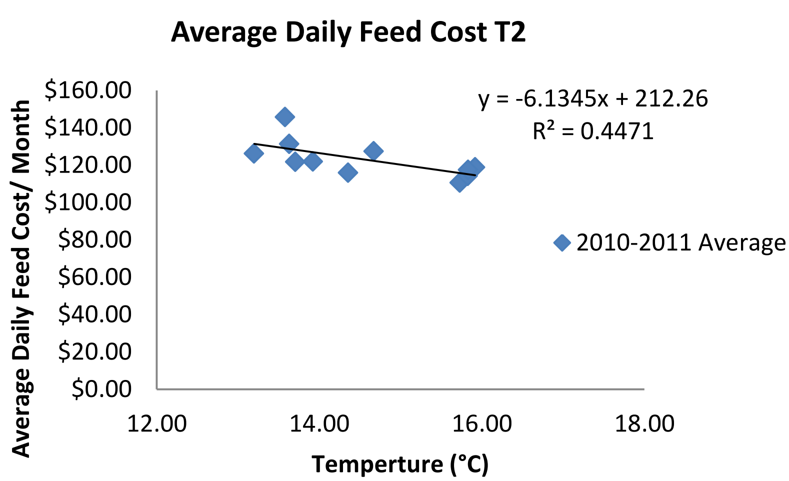

Figure 21: Average Daily Feed Cost per month as temperature increases in T2

5.2 Pumping

5.2.1 Hydraulic System Analysis

Head analysis revealed that total system head ranges from 61.7 to 79.6 feet and moving the operating point along the pump curve (Figure 22). This difference depends almost entirely on the state of the filters, with the higher number occurring when filters are dirty. In total the filters make up anywhere from 32-47% of total head.

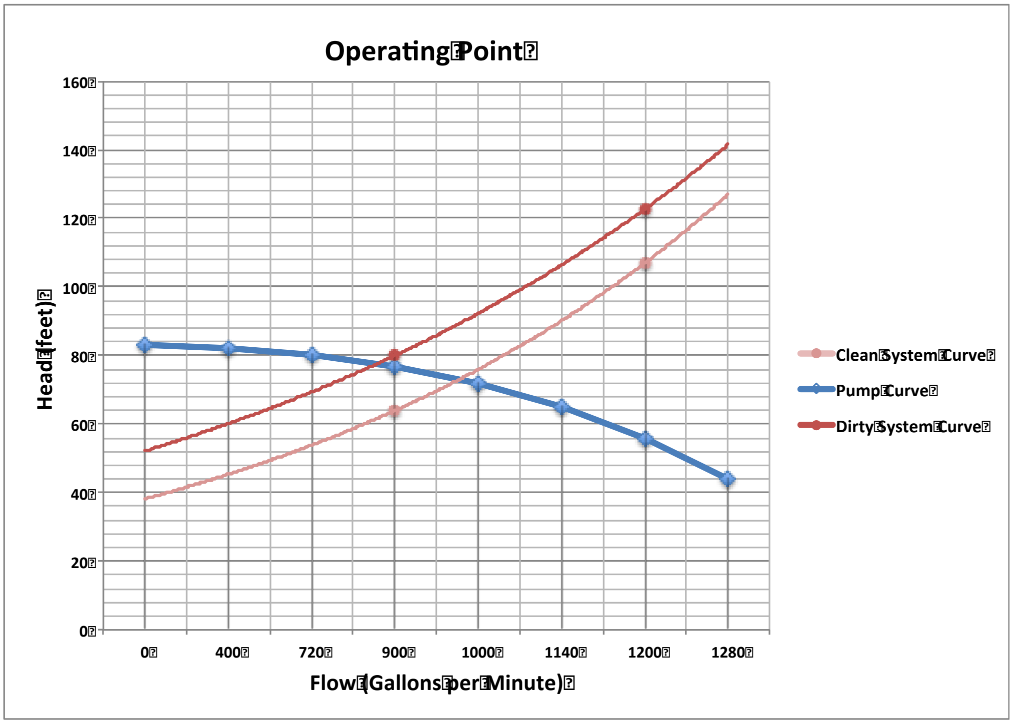

Figure 22: The operating point is where the system curve meets the pump curve. Cleaning the filters moves the operating point, increasing flow and decreasing head.

The other major source of system head was friction from pipes and fittings, at 35.9 feet. Most of this friction cannot be modified given the constraints of the system. However, the Team identified one friction source within this category that may provide an opportunity for head reduction. This was two paddle flow meters, which together add 8.52 feet of head. Paddle flow meters use the force of the moving fluid to turn a small wheel and measure the water velocity.

From these results, the Team decided to evaluate two alternatives for reducing head and increasing flow by moving the operating point to the right on the pump curve: 1) filter media replacement and 2) filter media replacement and flow meter replacement

Alternative 1) Filtration media replacement

Replacing the filtration media in the filters is estimated to significantly decrease head from pressure losses. The Team evaluated the effects of this upgrade on system head and flow rate.

Alternative 2) Filter and flow meter replacement

In contrast to paddle wheel flow meters, magnetic flow meters measure water velocity using the conductance of the fluid. This requires ions, which exist naturally in sea water. As a result, the Aquarium can completely eliminate resistance from the flow meters. Adding this upgrade to the filter replacement is expected to provide further gains for head and flow.

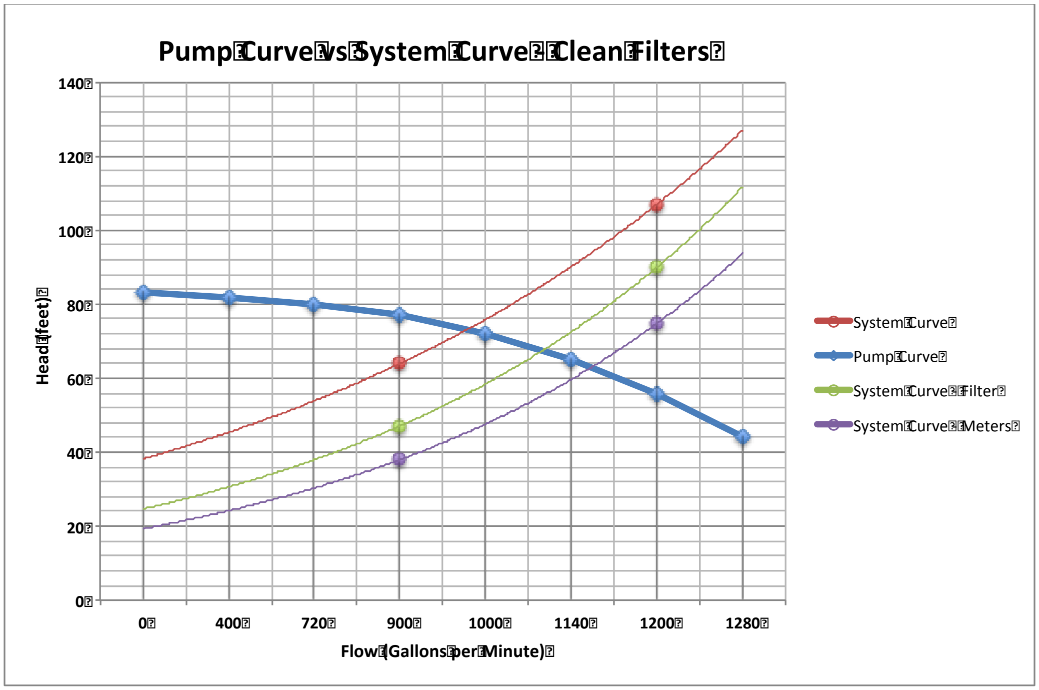

Figure 23: To improve the operating point, AOTB can replace filter media and flow meters.

Figures 23 and 24 demonstrate the head and flow relationship for the system when filters are clean and dirty. The blue line is the pump curve of the main life support system pumps. The red, green, and purple lines represent three possible system curves. The red curves are the current conditions, while the green curves indicate system conditions with new filtration media, and the purple curves include the filter changes plus replacement of flow meters.

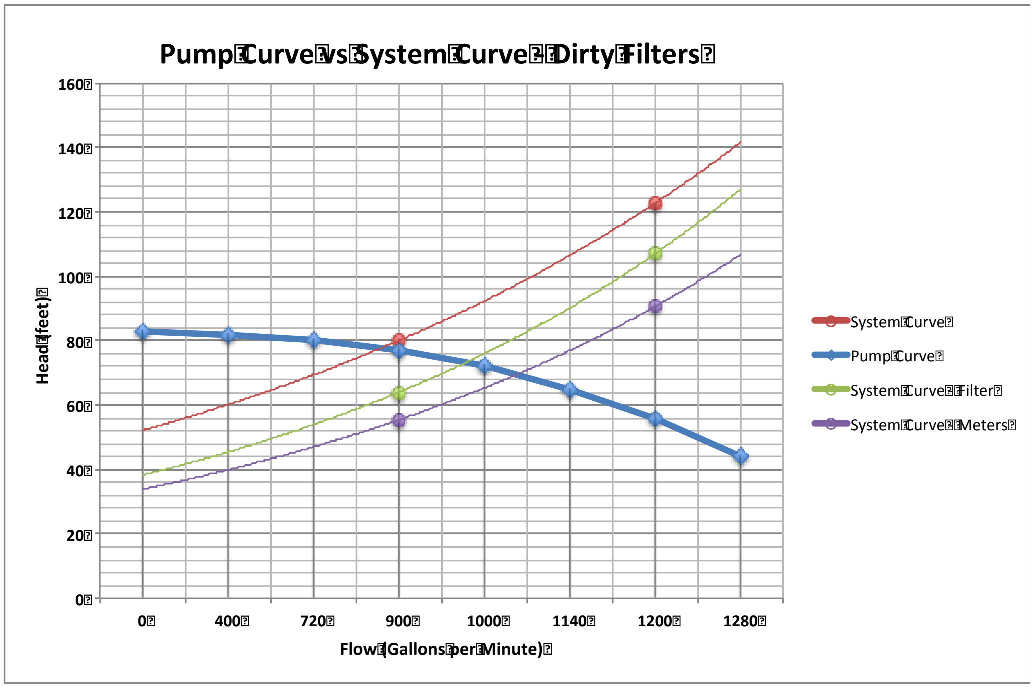

Figure 24: When the filters are dirty, the system operates less efficiently than it does when they are clean.

Results showed that changing the filtration media would increase system flow and decrease head. Replacing the flow meters improved these gains. Rather than operating at 975 gpm and 75 feet of head for the baseline, Alternative 1 operates at 1100 gpm and 60 feet of head, while Alternative 2 operates at 1150 gpm and 63 feet of head.

5.2.2 *Motor Replacement*

Replacement of 16 motors would pay itself off in just under three years and save almost $50,000 over 20 years. Table 6 provides an overview of these findings.

Table 6: Overview of motor replacement savings

Up-front Cost	Payback (yrs)	Cost-Benefit Ratio	NPV - 20 yr	Total CO2 Saved (lbs) - 20 yrs
$10,430	2.94	5.66	$48,623	276,346

The investment with the highest overall net present value is replacement of motors on the ozone booster pumps at $23,140. In general, the higher horsepower motors garnered more savings than smaller motors.

5.2.3 *Additional Pumps*

Another change being considered for increasing flow is installing two additional life support pumps on the system. The up-front cost would be $36,000 ($18,000 per pump) plus $5,400 for installation (Martin, 2003). Because this modification increases energy use, all metrics are zero or negative. Furthermore, the added flow through the system would increase system head to over

100 feet. Because the pumps are designed to operate at 75 feet, at best the pumps will operate inefficiently. At worst, the pumps will be operating completely beyond their capacity since cut-off head is at about 83 feet. The result could be severe lack of flow and damage to pumps in the form of high temperature, bearing load, and internal recirculation (Chaurette, 2002) . Aquarium staff may be able to compensate for these effects by adjusting system parameters such as valves, but this is not the most efficient or generally recommended method for operating a pumping system.

Table 7: Financial and environmental metrics on additional pumps.

Up-front Cost	Payback (yrs)	Cost-Benefit Ratio	NPV - 20 yr	Total CO2 Saved (lbs) - 20 yrs
$36,000	Indefinite	0	-$823,720	-6,981,795

5.2.4 Variable Frequency Drives (VFDs)

Replacing filtration media has a large up-front cost of $45,000 for all twelve filters, according to Aquarium staff (M. Jensen, personal communication, 2012a). However, this will significantly reduce head loss through the filtration to about 1.75 psi on clean filters (Appendix 2). As a result, flow would increase, positively affecting animal welfare as well as water clarity and chemistry. For cost comparison, each 25 hp pump consumes about $24,000 in energy each year. If filter media changes made additional pump purchases unnecessary, this could be a viable option.

Table 8: Changes of flow and head when after filter and paddle flow upgrades, as compared between dirty and clean filters.

Baseline	Clean	Dirty
Flow	975	875
Head (psi)	75	78
% Head	1.00	1.04
% Power	1.00	1.06
Alternative 1: Filter Upgrade		
Flow	1100	975
Head	68	73
% Head	0.9067	0.9733
% Power	0.8633	0.9603
Alternative 2: Filters + Meters Upgrade		
Flow	1150	1050
Head	63	69
% Head	0.84	0.92
% Power	0.77	0.88

Total installed cost for a VFD varies, but market analysis suggests that the cost is approximately $160 per horsepower ("Variable Frequency Drives," 2000). With total horsepower for the main LSS pumps at 150, the installed cost was calculated to be $24,000.

Alternative 1 increases flow by over 100 gpm per pump while decreasing head by 7 psi or 10%. Meanwhile, power required decreases by 14%. From Alternative 1 to Alternative 2, there is only a 6% decrease in head but a 9% decrease in energy usage. A flow meter for a 14" pipe is $5,500 with a $1,700 installation cost (RS Means, 2003) Installation cost was estimated using data for a 12" check valve (RS Means 2003). Total cost to purchase and install two flow meters is $13,700.

Table 9: Financial and environmental metrics on filter and paddle flow upgrades.

Alternative 1: Filter Upgrade				
Up-front Cost	**Payback (yrs)**	**Cost-Benefit Ratio**	**NPV - 20 yr**	**Total CO2 Saved (lbs) - 20 yrs**
$69,000	5.42	3.02	$139,143.74	161,116

Alternative 2: Filter + Flow Meters Upgrade				
Up-front Cost	**Payback (yrs)**	**Cost-Benefit Ratio**	**NPV - 20 yr**	**Total CO2 Saved (lbs) - 20 yrs**
$82,000	3.27	5.00	$328,489.20	317,790

Although Alternative 2 has an up-front cost $13,000 higher than Option 1, the payback is faster, the cost-benefit ratio is higher and net present value (NPV) is more than double. Moreover, the flow rate of 1150 gpm is close to the 1200 gpm identified by the Aquarium's engineers as optimal, without the high added cost and environmental impact associated with additional pumps (Table 9).

5.2.5 Demand Response Plan: Raw Water Pump

The demand response plan for the raw water intake pump yielded significant savings. There is a potential savings of $2,302 and over 25,000 lbs of CO_2 every year. This comes out to a NPV of $37,639 and savings of 501,176 lbs of CO_2 over the 20 year time horizon (Table 10).

Table 10: Demand Response Plan savings

	Annual Savings	**NPV 7**	**NPV 20**	**CO2 Savings (lbs/year)**
14 Hours	$2,302	$14,898	$37,639	25,059

5.2.6 Power Conditioners

Despite an initial upfront investment of $2,528, an 8% decrease in consumption would pay back the costs of the power conditioners in just over a month. With an annual savings of $13,946 with six motors and $17,701 with ten motors, the conditioners have an NPV of $226,140 and $285,024, respectively. Table 11 summarizes these results.

Table 11: Power Conditioner Results

	Power Factor Increase	Upfront Cost	Annual Savings	NPV 7	NPV 20	Payback (years)	Electricity Savings (kWh/year)	CO2 Savings (lbs/year)
6 Motors	8%	$1,890	$13,946	$88,365	$226,140	0.14	101,055	52,953
10 Motors	8%	$2,528	$17,701	$110,145	$285,024	0.14	128,270	67,214
Difference	--	$638	$3,756	$21,779	$58,884	0.01	27,216	14,261

A sensitivity analysis was conducted to evaluate uncertainty in the power factor improvement. With a 1% increase in power factor, the power conditioners still save $2,213 per year, significant enough to pay back the up-front cost in less than 14 months. If, however, the power conditioners are capable of improving the power factor to "unity power" for all ten motors (an increase of 14.5% for LSS pump motors, and 11.5% increase for ozone booster pump motors to bring PF to 100), the investment will produce substantially larger savings of over $30,000/year (Table 12)

Table 12: Power Conditioner Sensitivity Analysis

Power Factor Increase	Electricity Consumption (kWh/Year)	Annual Savings ($)	Payback (Years)
Baseline	1,603,378	--	--
1%	1,587,344	$2,213	1.14
8%	1,475,108	$17,701	0.14
14.5/11.5%	1,381,094	$30,675	0.08

5.2.7 Renewable Energy Purchase Option

Purchasing electricity from CleanPowerSF will substantially reduce the Aquarium's environmental impact, but as seen in Table 15 will cost over $40,000 more per. The 20 year NPV for this project is substantially negative, at -$658,351. Still, this option would make the facility carbon neutral from a Scope 2 carbon emissions perspective, preventing the release of 1,119,973 pounds of carbon per year.

Table 13: Renewable energy purchase option

Annual Cost	NPV (7)	NPV(20)	Annual CO2 Savings
-$40,262.59	-$260,579.13	-$658,351.07	1,119,373

5.3 Water Cooling

5.3.1 Baseline Heat Sources & Sinks

There are four pathways along which heat enters or exits the AOTB hydraulic system: heat conduction through non-insulated pipes, incoming raw seawater, contact with ambient air, and chilling. Using this baseline, scenarios could be developed to reduce the main heat sources and amplify the main heat sinks.

5.3.1.1 Exposed pipes

Non-insulated pipes conduct heat from warm, ambient air into AOTB's chilled water. An estimated 3.21×10^{8} kilojoules of heat are transferred through this process annually. The monthly heat transfer rate through the exposed pipes indicates that most heat enters the system from early to late summer, where temperature differences between air and water are greatest (Figure 25).

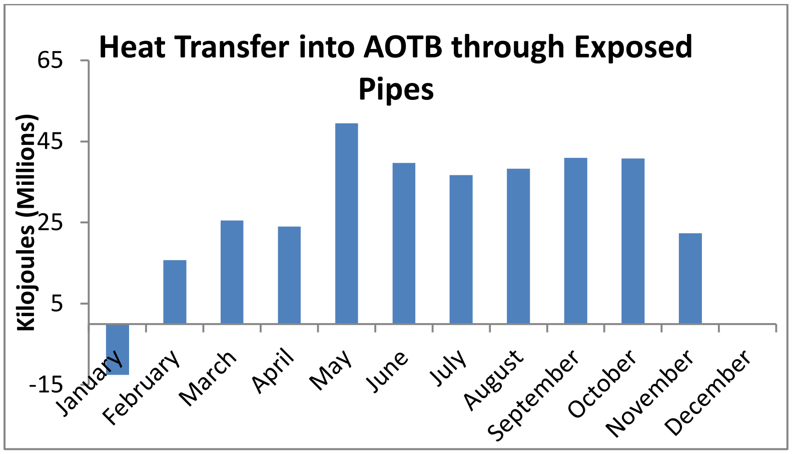

Figure 25: Monthly heat transfer in kilojoules through AOTB's exposed pipes.

5.3.1.2 Raw Sea Water

Incoming raw sea water temperatures from the San Francisco Bay are highest during summer months (Figure 26). An estimated 2.70×10^{11} kilojoules of heat enter the AOTB system from raw water annually, making it the most prominent source of heat for the AOTB water system. Thus, the most significant demand on the chiller is heat from raw water.

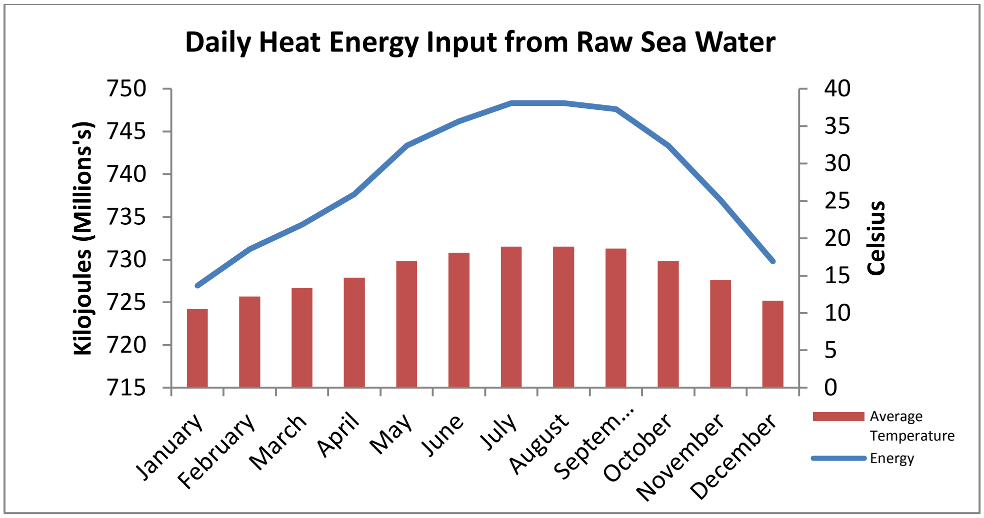

Figure 26: Average daily raw sea water temperatures and associated specific heat that enter AOTB per month.

5.3.1.3 Heat Flux into Tank 1 and Tank 2

When ambient air comes into contact with the surface water of uncovered tanks, heat is exchanged through infrared radiation (radiating to and from the water), latent heat of evaporation, and convective heat. Infrared radiation is both the most prominent means of heat entering and exiting the system, while latent and convective heat play less of a role (Figure 27).

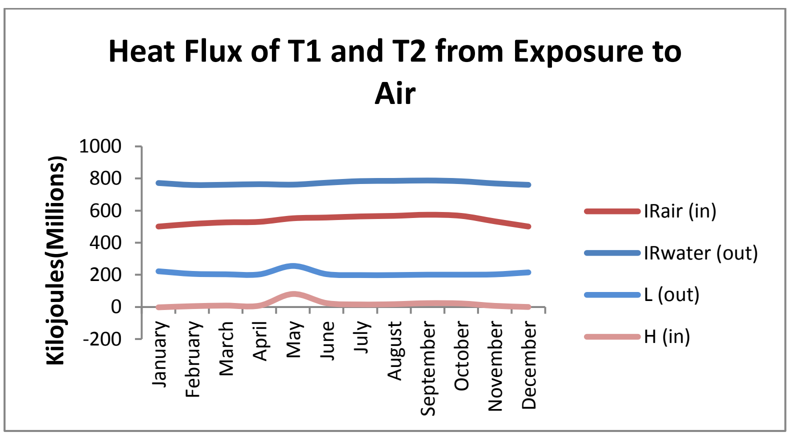

Figure 27: "In" signifies energy or heat that is coming into the water and "out" means heat is leaving the water

The amount of infrared radiation transferred from the exposed tanks to the air above is $9.27\text{x}10^9$ kilojoules per year, while only $6.5\text{x}10^9$ kilojoules of heat enter the system per year. Since the infrared heat exiting the system is greater than incoming heat, the air acts as a heat sink (Figure 27).

Evaporation also complements the chiller by removing an estimated $2.5\ \text{x}10^9$ kilojoules per year through latent heat exchange. On the other hand, sensible heat adds an estimated $2.10\text{x}10^9$ kilojoules per year from ambient air mixing with the water in T1 and T2.

Together, these four processes remove 4.59x10^8 kilojoules of heat annually, largely due to infrared heat exiting the water. Figure 28 below illustrates the net heat flux trend of T1 and T2 for each month. More infrared heat radiates into the water when there is a larger gap between water temperature and air temperature, so summer months exhibit less heat loss because of warmer air temperatures.

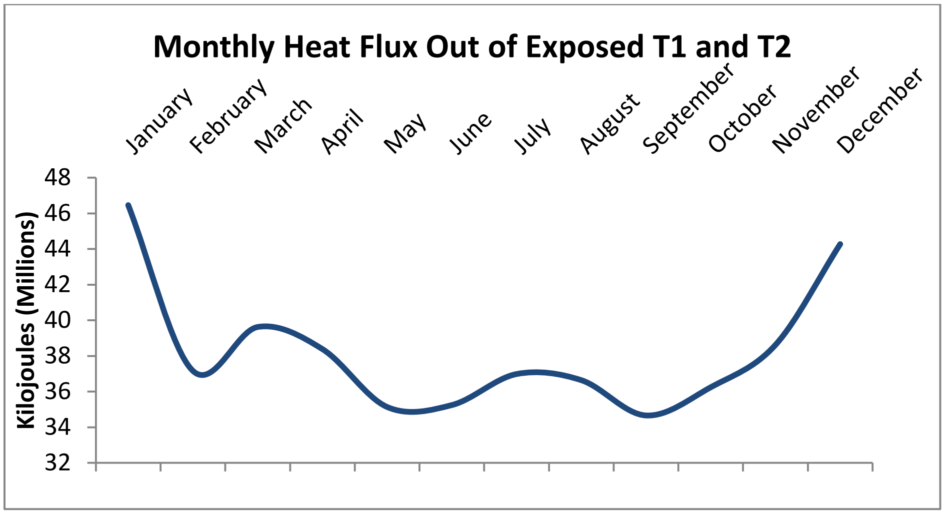

Figure 28: The most heat energy exits the tanks in the cooler winter months through infrared radiation and evaporation.

The primary means of controlling the water temperature, though, is the main chiller. Set to 83.2 tons per hour, the main chiller removes 9.23x10^9 kilojoules per year. This requires an estimated 677,983 kWh a year to operate with annual costs of $93,792. Despite expending a significant amount of energy, this chiller is only capable of cooling water to the minimum temperature levels that many of the animals need to survive. Hence, the marine life in AOTB would benefit from additional cooling.

Although water temperatures currently fluctuate between 14°C and 19°C, the ideal temperature range for AOTB is between 10°C and 14°C. Table 14 illustrates the factors which influence the temperature of the main system, annual incoming and outgoing heat. After incorporating chilling and evaporation, the total amount of heat remaining in the system is 2.61x10^{11} kilojoules per year. To bring water temperatures down to 14°C in order to meet biological requirements of the fish, only 1.66x10^{10} kilojoules of heat needs to be removed.

Table 14: AOTB annual heat sources and sinks.

Summary						
Annual	Exposed Pipes	Raw Seawater	Net Heat Flux	Chiller	Total	Total >14°C
Kilojoules of Heat	3.21E+08	2.70E+11	-4.59E+08	-9.23E+09	2.61E+11	1.66E+10

5.3.4 Alternative Scenarios

With a target of removing 1.66×10^{10} kilojoules of heat annually, the Team focused on carbon-reducing and cost-effective ways in which AOTB could achieve this.

5.3.4.1 Insulation

Heat conduction from the warm air into the cold water is reduced by insulating the exposed pipes. The three materials identified as being effective in reducing heat transfer rates are vinyl covered neoprene, elastomeric rubber, and polyethylene foam. The monthly energy savings based on existing indoor water temperatures for the three insulating materials are illustrated in Figure 29.

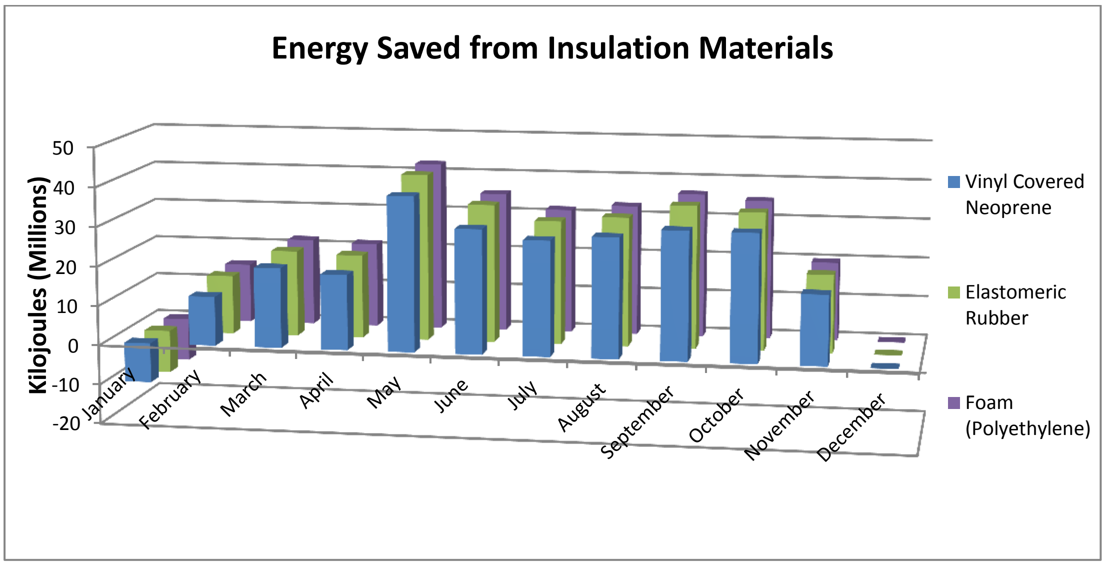

Figure 29: Amount of energy saved from entering AOTB each month due to three types of insulation

Savings are highest during summer months when temperature differences between the ambient air and cold water are the greatest. The annual amount of energy prevented from entering the water by the three insulation materials is shown in Table 17. Polyethylene foam is the most effective, saving 2.76×10^8 kilojoules of heat per year.

Table 15: AOTB's annual heat savings from insulation materials under existing water temperatures.

	Vinyl Covered Neoprene	Elastomeric Rubber	Foam (Polyethylene)
Total Kilojoules:	2.53×10^8	2.72×10^8	2.76×10^8

The Team also wanted to evaluate how much incoming heat the insulation would save if optimal water temperatures existed in the system. Figure 30 shows the energy savings from insulation at the optimal temperature range of (10°C-14°C). Not surprisingly savings are highest during the summer months when ambient air temperatures are highest.

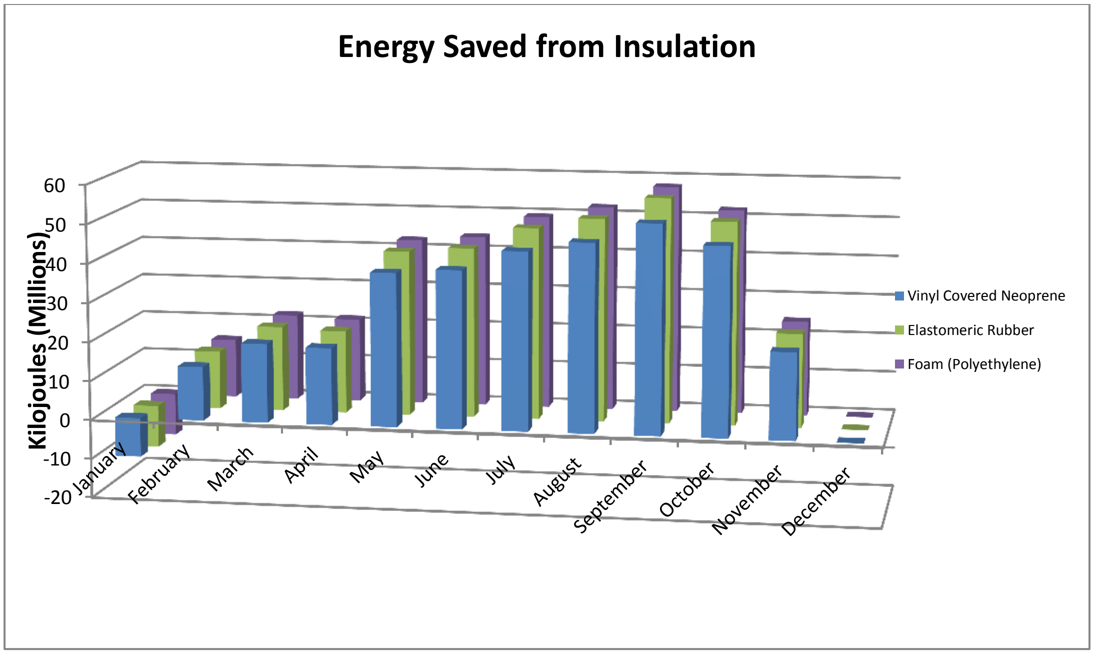

Figure 30: Amount of energy saved from entering AOTB each month due to three types of insulation

When the gap between the ambient air temperature and the water temperature is widens, the transfer of heat into the water increases accordingly. Therefore, insulation is more effective in protecting against convection when the water temperature is lower. Should AOTB achieve optimal water temperatures (below 14°C) within their system, the annual amount of heat the insulation materials would prevent from entering the pipes amounts up to $3.63x10^8$ kilojoules of heat per year (Table 16). Again, polyethylene foam is the most effective, saving 80 million kilojoules more during optimal conditions than with existing water temperatures.

Table 16: Annual heat savings from insulation materials with optimal water temperatures.

	Vinyl Covered Neoprene	Elastomeric Rubber	Foam (Polyethylene)
Total Kilojoules:	$3.33x10^8$	$3.58x10^8$	$3.63x10^8$

Figure 31 illustrates the energy savings differences in having insulation between baseline water temperatures and optimal water temperatures.

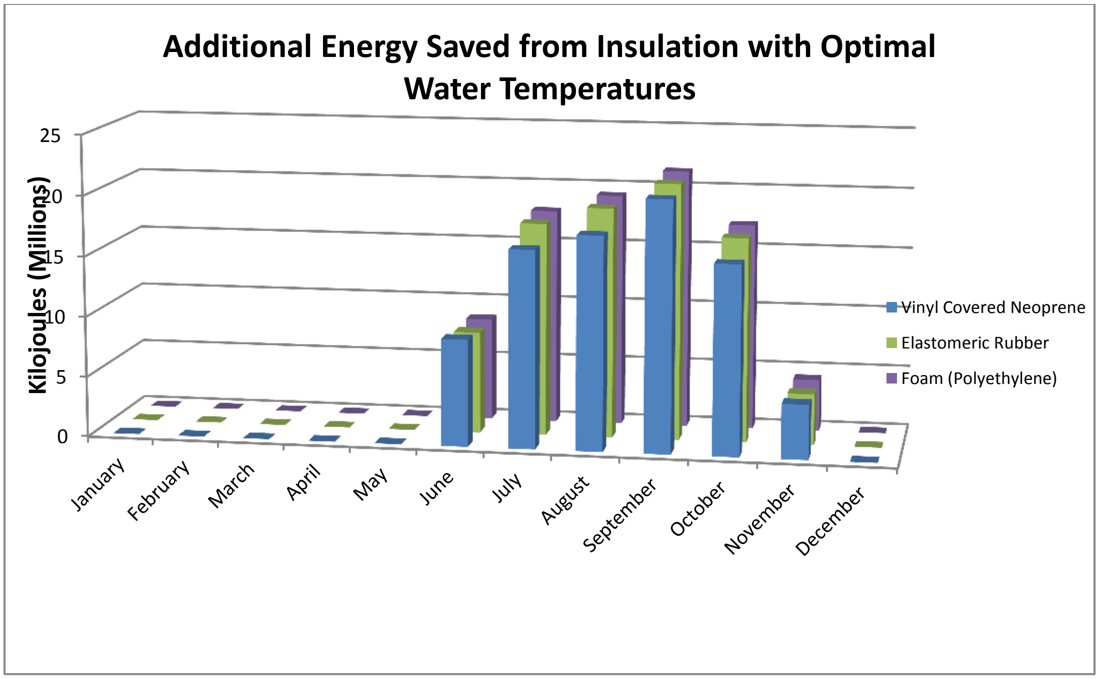

Figure 31: More heat can be prevented through insulating pipes with optimal water conditions because water is colder than baseline conditions. The difference between the baseline and optimal savings is greatest during the summer months, with no difference between December and May.

The difference in energy savings from the three insulation materials between the baseline temperature and optimal temperature scenarios is shown in Table 17. Again, polyethylene foam is highest in both scenarios, and saves roughly 80 million more kilojoules if optimal water temperatures are achieved.

Table 16: The annual heat savings difference between insulation materials for baseline and optimal temperatures.

	Vinyl Covered Neoprene	Elastomeric Rubber	Foam (Polyethylene)
Total Kilojoules:	8.38×10^7	8.73×10^7	8.84×10^7`

Insulation is a carbon-friendly solution to lowering water temperatures because it prevents heat from entering the system. This reduces the load on the chiller, saving energy and money. Table 18 shows the financial and environmental costs and benefits of offsetting the chiller load by installing insulation. Figure 32 looks specifically at the net present value of the three insulation materials, once again demonstrating that polyethylene would be the most economical option for AOTB.

Table 17: Cost Benefit Analysis for each insulation material under baseline water temperatures.

	Vinyl Covered Neoprene	Elastomeric Rubber	Foam (Polyethylene)
NPV Total (7 years)	-$204,987	-$182,340	-$220,071
NPV Total (20 years)	-$510,599	-$454,095	-$195,073
CB Ratios	0.07	0.08	0.17
ROI (years)	Indefinite	Indefinite	93
CO_2 Saved (pounds/year)	8,795	9,471	9,593

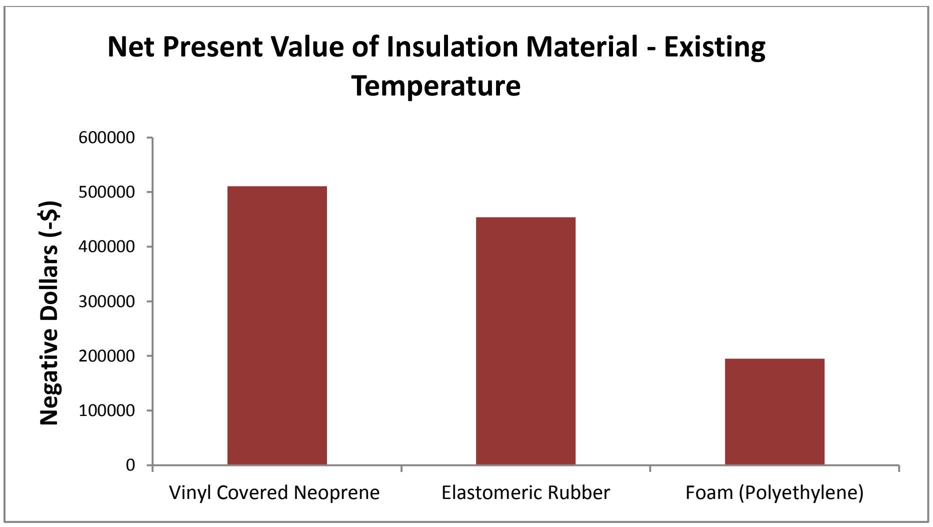

Figure 32: Illustration of NPV's for the three types of insulation under existing water temperatures.

Even though AOTB can reduce carbon emissions by installing insulation, the costs to install and maintain the insulation outweigh the financial benefits. This explains why the net present value is negative and the benefit cost ratio is less than 1 for all three materials. Of the three materials however, polyethylene foam has the best results. In addition to having the highest heat transfer savings, polyethylene foam also has the highest net present value, and will cost the Aquarium $195,073 over twenty years. This is $259,022 cheaper then the next best option. If the Aquarium seeks to reduce their carbon footprint, then insulation is a good solution because it can reduce energy expended by the main chiller. Over twenty years, polyethylene foam can save AOTB 9,593 pounds of CO_2 from offsetting the operating capacity of the main chiller. For optimal water temperatures, polyethylene remains the most cost-effective and environmentally superior option (Figure 33).

Table 18: Cost Benefit Analysis for each insulation material under optimal water temperatures.

	Vinyl Covered Neoprene	Elastomeric Rubber	Foam (Polyethylene)
NPV (7 years)	-$200,270	-$177,260	-$214,925
NPV (20 years)	-$498,680	-$441,258	-$182,071
CB Ratios	0.09	0.11	0.23
ROI (years)	Indefinite	Indefinite	71.10
CO2 Saved (pounds/year)	11,558	12,448	12,608

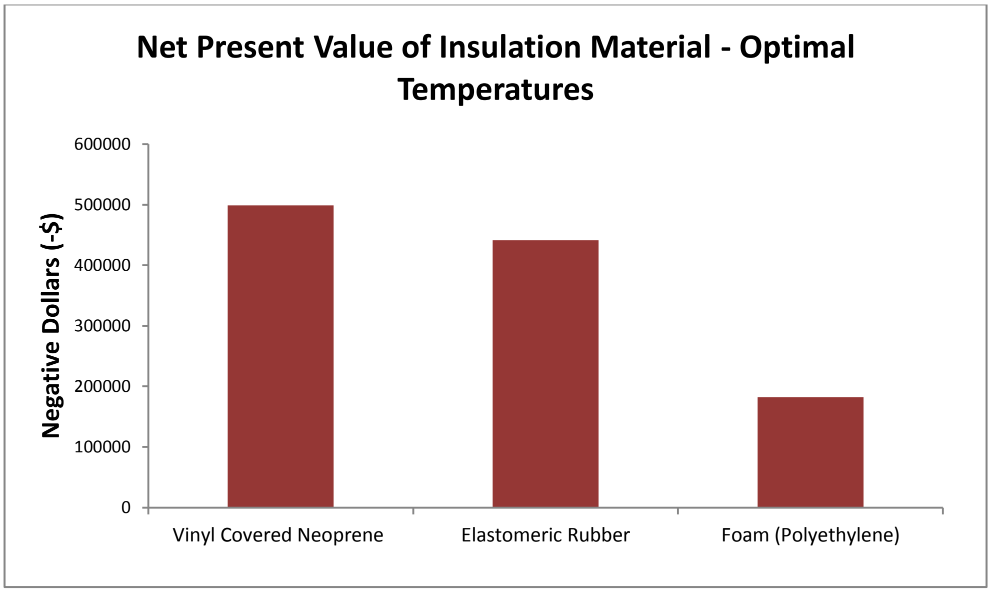

Figure 33: Illustration of NPV's for the three types of insulation under optimal water temperatures.

For optimal water temperatures, the net present values of the different types of insulation are still negative. This means insulation will cost AOTB more money than it will save. Polyethylene foam will only cost $182,071 when optimal temperatures are reached, a $13,002 savings when compared to existing water temperatures.

Overall, the material with the least cost and highest benefit cost ratio after 20 years is polyethylene foam for both baseline water temperatures and optimal water temperature scenarios. As such, this material is the best option for AOTB (Figure 36) should they decide to incorporate insulation into their system.

5.3.4.2 Heat Flux into Tank 1 and 2

After achieving data for the net heat flux of the exposed T1 and T2 tanks, the group wanted to find means of reducing incoming infrared radiation and increasing evaporation.

5.3.4.2.1 Pool Cover

A pool cover can potentially reduce the infrared radiation exchange from the atmosphere and water. However, results for implementing a pool cover showed $1.40x10^{11}$ kilojoules actually remained in tanks per year, mainly due to reduced evaporation. This outcome suggests a pool cover keeps heat in the exposed T1 and T2 tanks (Figure 34) and should not be further considered by AOTB.

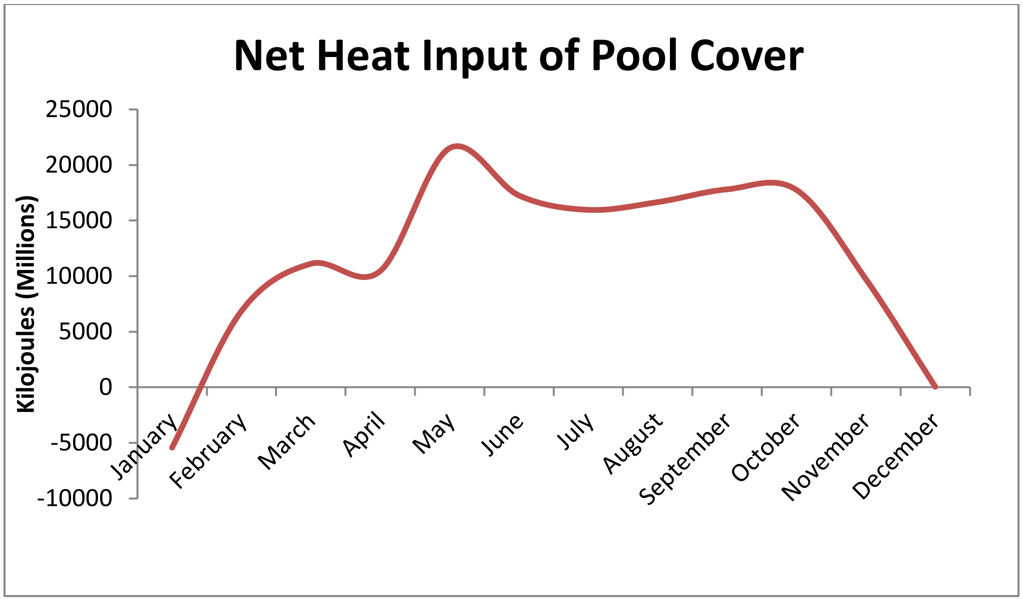

Figure 34: Monthly trend of heat remaining in T1 and T2 if a pool covered 90% of the tanks' tops.

5.3.4.2.2 Fan

A fan can be installed to generate wind currents that will increase evaporation. The monthly heat removed from the exposed T1 and T2 tanks is more than four times greater with a fan present (Figure 35).

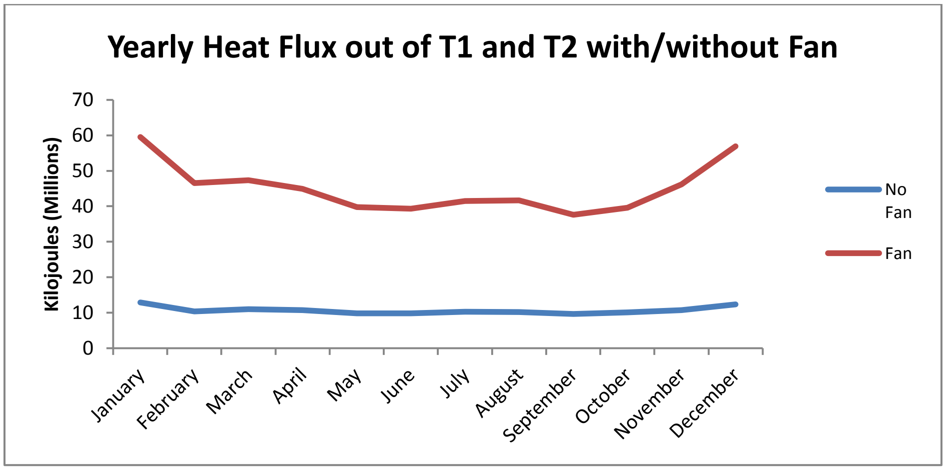

Figure 35: Difference in net heat flux into T1 and T2 from installing a fan

A fan will save an estimated 1.49×10^9 kilojoules of heat per year. This is less work that needs to be done by the chiller, saving roughly $13,600 per year (Table 20).

Table 20: Cost Benefit Analysis for implementation of an industrial fan.

NPV (7 years)	$74,550.06
NPV (20 years)	$193,589.27
CB Ratio	7.61
ROI (years)	0.28
CO_2 Saved (pounds/year)	49,959.52

The cost to run a fan is $452 per year, with an estimated energy requirement of 3267 kWh. However, comparing the energy input for the fan to the amount of heat lost to evaporation, the efficiency of the fan is 3018%. This is much higher than the efficiency of the chiller. Since the fan can be used to assist the main chiller in removing heat, the costs to operate the chiller can then be reduced. Over twenty years, the fan will save AOTB $193,589 as well as 49,959 pounds of CO_2.

5.3.4.3 Chiller

To help AOTB's main chiller reduce water temperatures to 14°C or below, the Team focused on two possible solutions: installing a second chiller or utilizing geothermal cooling.

5.3.4.3.1 Additional Chiller

As exhibited, roughly 1.66×10^{10} kilojoules needs be removed per year to keep temperatures under the 14^{o}C threshold. This amount equates to 2,084 tons of heat (or 2.64×10^7 kilojoules) per hour. Installing a second chiller with the capacity to chill 2,084 tons would consume 8.23×10^6 kWh of electricity and cost $1,145,205 per year. Over twenty years, this would release 4,337,777 pounds of CO_2 and cost $21,477,864. Carbon and monetary costs are substantial for the second chiller, but might be necessary expenditures for optimizing animal welfare.

5.3.4.3.2 Geothermal Cooling

A less energy intensive alternative to an additional chiller is submerging AOTB's piping system in the bay water below the aquarium. This process allows heat to be cooled to the temperatures of the bay water by convection through the pipes. To completely replace the cooling capacity of the chiller, geothermal cooling would require 20,041 meters (roughly 12 miles) of piping to be submerged. However, this will only reduce the AOTB water temperatures to the ambient San Francisco Bay temperatures. From April to November, bay water temperatures are above 14^{o}C; therefore, this alternative is not a viable solution (Table 21).

Table 21: Cost Benefit Analysis for implementation of geothermal cooling.

NPV (7 years)	**-$1,904,043.002**
NPV (20 years)	-$1,869,775.133
CB Ratio	0.45
ROI (years)	529.37
CO_2 Saved (pounds/year)	355,263.23

6. Discussion

6.1 Animal Care

6.1.1 Mortality

Due to the diversity of animals within AOTB, it is difficult to maintain conditions that are optimal for all species. For this reason, the animal care staff has identified the optimal temperature range of 9-14 $^{\circ}$C. Although mortality is a result of a variety of different factors, our results suggests that temperature fluctuations are a serious threat to animal health, especially in T1.

Over the past two years, 72 percent of all rockfish mortality occurred when temperature were above the optimal range, signifying the deadly effect of temperature fluctuations on rockfish health. It is important to note that other species such as the Giant Pacific Octopus are also sensitive to higher temperatures, but are not always present at the Aquarium (Scheel et al, 2007). A large portion of rockfish species on display naturally live in water colder than the exhibits offer (Green and Starr 2011), making rockfish sensitive to higher temperatures. Better regulation of temperature could not only improve rockfish health, but also benefit other animals such as the Giant Pacific Octopus.

In AOTB, rockfish mortality often starts with exophthalmia, or “pop-eye” which causes the animal’s eye to bulge (Seng et al 2006). Depending on the severity of the exophthalmia, the rockfish are removed for the exhibit and either euthanized or placed in a quarantine tank to recover. Exophthalmia is commonly a result of bacteria or fungal disease that infects the fish, (Seng et al, 2006). AOTB typical does not perform necropsies on the dead rockfish, so the exact causes of death have not been determined. A possible cause of the temperature related mortality is an increase in the infection of bacterial and fungal diseases. Warmer water causes the animals to become stressed, and vulnerable to diseases, therefore promoting exophthalmia (Noga, 2010).

6.1.2 Feed

AOTB’s life support system also affects the quantity of feed added to each tank. In T1, the Team found a slight positive correlation between temperature and average daily food cost. In T2, however, there was a negative correlation between the two. The differences observed in each tank are largely a result of the different types of animals found in each exhibit.

In Tank 1, the majority of the species are exothermic teleosts, meaning they are not able to regulate their own internal heat, and rely on surrounding temperatures for regulation (Levinton, 2001).The surrounding temperature affects their metabolic rates, which increases with temperature, therefore it is expected that the animals will eat more as temperatures increase (Clarke, 1999).

In Tank 2, the majority of the species are endothermic elasmobranches, meaning they are able to regulate their internal body heat, and are not dependent on surrounding temperature. (Levinton, 2001) According to observations by animal care staff, as the water in Tank 2 becomes warmer, the animals become stressed and lose their appetite, causing the amount of feed and associated costs to decrease (Herbert pers. comm., 2012). This is largely due to the natural habitats these animals a found in. Tank 2 contains deeper water species than naturally live in colder waters, therefore they are accustomed to feeding when it is colder.

Other factors contribute the quantity of feed given to each tank including the densities of each tank, types of animals present, reproductive stage of animals, and chemical characteristic of the water. Because there are other factors affecting the quantity of feed given to each tank, the correlations between temperature and feed cost were not very strong. However, they show that there is a relationship between temperature and feed cost.

6.1.3 Alternative Scenarios

6.1.3.1 Remove Sensitive Rockfish Species

Removing sensitive rockfish species can lead to a reduction of overall mortality, without increasing overall chilling demand. The Aquarium has 21 rockfish species present, seven of which have not died the past two years. Those seven rockfish species represent only 17 percent of the total rockfish population; therefore it may be unrealistic to remove the other 83 percent of the population.

Black, brown, and grass rockfish however, have experienced the highest mortality, with eight or more deaths for each species over the past two years. These species represent roughly 20 percent of the total rockfish population. Based on these results, removing these species could decrease rockfish mortality by up to 50 percent and total T1 mortality by roughly 25 percent, assuming these trends continue.

6.1.3.2 Separate Rockfish Exhibit

Another option is to create a separate rockfish exhibit. If temperatures are kept within the optimal range in a separate rockfish exhibit, rockfish mortality could be reduced by up to 72 percent. In addition, the lowest temperature at which rockfish mortality occurred was around 12 °C. Assuming temperatures of the rockfish exhibit will remain below 12 °C, temperature related rockfish deaths may vastly decrease.

6.2 Pumping

6.2.1 Motor Options

6.2.1.1 Pump Motor Replacement

One of the most viable options for improving energy efficiency at the facility is replacement of pump motors. Replacing 16 motors with more efficient models can save $3,540.67 per year and a 20 year discounted amount of $48,623. This option will also reduce the Aquarium's carbon impact by 13,817 pounds of CO_2 per year and 276,346 pounds over 20 years. In addition, the up-front cost of this efficiency option is among the lowest the Team analyzed. Finally, some of the motors at the Aquarium are likely reaching the end of their lifespan, so replacement has the benefit of choosing when these pumps are serviced. If this option is implemented, the Aquarium should consult with PG&E regarding rebates for efficient motors.

6.2.2 Increased Pumping Capacity

Although adding a pair of life support pumps to the existing system would increase flow, this option is expensive and risky in comparison to those involving variable frequency drives (VFDs). Moreover, the changes would increase carbon emissions and energy use. Finally, due to the flow and efficiency benefits associated with VFDs, the Team recommends that the Aquarium not pursue this option.

6.2.2.1 Filter and Flow Meter Upgrade with VFD

Replacing filtration media has a large up-front cost, according to Aquarium staff (Jensen, pers. comm. 2012a). However, implementing this measure will significantly reduce head loss through the filters to about 1.75 psi on clean filters.

The second upgrade, flow meter replacement, will likely eliminate all friction originating from the two paddle flow meters. Analysis found that for this option to be effective, it must be combined with the filter upgrade to achieve reasonable VFD savings. In contrast, the filter upgrade can be implemented separately and have energy saving benefits.

The variable frequency drive is necessary to achieve savings, because it controls the speed of the motor to take advantage of the decrease in pumping load. Implementing these changes would result in increase in flow of 175 gpm and bring flow rates very close to the optimal flow rate. The Team also expects the upgrade to improve animal welfare through reduced disease and more stable water chemistry. As with motor replacement, the Aquarium should consult with PG&E regarding rebates for the purchase of variable frequency drives.

Although this project has a significant up-front cost, it is estimated to save over $24,000 a year, about what it costs to run one 25 hp pump. The upgrades presented here achieve this while increasing flow and making the installation of additional life support pumps unnecessary.

6.2.3 Demand Response Plan

The demand response plan (DRP) for the raw water pump presents a no-cost opportunity to reduce demand charges and carbon emissions. Because the Aquarium has staff present 24 hours a day, off peak operation is a credible option. One limitation of this analysis is that he calculations are based on the maximum possible savings from switching exclusively from peak and part-peak operation to off-peak operation. Pumping times are governed to some extent by tidal cycles, which will preclude some off-peak use. However, the results illuminate the savings possible with this type of management. Aquarium staff have expressed an interest in doubling pumping capacity, which could make demand response a much more viable option in the near future. Additionally, a DRP allows the flexibility to respond to changing seasonal conditions and can be easily reversed, if needed, at no cost.

6.2.4 Power Conditioners

Power conditioners proved to have a surprisingly quick payback, with significant continued financial and environmental benefits. The Team recommends installing a power conditioner for the 10 life support and ozone pumps described earlier. A marginal increase in up-front cost nets much larger savings over time. The sensitivity analysis shows that even a small improvement in power factor will save money and energy. Overall, given financial constraints, larger pumps should be prioritized and could serve as a pilot project to confirm the savings and feasibility at the Aquarium. Again, PG&E may have rebates for this type of upgrade.

6.2.5 CleanPowerSF

Switching to a renewable electricity provider has less clear trade-offs. Although this option has the potential to eliminate the Aquarium's Scope 2 carbon emissions, the added financial cost would be quite high. The organization already spends a significant portion of its budget on electricity and increasing costs for this service is unlikely.

However, there are a few arguments that could help improve the [image of] this alternative. For example, many municipalities are opting for Community Choice Aggregation (CCA) CleanPowerSF based on the rising cost of fossil fuels. Providers like PG&E, which rely on a significant percentage of fossil fuel sources for their energy, are likely to see experience increased prices for energy costs in the near future. Moreover, the price of renewable technologies is expected to fall sharply in coming years.

In addition to cost, the Aquarium expressed concerns regarding the reliability of power from CleanPowerSF. As a comparison, Marin Clean Energy (MCE) is an established CCA program north of San Francisco. A preliminary search revealed no supply issues. In fact, one of MCE's objectives is to provide reliable power, in part because it was founded in response to PG&E blackouts. Still, the Aquarium may want to verify the reliability of the new program before considering a change in providers.

One final option is to purchase carbon offsets in the meantime. Offsets provide a compelling alternative because they are scalable to the carbon reduction goals and financial capacity of the organization.

6.3 Water Cooling

6.3.1 Heat Sources

The Team considered three potential sources of heat flow into the hydraulic system: heat from the warm air entering the cooler water through exposed pipes, heat flux of the exposed T1 and T2 tanks, and heat from incoming raw seawater. The Team found that incoming heat was highest during summer months, when incoming raw seawater is at its warmest, and the temperature difference between the warm air and cool indoor water is at its greatest.

The Team found that the main heat source into AOTB system is the raw seawater that is pumped in, on average, at 168,000 gallons a day. In fact, heat from raw seawater accounts for roughly 99.8% of total incoming heat. The other 0.2% is due to heat entering through main system's exposed pipes. The Team also discovered that the net heat flux of the exposed T1 and T2 tanks actually removes heat from the system instead of acting as a source. Specifically, the net heat flux removes an estimated 0.17% of the incoming heat. Though this may seem insignificant, it is more than the heat that enters via the exposed pipes.

6.3.2 Main Chiller

The main chiller removes roughly 15.9% of the annual incoming heat. Monetary and energy costs to remove this amount of heat are estimated to be $93,792 and 677,983 kWh of energy per year. This is equivalent to 355,263 pounds of carbon dioxide emissions annually. The ratio of the energy required to operate the chiller to the amount of heat the chiller removes is 12.9. This means that for every 1 kW the chiller uses, it removes 12.9 kW of heat from the water.

6.3.4 Summary of Heat Fluxes in AOTB

Overall, there is more heat entering the system than is being removed by evaporation and the chiller. Our results estimate that only 3.53% of the incoming heat is being removed each year, resulting in water above the 14°C threshold the Team identified. To keep temperatures below 14°C and maintain optimal animal welfare, additional water cooling is needed. The Team found that this amount of energy is 2.31×10^{11} kilojoules per year, or on average 2,084 tons an hour (more during peak months between June and November, and less during the rest of the year).

6.3.5 Alternative Scenarios

The Team determined that the best solution to the temperature control problem is to prevent heat from entering via the raw sea water. However, the current design of the system makes this hard to achieve. Raw sea water, and its associated heat, mixes with the existing system water system. This water either flows to the pumps and chillers or, if the two large tanks are already full, to sewage. According to Aquarium engineers, the tanks are rarely full, meaning that most of this water remains in system and increases water temperature. The amount of raw water remaining in the system greatly affects the amount of cooling needed. A difference in only a few thousand gallons of raw water a day changes the cooling tonnage required by orders of magnitude. As a result, the calculations reflect an average.

From the analysis, three cooling-related alternatives were determined to be feasible: pipe insulation, an industrial fan, and a second chiller. Of the three types of insulation analyzed, Polyethylene foam was found most suitable for a couple reasons. First, according to literature reviews and industry surveys, there is no demonstrated life expectancy of this material whereas the other materials would need to be replaced every ten years or so. This difference resulted in Polyethylene foam being the only material with a payback period and smallest negative NPV over 20 years. Second, the material was also estimated to be the best performing in terms of reducing heat transfer for current and optimal water temperatures. However, Polyethylene Foam still has a negative NPV because costs outweigh benefits. It would take 93.4 years to pay back the investment of the foam insulation. If AOTB is willing to sacrifice monetary resources, insulation should be considered as a tool for improving the sustainability of AOTB.

6.3.5.1 Industrial Fan

Installing a fan is relatively cheap to purchase (around $1500) and operate (3,267 kWh or $451.00 a year). More importantly, the fan is much more efficient at removing heat than the chiller. For every kilowatt-hour the fan requires, it saves 30 kWh in cooling. With the chiller's efficiency ratio at 1:12.9, the fan is nearly three times more efficient. Annually, the fan can save AOTB $13,629.47 in chilling costs.

However, there are some limits to a fan option. First, the fan cannot be too powerful. The Team researched a fan that would create a wind speed of 1 m/hour. In addition, the larger the fan the more evaporation will occur, which means more raw sea water will need to be pumped in. This brings in more heat, since raw sea water is the main source of thermal energy to the system. The fan that the Team considered is estimated to reduce water levels 40 cm per year in T1 and T2, or roughly 80,000 gallons. The second limit is that the cost to physically install a cabinet style fan in the concrete walls of AOTB is unknown, meaning the Team used costs to install other types of fans and extrapolate those values to the current scenario. Nonetheless, could have a positive impact on cooling costs.

6.3.5.2 Additional Chiller

The results indicate that reducing system water temperatures to below 14°C would require a second chiller. Assuming the Aquarium implements insulation and a fan, which would reduce the size of a chiller needed, an average of 172 tons of heat needs to be removed. When operating at 2,084 tons per hour, this second chiller would require an additional 8,278,200 kWh or $1,145,205 a year to run. Interestingly, installing a second chiller can actually make the current main chiller more efficient by lessening its cooling load. By integrating a second chiller, the leaving water temperatures of both chillers can be raised closer to 14 °C or 57.2 °F, increasing efficiency for both and reducing carbon emitted per ton cooled.

Despite the improved efficiencies, a second chiller would require 8,278,200 kWh a year to operate and producing 4,337,777 pounds of carbon dioxide emissions. Furthermore, the cost to purchase, install and operate a second chiller over 20 years is $21.5 million. As a result, improving animal welfare, reducing carbon emissions, and utilizing minimum costs have major trade-offs.

7. Scenario Recommendations

7.1 Scenario 1: Carbon Focused

In the first scenario, the Team identified recommendations that reduce the environmental impact of the Aquarium as much as possible. The objective is to reduce Aquarium of the Bay's environmental impact without compromising the welfare of the exhibit animals. Many of the chosen actions have animal welfare and financial benefits, but these are all ancillary effects of the scenario.

Included in Scenario 1 are the following recommendations:
1. Install foam insulation
2. Replace pump motors
3. Install power conditioners
4. Implement the demand response plan
5. Switch utility providers to CleanPowerSF
6. Remove the sensitive rockfish species

This scenario has a projected annual electricity reduction of 281,000 kWh. In addition, virtually all of the Aquarium's carbon emissions are offset by purchasing renewable electricity from CleanPowerSF. However, this plan also has significant associated costs with overall costs of $307,000 (Table 22).

Table 22: Metrics from the Carbon Focused Scenario

Annual kWh Saved (1000's)	Upfront Costs (1000's)	NPV (7) (1000's)	NPV (20) (1000's)	C02 Saved (1000's)	Mortality	Flow
280.82	-227.68	-273.04	-307.18	1,273.57	Status Quo	Status Quo

7.2 Scenario 2: Animal Focused

In the second scenario, the Team sought to improve environmental sustainability, while creating an optimal environment for the animal life. As shown previously, animal health is directly related to water temperature and flow. This objective required the installation of a second chiller. As a result of these changes, the Team does not recommend removing sensitive species because water temperatures would be in the optimal range. Variable frequency drives meet the goals of both animal welfare and energy savings.

Included in Scenario 2 are the following recommendations:

7. Install Foam Insulation
8. Install an evaporation inducing fan
9. Install a second chiller
10. Replace pump motors
11. Install variable frequency drive
12. Implement the demand response plan
13. Install power conditioners

Most notable is that all of the major metrics are negative, including CO_2 and NPV (Table 23). This is largely due to the environmental and financial impacts of the additional chiller. However, the results indicate that water temperature cannot be controlled using other, more sustainable technologies. If the Aquarium determines that animal welfare is a priority, they may need to phase in elements of this scenario with positive NPV projects being implemented first.

Table 23: Metrics from the Animal Focused Scenario

	Annual kWh Saved (1000's)	Upfront Costs (1000's)	Annual Savings (1000's)	NPV (7) (1000's)	NPV (20) (1000's)	C02 Saved (1000's)	Mortality	Flow
Green + Animals	-1091.14	-407.34	-155.39	-1305.55	-2585.66	-564.71	[decrease]	[increase]

7.3 Scenario 3: Balanced

Scenario 3 builds off of the Animal Focused scenario by not including the chiller, and removing sensitive rockfish in its stead. This improved upon the second scenario in all aspects, including becoming revenue positive, improving animal welfare, and reducing the carbon footprint.

Included in the Balanced scenario are the following recommendations:
14. Install an evaporation inducing fan
15. Replace pump motors
16. Replace the media in the sand filters
17. Install variable frequency drives
18. Implement the demand response plan
19. Install power conditioners
20. Remove sensitive species

Table 24: Metrics from the Balanced Scenario

Annual kWh Saved (1000's)	Upfront Costs (1000's)	NPV (7) (1000's)	NPV (20) (1000's)	C02 Saved (1000's)	Mortality	Flow
188.65	-80.89	180.85	589.44	102.63	[decrease]	[increase]

Looking at the results for the Balanced scenario, all metrics are positive except for upfront costs. With an annual energy savings of 188,650 kWh 102,630 pounds of carbon dioxide, this set of recommendations offers significant energy savings. In addition, this scenario is the only one with a positive net present value for the 7 and 20 year time periods.

The figures 36, 37, and 38 compare the results of Scenarios 1, 2, & 3.

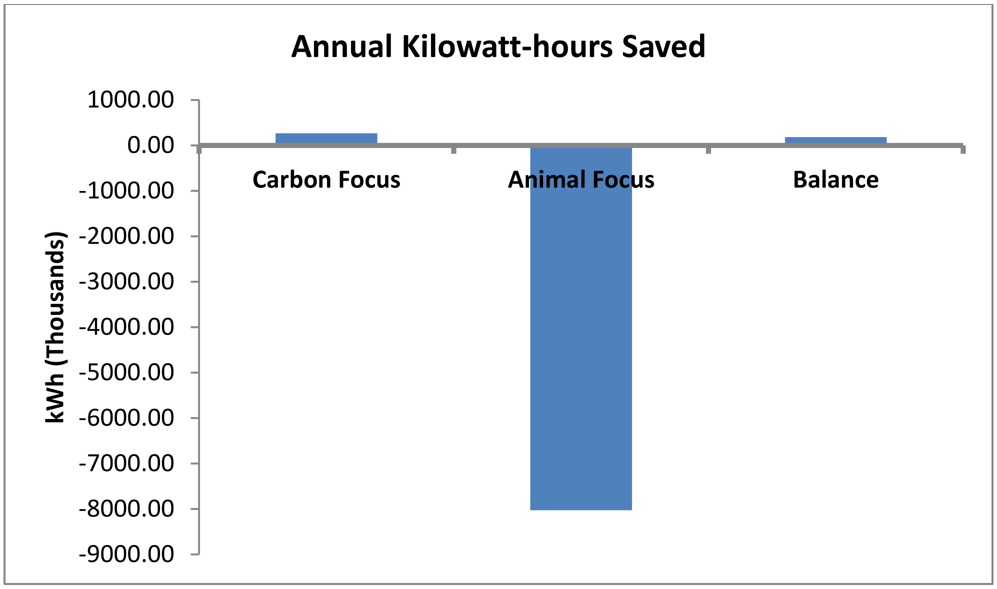

Figure 36: Annual amount of electricity saved under "Carbon Focused", "Animal Focused", and "Balanced" Scenarios.

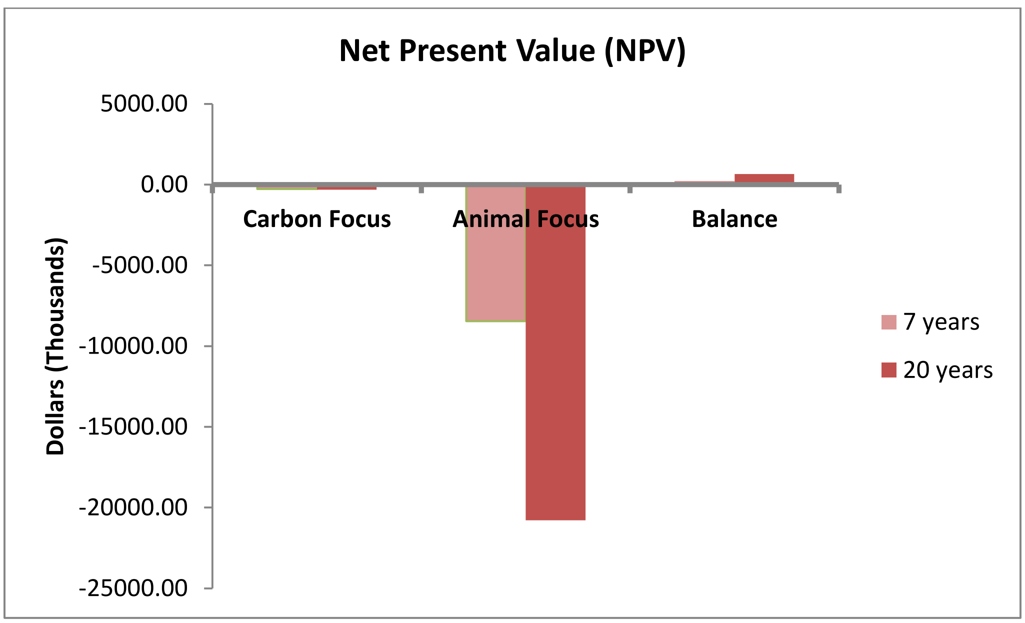

Figure 37: Annual Net Present Value under "Carbon Focused", "Animal Focused", and "Balanced" Scenarios.

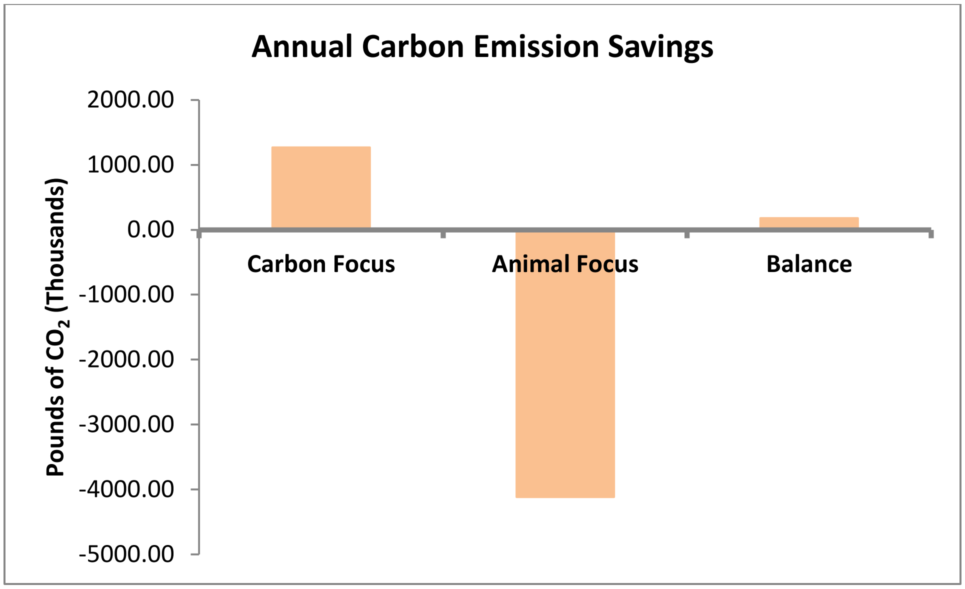

Figure 38: Annual amount of carbon emission saved under " Carbon Focused". "Animal Focused", and "Balanced" scenarios.

Comparing Scenario 1 and Scenario 2 shows that they have quite different outcomes. While Scenario 1 reduces carbon emissions and saves energy, Scenario 2 increases these impacts. The latter scenario also has a large associated cost. By combining different aspects of these two scenarios, the Team was able to create a scenario that saves money and energy, reduces carbon emissions, and has a positive impact on animal welfare. For these reasons, the Team believes that the Balanced scenario is the best option for the Aquarium. This scenario is financially beneficial, allows the organization to further their progress toward sustainability, and positively impacts their conservation mission.

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9. Acknowledgements

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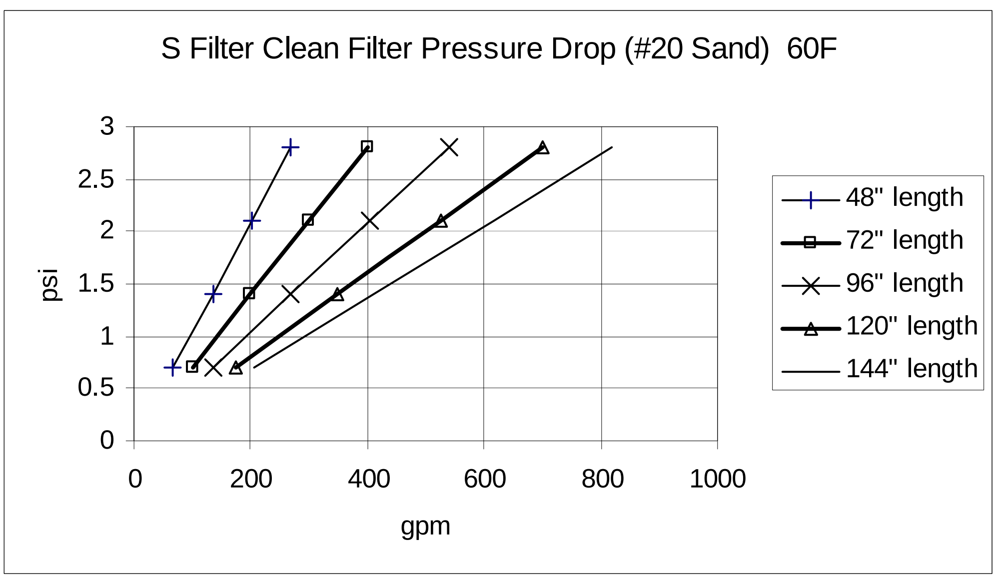
10. Appendices

Appendix 1: Motor Replacement Models

Original	Replacement	# of Type	Annual Savings ($)	Annual Savings (CO2)
Unimount A920A	Baldor Reliance EM3771T	4	1,678	6,372
Worldwide WW[5]5-18-184T	Baldor Reliance EM3665T	1	149	565
Weg 00236ES3ED56C	Baldor CEM3555	1	93	354
Baldor 35J337Y331	Baldor CEM3550	2	539	2,046
Baldor VJMM3211T	Baldor EJMM3611T	2	462	1,753
Baldor 35F904Q384G1	Baldor Reliance EM3550	2	326	1,239
Baldor JL3513A	Baldor Reliance EM3550	1	290	1,101
Baldor JL3503A	Baldor JM3460	1	75	284
A.O. Scott K48N2N104	Baldor JM3555	2	27	104

Appendix 2: New Media Filter Pressure Drop



Appendix 3: Operating specifications for AOTB present chiller.

Table P-15 – RTUA 80 Performance Data

English

LWT	Entering Condenser Air Temperature (Degrees F)														
	75			85			95			105			115		
(Deg. F)	Tons	kW	EER	Tons	kW	EER	Tons	kW	EER	Tons	kW	EER	Tons	kW	EER
40	83.2	77.5	12.9	78.1	83.8	11.2	72.7	90.9	9.6	67.2	98.8	8.2	61.6	107.4	6.9
42	86.4	78.7	13.2	81.1	85.0	11.4	75.6	92.1	9.8	69.9	99.5	8.4	64.1	108.6	7.1
44	89.6	79.9	13.5	84.1	86.2	11.7	78.5	93.3	10.1	72.7	101.2	8.6	66.7	109.9	7.3
46	92.9	81.1	13.7	87.3	87.4	12.0	81.5	94.5	10.3	75.5	102.4	8.8	69.4	111.1	7.5
48	96.2	82.3	14.0	90.5	88.7	12.2	84.5	95.8	10.6	78.4	103.7	9.1	72.1	112.4	7.7
50	99.6	83.6	14.3	93.7	89.9	12.5	87.6	97.1	10.8	81.3	105.0	9.3	74.9	113.7	7.9

Notes:

1. Ratings based on sea level altitude and evaporator fouling factor of 0.00010.
2. Consult Trane representative for performance at temperatures outside of the ranges shown.
3. kW input is for compressors only.
4. EER = Energy Efficiency Ratio (Btu/watt-hour). Power inputs include compressors, condenser fans and control power.
5. Ratings are based on an evaporator temperature drop of 10 F.
6. Interpolation between points is permissible. Extrapolation is not permitted.
7. Rated in accordance with ARI Standard 550/590-98.

Appendix 4:Natural refrigerants and their global warming potentials as well as their refrigeration capacities:

Table 1 Characteristics and properties of some refrigerants

Tableau 1 *Caractéristiques et propriétés de certains frigorigènes*

Refrigerant	CFC12	HCFC22	HFC134a	NH_3 R717	C_3H_8 R290	CO_2
Natural substance	No	No	No	Yes	Yes	Yes
ODP	1.0	0.05[a]	0	0	0	0
GWP[b]						
100 years	7100	1500	1200	0	0	1(0)[c]
20 years	7100	4100	3100			1(0)
TLV_{8h} (ppm)	1000	1000	1000[d]	25	1000	5000
IDLH[e]	50 000	–	–	500	20 000	50 000
Amount per room vol[f] (vol%/kg m^{-3})	4.0/0.2	4.2/0.15	–	–	0.44/0.008	5.5/0.1
Flammable or explosive?	No	No[g]	No[g]	Yes	Yes	No
Flammability limits in air (vol%)	–	–	–	15.5/27	2.2/9.5	-
Toxic/irritating decomposition products?	Yes	Yes	Yes	No	No	No
Approx. relative price	1	1	3–5	0.2	0.1	0.1
Molar mass	120.92	86.48	102.03	17.03	44.1	44.01
Volumic[h] refr. capacity at 0 °C (kJ m^{-3})	2740	4344	2860	4360	3870	22600

[a]Somewhat higher values have been suggested by recent studies.
[b]Global warming potential in relation to CO_2, with 20 and 100 years integration time (IPCC 1990, 1992).
[c]Abundant amounts of CO_2 are recovered from waste gas. Thus, the effective GWP of commercial carbon dioxide, for instance used as refrigerant, is 0.
[d]Suggested by ICI *etc.*
[e]Maximum level from which one could escape within 30 min without any escape-impairing symptoms or any irreversible health effects[17].
[f]Maximum refrigerant charge in relation to refrigerated room volume, as suggested in ANSI/ASHRAE 15-1989: Safety Code for Mechanical Refrigeration.
[g]Although considered to be non-flammable, both R22 and R134a are combustible in certain mixtures with air at elevated pressures, but ignition

Appendix 5: Rockfish species present in Aquarium of the Bay based on 2011 inventory

Rockfish Species	Name	# Present 2011	% of Total Rockfish
Sebastes constellatus	Starry Rockfish	1	0.24%
Sebastes pinniger	Canary Rockfish	5	1.22%
Sebastes rosaceus	Rosy Rockfish	1	0.24%
Sebastes rubirrimus	Yelloweye Rockfish	6	1.46%
Sebastes rubrivinctus	Flag Rockfish	41	10.00%
Sebastes serriceps	Treefish	15	3.66%
Sebastes unbrosus	Honeycomb Rockfish	3	0.73%
Sebastes atrovirens	**Kelp Rockfish**	13	3.17%
Sebastes flavidus	**Yellowtail Rockfish**	3	0.73%
Sebastes maliger	**Quillback Rockfish**	10	2.44%
Sebastes miniatus	**Vermilion Rockfish**	17	4.15%
Sebastes nigrocinctus	**Tiger Rockfish**	5	1.22%
Sebastes caurinus	**Copper Rockfish**	23	5.61%
Sebastes chrysomelas	**Black and Yellow Rockfish**	35	8.54%
Sebastes mystinus	**Blue Rockfish**	92	22.44%
Sebastes nebulosus	**China Rockfish**	19	4.63%
Sebastes carnatus	**Gopher Rockfish**	37	9.02%
Sebastes paucispinis	**Bocaccio**	3	0.73%
Sebastes auriculatus	**Brown Rockfish**	37	9.02%
Sebastes melanops	**Black Rockfish**	39	9.51%
Sebastes rastrelliger	**Grass Rockfish**	5	1.22%

No mortality
1 mortality
2 mortalities
4 mortalities
8 or more mortalities

Appendix 6: Rockfish Mortality and Temperature after the removal of black, brown, and grass Rockfish from data set