A Light-Emitting Diode Fixture
for
Sustainable Captive Marine Ecosystems

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ENM 590
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CHAPTER 1 - INTRODUCTION

Problem Introduction, Relevance, and Importance

For decades, aquarists have attempted to maintain captive marine ecosystems through various lighting technologies, such as normal fluorescents, high output fluorescents, power compact fluorescents, metal halides, and even plasma fixtures. Coral grown in these ecosystems are usually photosynthetic and have high light intensity and specific spectral needs. Additionally, the user tends to prefer a lighting system that has a low life cycle cost, does not exude large amounts of heat, and is customizable. Unfortunately, the aforementioned lighting systems do not usually meet all of the needs of the aquarium inhabitants or the user.

Recently, aquarists have started to turn to light-emitting diode (LED) fixtures since they have high potential performance, a low life cycle cost, run relatively cool, and offer many controllable features. To meet the demand, companies all over the world produce aquarium-targeted LED fixtures. However, these fixtures appear as though do-it-yourselfers (DIYers) haphazardly designed them through trial and error. Therefore, most LED systems have a limited spectrum output, have a shorter-than-designed life, have a high mean-time-between-repair (MTBR), and/or have a high mean-time-between-failure (MTBF).

Using the systems engineering process, an LED fixture for a sustainable captive marine ecosystem was designed and built. The “Light-Emitting Diode for Sustainable Captive Marine Ecosystems” project assessed the lighting needs of typical corals and other photosynthetic invertebrates, requirements of aquarists, and determined a suitable design. In addition, basic “rules-of-thumb” were developed and/or refined to help other interested aquarists design their own system. The system was built and integrated with a controller in order to manipulate the lighting schedule, spectrum, and intensity. The requirements analysis was completed in ENM 595, which outlined the user and aquarium inhabitant needs and wants. The systems engineering analysis was completed in ENM 505, which covered the work breakdown structure, schedule, risk analysis, and preliminary designs. In ENM 590, the chosen design was built, integrated with control equipment (internet-enabled devices and an analog interface), and tested, all while adhering to the systems engineering process.

The largest international forum for saltwater aquariums (ReefCentral.com) has over 240,000 members. Many countries (especially Germany, Italy, Thailand, and Japan) have world-renown aquariums, and the United States is quickly reaching the bar. If a fully functional, maintainable, high performance, integrated, and cost-effective LED lighting system was developed, the demand already exists worldwide. The payback period for this light fixture first article build is less than three years with no profit margin.

Problem and Research Statement

Inefficient and high maintenance lighting fixtures have dominated the reefkeeping hobby for decades. LED fixtures are breaking their way into the mainstream due to their efficiency rating and low maintenance costs, but most fixtures are lacking in features, capability, or performance. This project will attempt to apply scientific research and the systems engineering process to a design.

An LED lighting system was built that met user and inhabitant needs while following the systems engineering process. It addressed environmental concerns, such as the minimization of corrosion from salt creep and humidity and the regulation of fixture temperature. Light intensity is sufficient for the most demanding species of coral in the hobby while featuring a dimmable function to simulate deep-water conditions for more sensitive animals. The spectrum available is fully customizable by the user, but it targets the spectral characteristics of sunlight penetration through 30 feet of water. It also simulates the spectrum and phase (intensity) of moonlight throughout the month to entice spawning within the aquarium. Through integration with a controller and specially designed power heads, the light fixture can simulate clouds, tides (matched with the time of a specific geographical location), and storms. A rudimentary sunrise/sunset function is also available. If this lighting system was adapted for a six foot or longer aquarium, then the sunrise/sunset function would be fully operational. However, this system was designed for a four-foot long aquarium, which limited the feature.

A user-survey was developed and distributed across several reefkeeping online forums, including the Wasatch Marine Aquarium Society, Reef Central, and Nano-Reefs. Additional user statistics and requirements were gathered from Facebook and Reef Central.

Scope and Limitations

This project demonstrates initial basic research in a particular field, through requirements analysis, design, first article build, and initial testing. The first article build will be the only article built, as this system will not be available to the public. This project consists of three phases. Phase 1 coincided with ENM 505, the systems engineering analysis, and ENM 595, the system requirements analysis. Phase 2 coincides with ENM 595, where the system was built and underwent initial verification, validation, and an overall test and evaluation conducted in compliance with the systems engineering process. However, the majority of testing will occur in Phase 3, which will take place outside of the graduate engineering program. Corals can take up to six months to show a photosynthetic response to lighting changes, so the majority of this long-term testing will not be included.

Background

A captive marine ecosystem is essentially an aquarium that simulates an ocean environment. For example, there are aggressive fish tanks, coldwater-species tanks, species-only tanks, and the typical reef aquarium, which contains various peaceful species of warm-water inhabitants. Three main types of aquariums dominate the hobby: the fish-only (FO), the fish only with live rock (FOWLR), and the coral reef. (Bridges, 2013)

Contrary to popular belief, corals are invertebrates, not plants. They consist of a growing calcium-based skeleton, tissues, a mouth with digestive tract, and tentacles. Most corals also contain symbiotic photosynthetic algae, called zooxanthallae. This alga provides the coral with the majority of its energy in the form of sugars and proteins in exchange for the coral to provide it a safe habitat in which to live. The coral can expel the zooxanthallae under various conditions (stress, overpopulation, et cetera), and if zooxanthallae populates declines too much, the coral can catch its own food with its tentacles and digestive system. (Bridges, 2013)

There are two main groups of corals: the hard (Scleractinian) and soft (Alcyonacea) corals. Soft corals, as the name implies, do not build solid skeletons; they build calcium particle splinters, called “sclerites”, that they can arrange as a simulated skeleton. These corals are, in general, quite tolerant of poor water and lighting conditions, but they are often less attractive and are more toxic than hard corals. Scleractinian corals are the reef builders since they build calcium-carbonate skeletons that eventually form most rocks on a reef. They are further subdivided into two groups based on the coral polyp relative size (small and large). Small-polyp Scleractinian (SPS) corals are the most demanding of their water conditions and lighting. (Bridges, 2013)

The main components of a coral reef aquarium are the tank itself, stand, lighting system, flow system, nutrient import/export, heating/cooling system, and the substrate. The lighting system required depends on the inhabitants. FO aquariums perform quite well with normal fluorescent (NO) lighting. Power compact (PC) fluorescents are mainly used for FOWLR aquariums, although they can be used on FO and some coral reef aquariums. T-5 very high output (VHO) fluorescent lighting is an excellent choice for reef aquariums, as well as FO and FOWLR tanks. However, they do not have quite the intensity capability as metal halides, and they are subject to a red-shift phenomenon within about a ten-month period. Metal halide (MH) lighting is currently the most powerful, and it is typically used to light the most sensitive and demanding aquariums. Although MH have a great intensity profile and spectrum, they still often require supplemental lighting in the blue region (as the T-5 bulbs mentioned) to help offset the red-shift trend that the bulbs have over a single year before they require replacement. Each of these systems has its own positive and negative characteristics. For example, NO lighting systems are not sufficient for most coral, but metal halide systems can have prohibitively high electrical requirements. Due to these characteristics, many aquarists have started to make the transition to LED systems. LEDs do not shift in color (minor shifts are negligible), and the components specified in Phase 1 retained 70% of their intensity after ten years. Additionally, LEDs come in a variety of colors and create a customized spectrum with various color combinations. Japan and other countries often use LEDs to create spotlighting effects to highlight particular corals or the rockwork structure. LEDs produce less heat and are more efficient than metal halides, and their light output is quickly gaining in capability. (Bridges, 2013)

Currently, most LED lighting systems are only meeting the “budget-minded” segment of the reefkeeping hobby and industry, as the systems are not aesthetically pleasing, performance oriented, or well-designed for the life cycle. Most systems on the market were designed through trial-and-error, without a requirements analysis. As a result, systems are either overpowered, underpowered, lack control, or emit an unhealthy spectrum for the coral. Additionally, the user tends to prefer a lighting system that has a low life cycle cost, does not exude large amounts of heat, and is customizable. Unfortunately, the aforementioned lighting systems do not meet the needs of the aquarium inhabitants or the user. With a target population of nearly 300,000 people worldwide, many of whom spend thousands yearly on their aquariums, there is a market for such a performance LED system. (Bridges, 2013)

As an example, the author’s 200-gallon display system currently uses two 400-watt metal halide lights, two 54-watt T-5 lights, and LED moonlights (Figure 1). A lighting system of nearly 1000 watts produces an excessive amount of heat. To prevent the aquarium from overheating, two fans blow across the water surface for evaporative cooling. This additional electrical cost increases indoor humidity and requires frequent aquarium refilling with specially filtered water. The overheating issue also requires a specialized controller with a temperature sensor. When the water temperature rises above a specification, the controller turns the lights off. The maintenance costs on the lighting system alone are approximately $200 per year, the electrical costs are over $480 per year, and the initial equipment purchase price was nearly $2,000.

Figure 1: Author's Lighting System; Two x 400W MH and Two x 54W T-5

The material budget for this lighting fixture project was $1200, which will have no annual maintenance costs, and the expected electrical costs are less than $200 per year. It will also save water, help prevent mildew issues indoors, and will increase the time the aquarium can go without human intervention.

CHAPTER II – LITERATURE REVIEW

Although many sources were used for research, the majority of information came from *Advanced Aquarist*, an online magazine specializing in innovative marine husbandry topics. This is due to the limited research available on coral photosynthesis. Dana Riddle, of Riddle Laboratories, is the most predominant author and researcher in the field. This does present a potential bias, but at this time, there is no known contrasting data.

Other sources, such as Methods of Cell Biology, *Biology Bulletin*, *Proceedings of the National Academy of Sciences*, and the *Marine Ecology Progress Series*, were used to determine and confirm applicable coral fluorescent and pigment excitation/emission spectra. Methods of

Cell Biology is an ongoing book series in publication for over thirty years that has renowned editors from the University of California and the Massachusetts Institute of Technology. *Biology Bulletin* is a scientific journal that covers fundamental studies in general biology, proceedings from scientific conferences, and new books. The *Proceedings of the National Academy of Sciences* is another scientific journal in publication since 1914. Its publications cover biological, physical, and social sciences, and its articles are peer-reviewed. The *Marine Ecology Progress Series* covers life in the oceans and coastal waters and is peer-reviewed.

Several online forums, aquarium hobbyists, and electronics hobbyists were consulted as well to cover emerging techniques not yet formally documented or peer-reviewed. These sources are not as reliable as the peer-reviewed journals and books, but they are the best sources available at this time in their respective areas.

CHAPTER III – DATA COLLECTION

The primary user of this lighting system was determined to be a male of age 25-34 years located in the United States. Figure 2 shows a sample of 112 reefkeepers, their age, and their gender. This data was obtained from the author's Facebook group statistics (Facebook compiled the data, and the author interpreted it. Facebook did not sponsor, endorse, or participate in this study.) This cross section was compared to other reefkeeping groups, and was found to be consistent. The country of residence varied by ±0-9%, but the United States was still the predominant country of reefkeeping groups based in the United States (Figure 3).

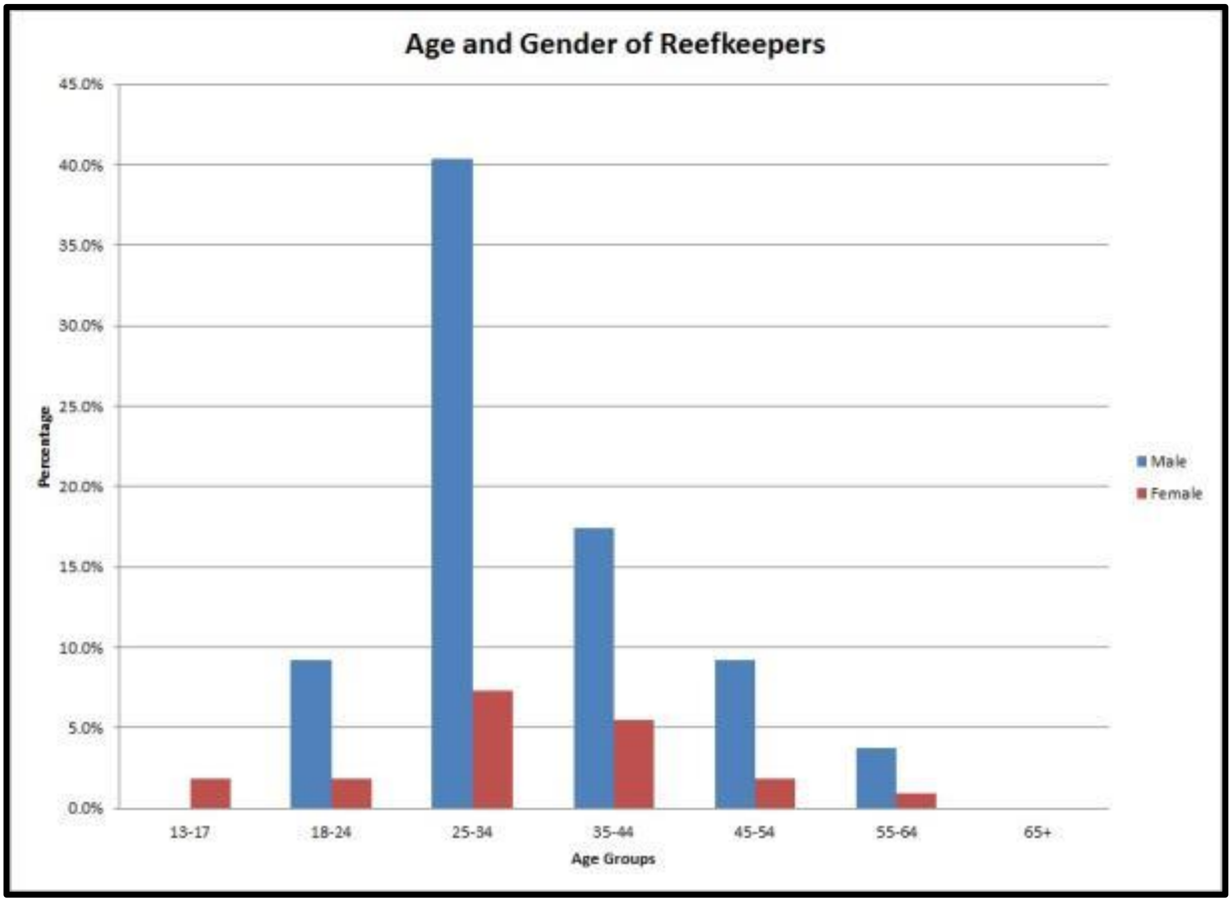


Figure 2: Age and Gender of Reefkeepers

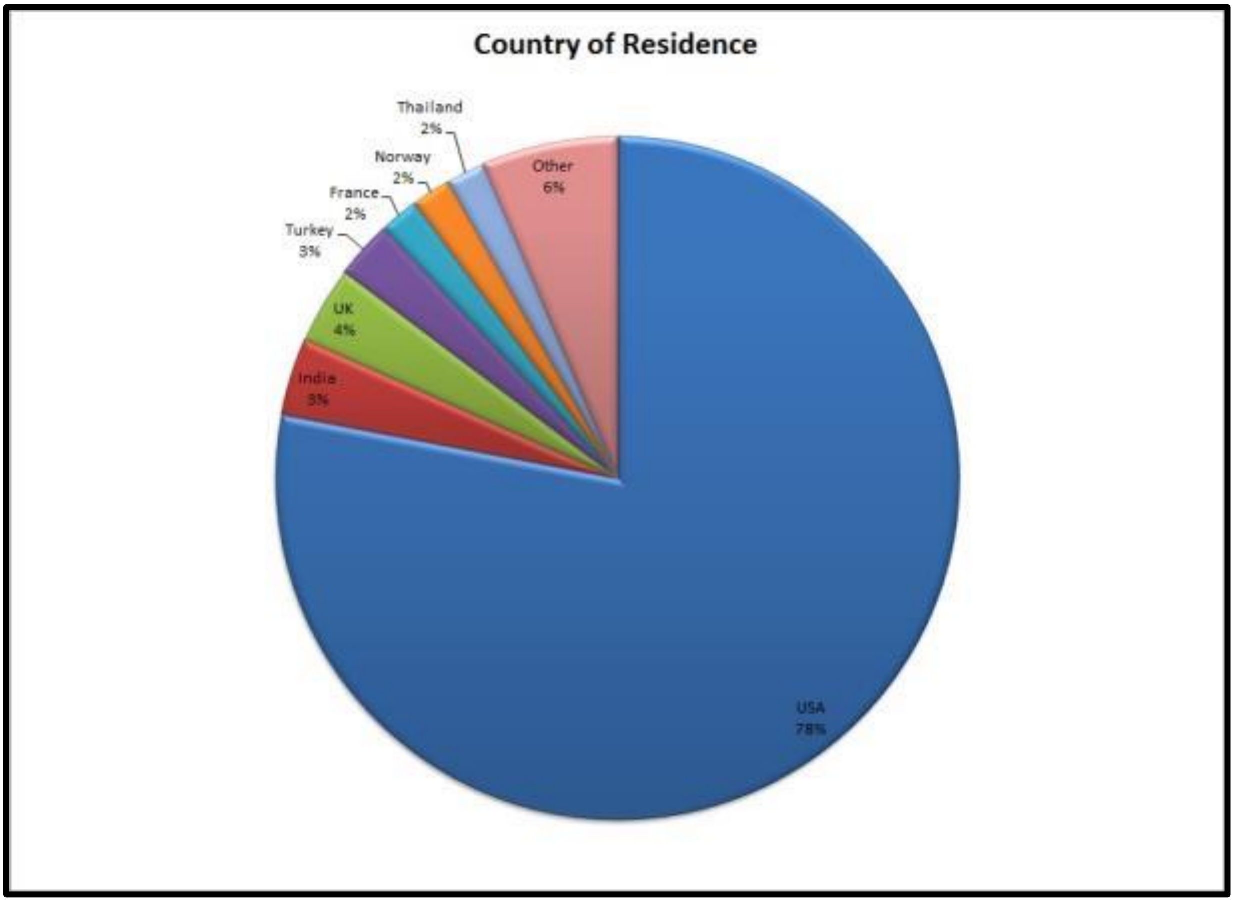


Figure 3: Country of Residence of Reefkeepers in U.S.-Based Groups

A survey was developed and distributed across several reefkeeping online forums for LED users, including the Wasatch Marine Aquarium Society, Reef Central, and Nano-Reefs. Approximately 85 responses were received (some were incoherent or otherwise unusable and were not counted.) The questions were as follows:

1. What are the dimensions of your tank (length x width x height)?
2. How far is your fixture above the water?
3. Are there any corals that you think were adversely affected by the LEDs?
4. What color and quantity of LEDs do you have? What optics are paired with them?
5. Is your setup dimmable, and if so, what are you running?
6. How many watts total, and how many of each size (1W, 3W, 5W, etc.)?
7. What made you decide to go with LEDs, and if you had the chance, would you do it again?
8. What brand of a setup are you using?
9. Are you using the fixture for moonlights, and if so, what combination of lights/percent power?
10. Is there any other pertinent info that might help about your setup? Also, please leave your contact info if you wish.

CHAPTER IV – METHODOLOGY

The objective of this project was to follow the system engineering process, research the field, complete a requirements analysis, design a fixture, complete the first article build, and conduct test and evaluation. Particularly, the project must determine and include the optimal light spectrum(s) and intensity for coral growth and color.

Systems Engineering Process

Project Work Breakdown Structure

This project consisted of a three-level work breakdown structure (WBS), as shown in Figure 4, where level one (highest level) signifies the overall project and level three consists of the lowest level tasks. Level two is comprised of the previously mentioned tasks, such as market research, conceptual design, and initial test and evaluation. A large format image of Figure 4 is located in APPENDIX C: Large Format Tables and Figures, as Figure 49.

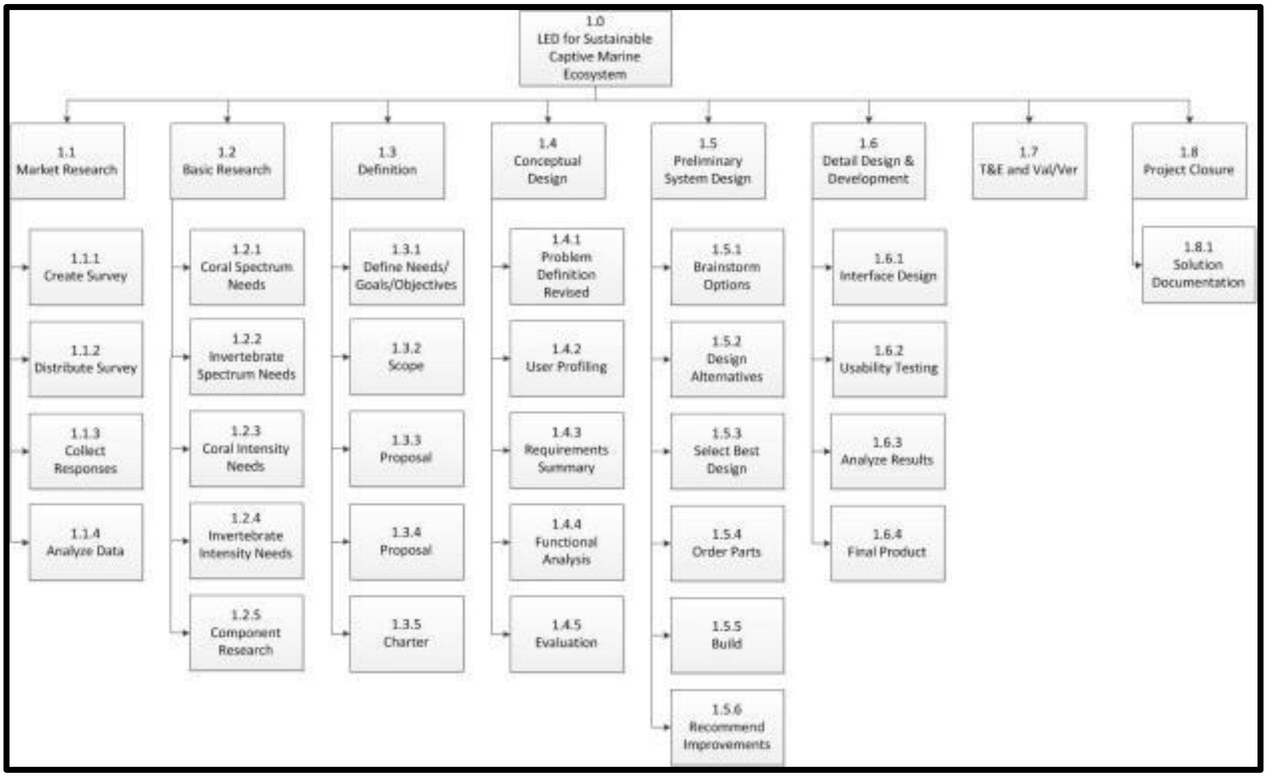


Figure 4: Work Breakdown Structure

Responsibility Assignment

The project manager oversees the entire project (Figure 5) and coordinates with the various engineers, marketing, and the marine biologist. The project engineer is essentially the system engineer and leads the integration of the electrical, mechanical, and software systems.

Although this project is composed of various fields of expertise, in reality, the author must function in each of these roles.

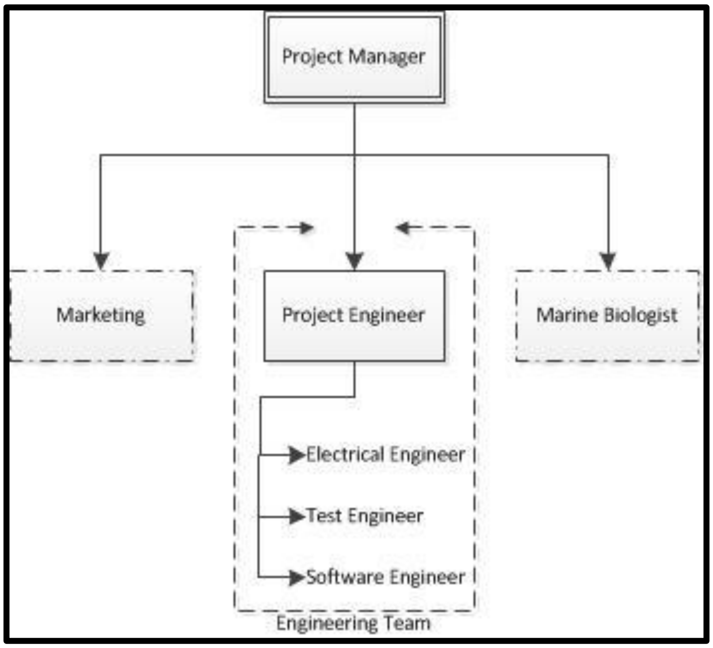
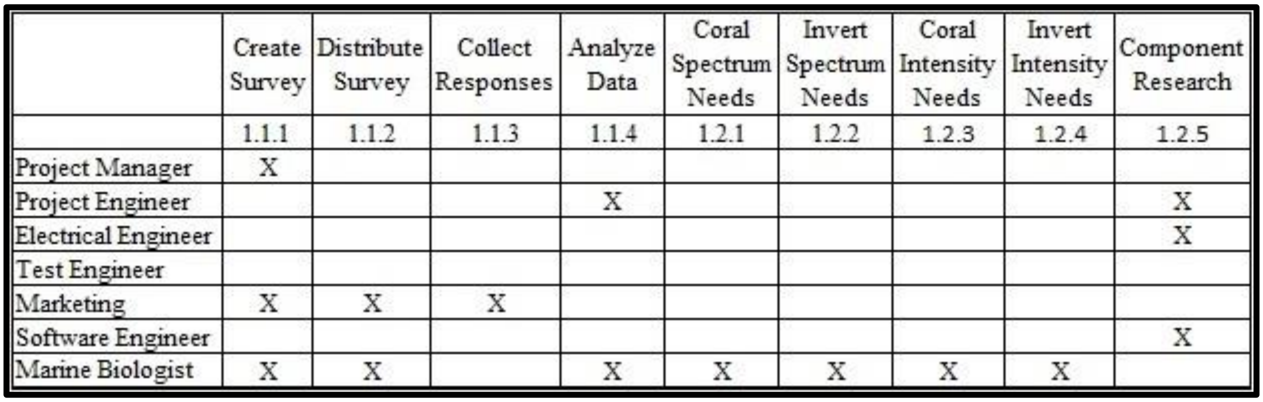


Figure 5: Organizational Structure

Initially, the Marine Biologist and Marketing have the most responsibilities as they gather requirements. As the project progresses, the responsibilities shift more to the engineers and the Project Manager. A sample of the Responsibility Matrix is in Table 1, but the entire matrix is located in APPENDIX C: Large Format Tables and Figures, as Figure 50 and Figure 51.

Table 1: Responsibility Matrix



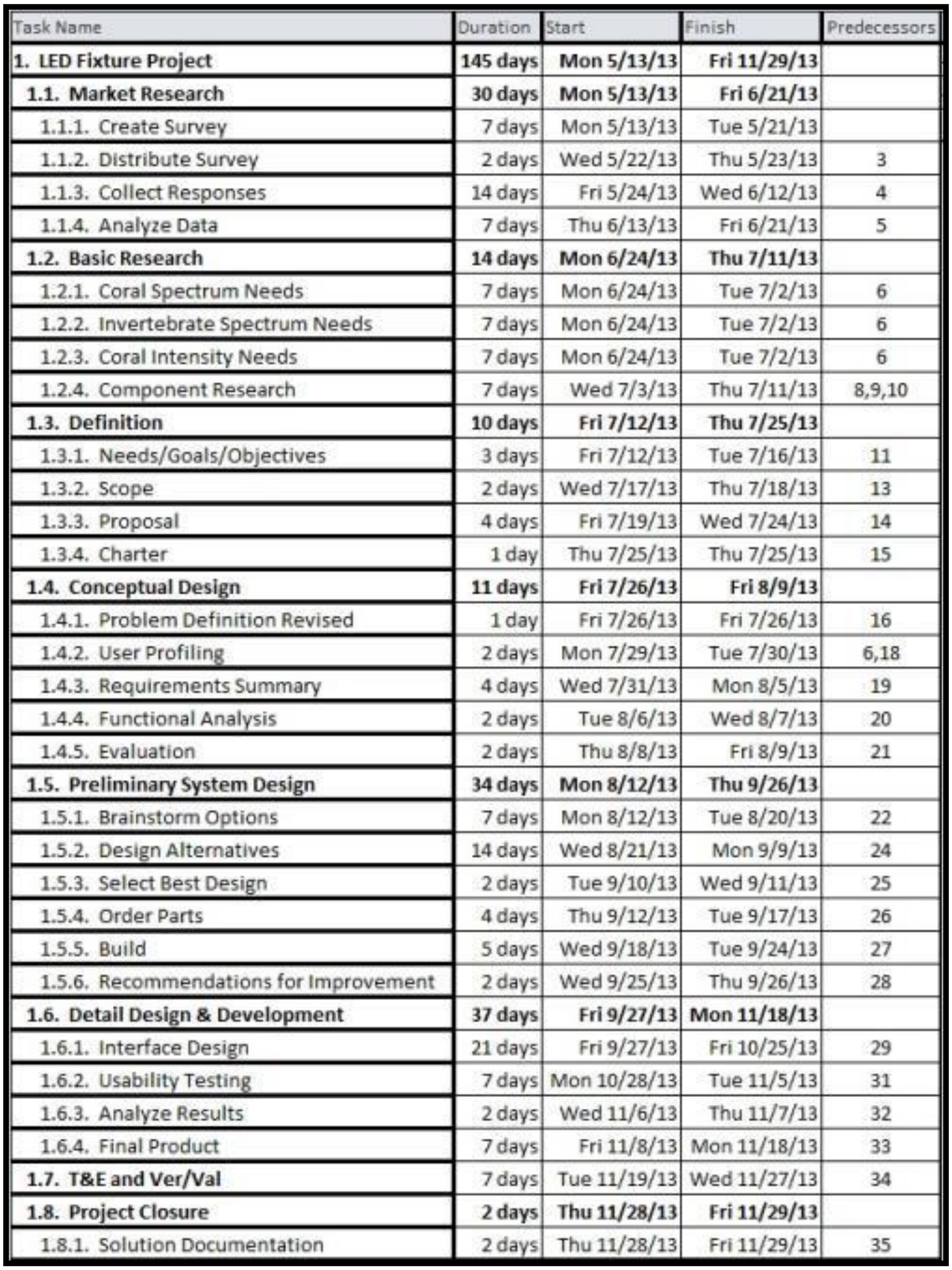
	Create Survey	Distribute Survey	Collect Responses	Analyze Data	Coral Spectrum Needs	Invert Spectrum Needs	Coral Intensity Needs	Invert Intensity Needs	Component Research
	1.1.1	1.1.2	1.1.3	1.1.4	1.2.1	1.2.2	1.2.3	1.2.4	1.2.5
Project Manager	X								
Project Engineer				X					X
Electrical Engineer									X
Test Engineer									
Marketing	X	X	X						
Software Engineer									X
Marine Biologist	X	X		X	X	X	X	X	

Project Schedule

Table 2 outlines the overall project, main tasks, and subtasks. It provides the duration, start dates, and finish dates. The project was started on 13 May 2013. Phase 1 ended on 31 July

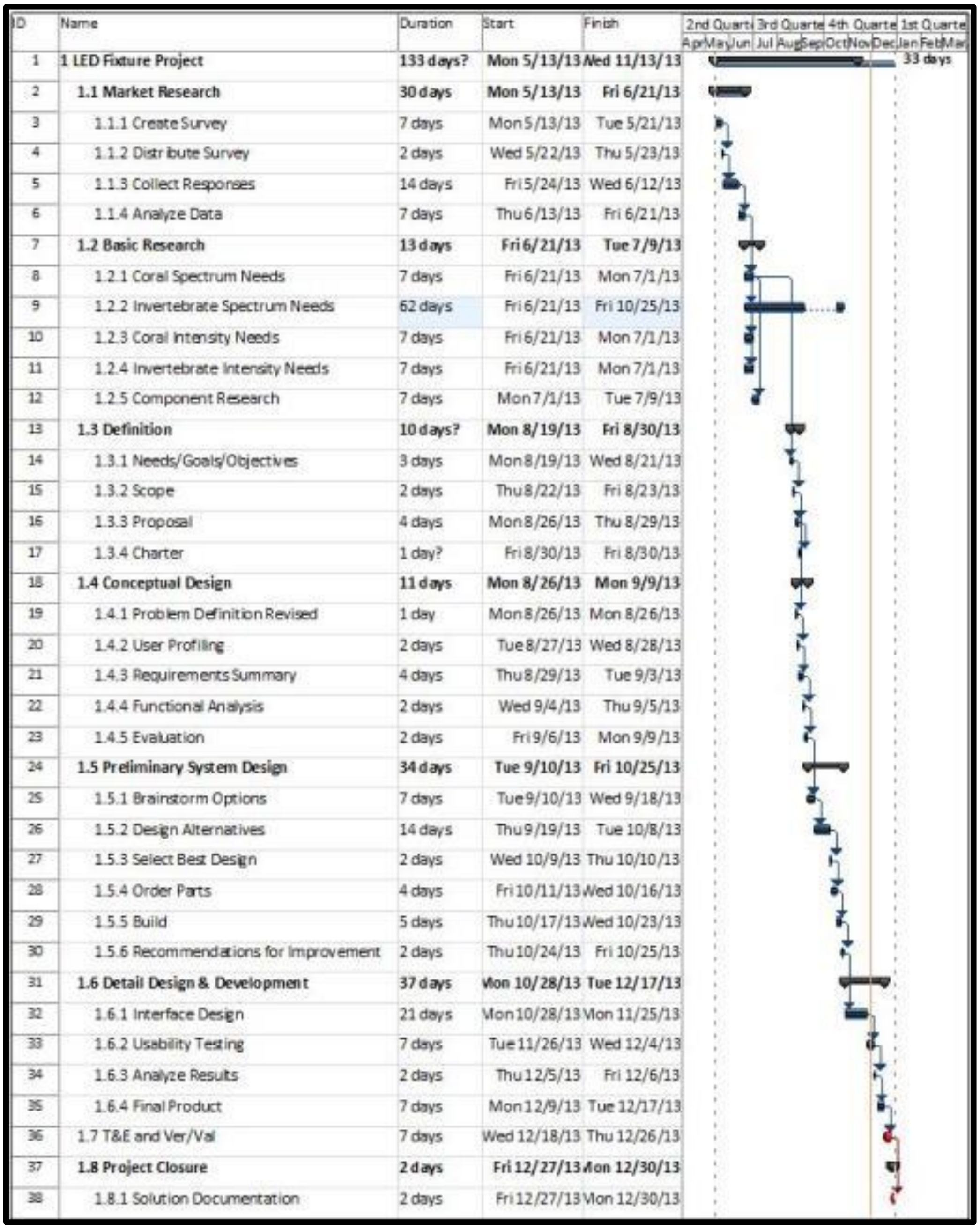
2013, which was partially through Conceptual Design (along with the end of ENM 505). Phase 2 immediately started (prior to ENM 590), and it has a hard end date of 10 December 2013, concurrent with the end of ENM 590. Phase 3 will then start (not included in this project), and its end is performance-based (dependent on coral photosynthesis response, which may take up to six months.) The expected project duration (Phase 1 and Phase 2) is a nominal 145 days. An enlarged version of Table 2 is in APPENDIX C: Large Format Tables and Figures, as Table 23.

Table 2: Project Schedule



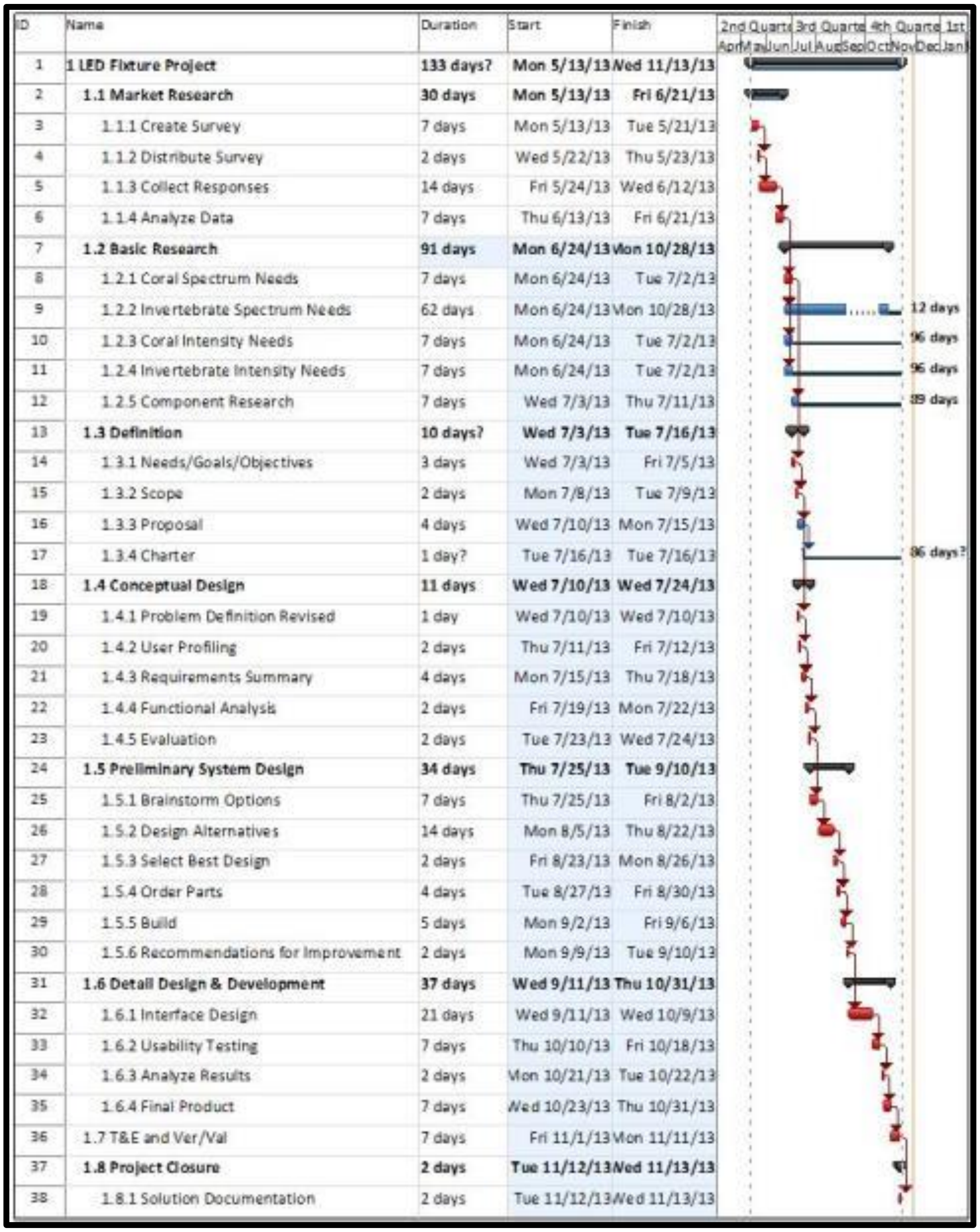
Task Name	Duration	Start	Finish	Predecessors
1. LED Fixture Project	**145 days**	**Mon 5/13/13**	**Fri 11/29/13**	
1.1. Market Research	**30 days**	**Mon 5/13/13**	**Fri 6/21/13**	
1.1.1. Create Survey	7 days	Mon 5/13/13	Tue 5/21/13	
1.1.2. Distribute Survey	2 days	Wed 5/22/13	Thu 5/23/13	3
1.1.3. Collect Responses	14 days	Fri 5/24/13	Wed 6/12/13	4
1.1.4. Analyze Data	7 days	Thu 6/13/13	Fri 6/21/13	5
1.2. Basic Research	**14 days**	**Mon 6/24/13**	**Thu 7/11/13**	
1.2.1. Coral Spectrum Needs	7 days	Mon 6/24/13	Tue 7/2/13	6
1.2.2. Invertebrate Spectrum Needs	7 days	Mon 6/24/13	Tue 7/2/13	6
1.2.3. Coral Intensity Needs	7 days	Mon 6/24/13	Tue 7/2/13	6
1.2.4. Component Research	7 days	Wed 7/3/13	Thu 7/11/13	8,9,10
1.3. Definition	**10 days**	**Fri 7/12/13**	**Thu 7/25/13**	
1.3.1. Needs/Goals/Objectives	3 days	Fri 7/12/13	Tue 7/16/13	11
1.3.2. Scope	2 days	Wed 7/17/13	Thu 7/18/13	13
1.3.3. Proposal	4 days	Fri 7/19/13	Wed 7/24/13	14
1.3.4. Charter	1 day	Thu 7/25/13	Thu 7/25/13	15
1.4. Conceptual Design	**11 days**	**Fri 7/26/13**	**Fri 8/9/13**	
1.4.1. Problem Definition Revised	1 day	Fri 7/26/13	Fri 7/26/13	16
1.4.2. User Profiling	2 days	Mon 7/29/13	Tue 7/30/13	6,18
1.4.3. Requirements Summary	4 days	Wed 7/31/13	Mon 8/5/13	19
1.4.4. Functional Analysis	2 days	Tue 8/6/13	Wed 8/7/13	20
1.4.5. Evaluation	2 days	Thu 8/8/13	Fri 8/9/13	21
1.5. Preliminary System Design	**34 days**	**Mon 8/12/13**	**Thu 9/26/13**	
1.5.1. Brainstorm Options	7 days	Mon 8/12/13	Tue 8/20/13	22
1.5.2. Design Alternatives	14 days	Wed 8/21/13	Mon 9/9/13	24
1.5.3. Select Best Design	2 days	Tue 9/10/13	Wed 9/11/13	25
1.5.4. Order Parts	4 days	Thu 9/12/13	Tue 9/17/13	26
1.5.5. Build	5 days	Wed 9/18/13	Tue 9/24/13	27
1.5.6. Recommendations for Improvement	2 days	Wed 9/25/13	Thu 9/26/13	28
1.6. Detail Design & Development	**37 days**	**Fri 9/27/13**	**Mon 11/18/13**	
1.6.1. Interface Design	21 days	Fri 9/27/13	Fri 10/25/13	29
1.6.2. Usability Testing	7 days	Mon 10/28/13	Tue 11/5/13	31
1.6.3. Analyze Results	2 days	Wed 11/6/13	Thu 11/7/13	32
1.6.4. Final Product	7 days	Fri 11/8/13	Mon 11/18/13	33
1.7. T&E and Ver/Val	7 days	Tue 11/19/13	Wed 11/27/13	34
1.8. Project Closure	**2 days**	**Thu 11/28/13**	**Fri 11/29/13**	
1.8.1. Solution Documentation	2 days	Thu 11/28/13	Fri 11/29/13	35

Figure 6 depicts the actual project schedule detail for Phase 1 and Phase 2. It expands on Table 2, and Figure 7 includes the critical path (highlighted in red.) Nearly all subtasks are on this path, so it is essential that they are kept on schedule. So far, all tasks were completed on schedule. Enlarged copies of Figure 6 and Figure 7 are located in APPENDIX C: Large Format Tables and Figures, as Figure 52 and Figure 53.



ID	Name	Duration	Start	Finish
1	**1 LED Fixture Project**	**133 days?**	**Mon 5/13/13**	**Wed 11/13/13**
2	**1.1 Market Research**	**30 days**	**Mon 5/13/13**	**Fri 6/21/13**
3	1.1.1 Create Survey	7 days	Mon 5/13/13	Tue 5/21/13
4	1.1.2 Distribute Survey	2 days	Wed 5/22/13	Thu 5/23/13
5	1.1.3 Collect Responses	14 days	Fri 5/24/13	Wed 6/12/13
6	1.1.4 Analyze Data	7 days	Thu 6/13/13	Fri 6/21/13
7	**1.2 Basic Research**	**13 days**	**Fri 6/21/13**	**Tue 7/9/13**
8	1.2.1 Coral Spectrum Needs	7 days	Fri 6/21/13	Mon 7/1/13
9	1.2.2 Invertebrate Spectrum Needs	62 days	Fri 6/21/13	Fri 10/25/13
10	1.2.3 Coral Intensity Needs	7 days	Fri 6/21/13	Mon 7/1/13
11	1.2.4 Invertebrate Intensity Needs	7 days	Fri 6/21/13	Mon 7/1/13
12	1.2.5 Component Research	7 days	Mon 7/1/13	Tue 7/9/13
13	**1.3 Definition**	**10 days?**	**Mon 8/19/13**	**Fri 8/30/13**
14	1.3.1 Needs/Goals/Objectives	3 days	Mon 8/19/13	Wed 8/21/13
15	1.3.2 Scope	2 days	Thu 8/22/13	Fri 8/23/13
16	1.3.3 Proposal	4 days	Mon 8/26/13	Thu 8/29/13
17	1.3.4 Charter	1 day?	Fri 8/30/13	Fri 8/30/13
18	**1.4 Conceptual Design**	**11 days**	**Mon 8/26/13**	**Mon 9/9/13**
19	1.4.1 Problem Definition Revised	1 day	Mon 8/26/13	Mon 8/26/13
20	1.4.2 User Profiling	2 days	Tue 8/27/13	Wed 8/28/13
21	1.4.3 Requirements Summary	4 days	Thu 8/29/13	Tue 9/3/13
22	1.4.4 Functional Analysis	2 days	Wed 9/4/13	Thu 9/5/13
23	1.4.5 Evaluation	2 days	Fri 9/6/13	Mon 9/9/13
24	**1.5 Preliminary System Design**	**34 days**	**Tue 9/10/13**	**Fri 10/25/13**
25	1.5.1 Brainstorm Options	7 days	Tue 9/10/13	Wed 9/18/13
26	1.5.2 Design Alternatives	14 days	Thu 9/19/13	Tue 10/8/13
27	1.5.3 Select Best Design	2 days	Wed 10/9/13	Thu 10/10/13
28	1.5.4 Order Parts	4 days	Fri 10/11/13	Wed 10/16/13
29	1.5.5 Build	5 days	Thu 10/17/13	Wed 10/23/13
30	1.5.6 Recommendations for Improvement	2 days	Thu 10/24/13	Fri 10/25/13
31	**1.6 Detail Design & Development**	**37 days**	**Mon 10/28/13**	**Tue 12/17/13**
32	1.6.1 Interface Design	21 days	Mon 10/28/13	Mon 11/25/13
33	1.6.2 Usability Testing	7 days	Tue 11/26/13	Wed 12/4/13
34	1.6.3 Analyze Results	2 days	Thu 12/5/13	Fri 12/6/13
35	1.6.4 Final Product	7 days	Mon 12/9/13	Tue 12/17/13
36	1.7 T&E and Ver/Val	7 days	Wed 12/18/13	Thu 12/26/13
37	**1.8 Project Closure**	**2 days**	**Fri 12/27/13**	**Mon 12/30/13**
38	1.8.1 Solution Documentation	2 days	Fri 12/27/13	Mon 12/30/13

Figure 6: Project Schedule Detail



ID	Name	Duration	Start	Finish
1	**1 LED Fixture Project**	**133 days?**	**Mon 5/13/13**	**Wed 11/13/13**
2	**1.1 Market Research**	**30 days**	**Mon 5/13/13**	**Fri 6/21/13**
3	1.1.1 Create Survey	7 days	Mon 5/13/13	Tue 5/21/13
4	1.1.2 Distribute Survey	2 days	Wed 5/22/13	Thu 5/23/13
5	1.1.3 Collect Responses	14 days	Fri 5/24/13	Wed 6/12/13
6	1.1.4 Analyze Data	7 days	Thu 6/13/13	Fri 6/21/13
7	**1.2 Basic Research**	**91 days**	**Mon 6/24/13**	**Mon 10/28/13**
8	1.2.1 Coral Spectrum Needs	7 days	Mon 6/24/13	Tue 7/2/13
9	1.2.2 Invertebrate Spectrum Needs	62 days	Mon 6/24/13	Mon 10/28/13
10	1.2.3 Coral Intensity Needs	7 days	Mon 6/24/13	Tue 7/2/13
11	1.2.4 Invertebrate Intensity Needs	7 days	Mon 6/24/13	Tue 7/2/13
12	1.2.5 Component Research	7 days	Wed 7/3/13	Thu 7/11/13
13	**1.3 Definition**	**10 days?**	**Wed 7/3/13**	**Tue 7/16/13**
14	1.3.1 Needs/Goals/Objectives	3 days	Wed 7/3/13	Fri 7/5/13
15	1.3.2 Scope	2 days	Mon 7/8/13	Tue 7/9/13
16	1.3.3 Proposal	4 days	Wed 7/10/13	Mon 7/15/13
17	1.3.4 Charter	1 day?	Tue 7/16/13	Tue 7/16/13
18	**1.4 Conceptual Design**	**11 days**	**Wed 7/10/13**	**Wed 7/24/13**
19	1.4.1 Problem Definition Revised	1 day	Wed 7/10/13	Wed 7/10/13
20	1.4.2 User Profiling	2 days	Thu 7/11/13	Fri 7/12/13
21	1.4.3 Requirements Summary	4 days	Mon 7/15/13	Thu 7/18/13
22	1.4.4 Functional Analysis	2 days	Fri 7/19/13	Mon 7/22/13
23	1.4.5 Evaluation	2 days	Tue 7/23/13	Wed 7/24/13
24	**1.5 Preliminary System Design**	**34 days**	**Thu 7/25/13**	**Tue 9/10/13**
25	1.5.1 Brainstorm Options	7 days	Thu 7/25/13	Fri 8/2/13
26	1.5.2 Design Alternatives	14 days	Mon 8/5/13	Thu 8/22/13
27	1.5.3 Select Best Design	2 days	Fri 8/23/13	Mon 8/26/13
28	1.5.4 Order Parts	4 days	Tue 8/27/13	Fri 8/30/13
29	1.5.5 Build	5 days	Mon 9/2/13	Fri 9/6/13
30	1.5.6 Recommendations for Improvement	2 days	Mon 9/9/13	Tue 9/10/13
31	**1.6 Detail Design & Development**	**37 days**	**Wed 9/11/13**	**Thu 10/31/13**
32	1.6.1 Interface Design	21 days	Wed 9/11/13	Wed 10/9/13
33	1.6.2 Usability Testing	7 days	Thu 10/10/13	Fri 10/18/13
34	1.6.3 Analyze Results	2 days	Mon 10/21/13	Tue 10/22/13
35	1.6.4 Final Product	7 days	Wed 10/23/13	Thu 10/31/13
36	1.7 T&E and Ver/Val	7 days	Fri 11/1/13	Mon 11/11/13
37	**1.8 Project Closure**	**2 days**	**Tue 11/12/13**	**Wed 11/13/13**
38	1.8.1 Solution Documentation	2 days	Tue 11/12/13	Wed 11/13/13

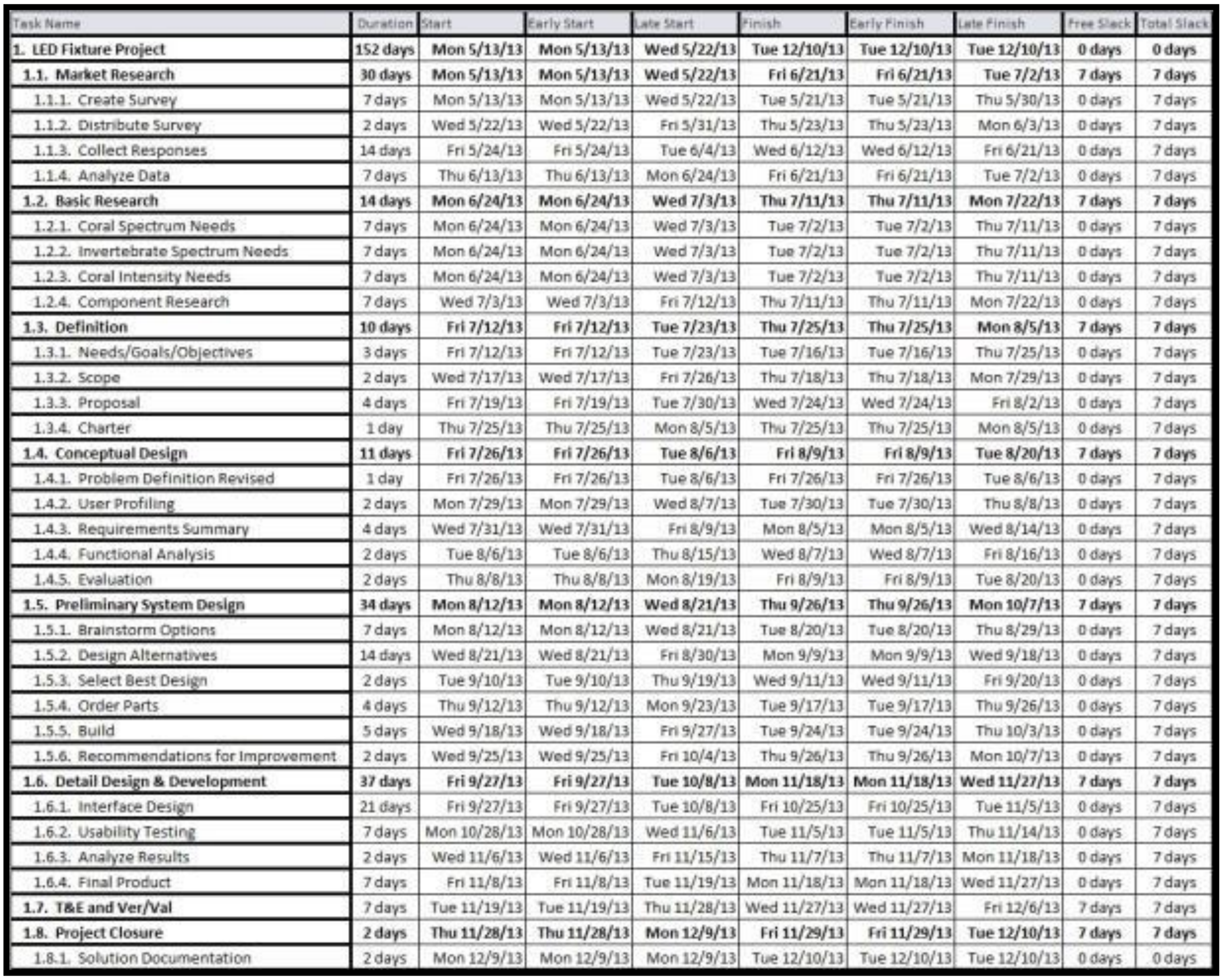
Figure 7: Project Schedule Critical Path

Sensitivity Analysis

The critical path was analyzed for its sensitivity to changes in time with a set end date of 10 December 2013. Table 3 shows the baseline duration, start, and finish, as well as the earliest start date for each task, earliest finish date for each task, free slack, and total slack. Table 4 shows the impact to the critical path based on what-if scenarios if the schedule was increased and decreased by 10%. Table 5 and Table 6 show the impact to the schedule and slack analysis with 10% more time and less time, respectively. Since all tasks were on the critical path of the original schedule, an increased/decreased schedule did not change the critical path. However, if Phase 2 extended out to 20 December 2013, then the requirements would not be met for ENM

590. Table 3, Table 5, and Table 6 are shown enlarged in APPENDIX C: Large Format Tables and Figures, as Table 24, Table 25, Table 26, respectively.

Table 3: Baseline Sensitivity Analysis

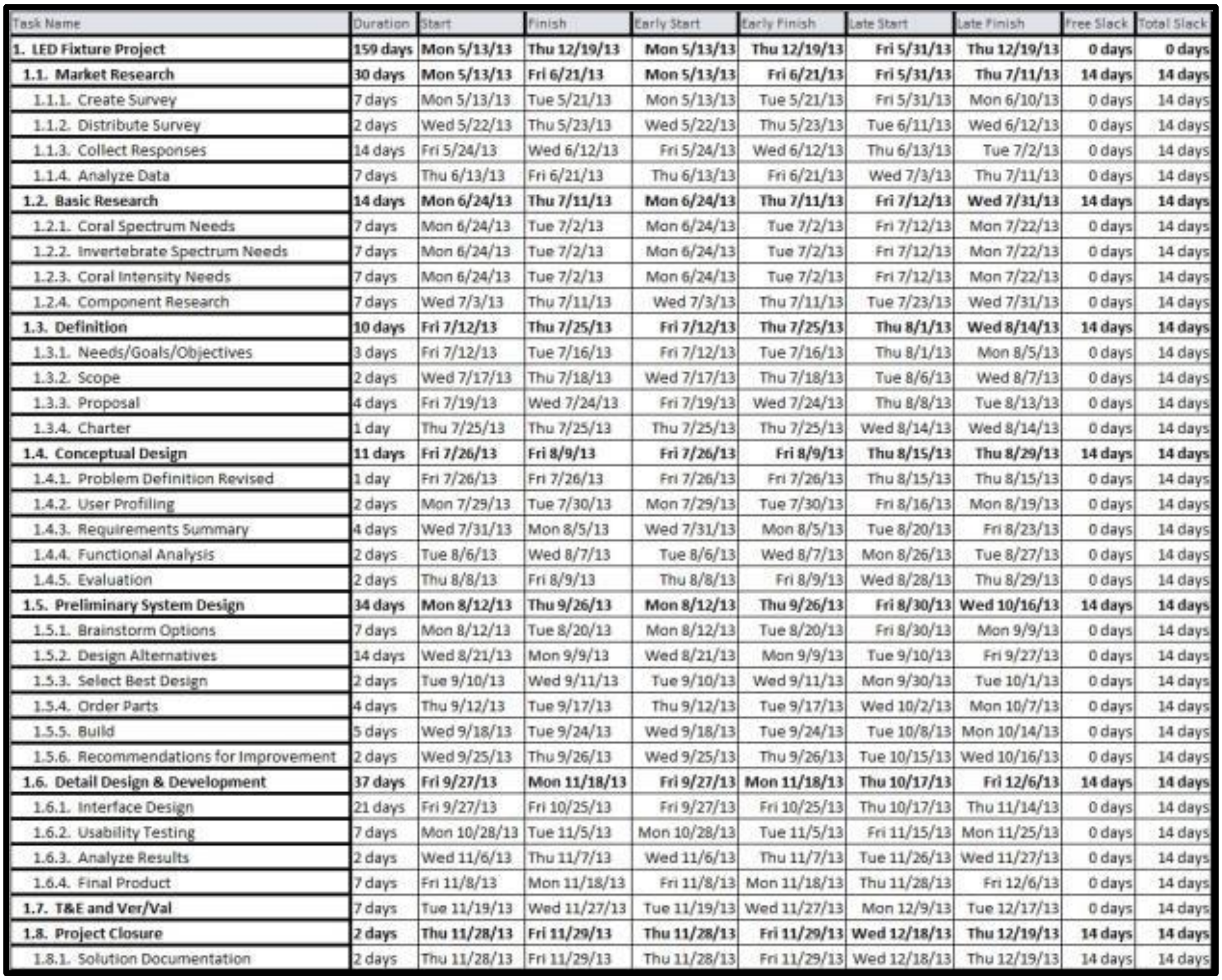


Task Name	Duration	Start	Early Start	Late Start	Finish	Early Finish	Late Finish	Free Slack	Total Slack
1. LED Fixture Project	**152 days**	**Mon 5/13/13**	**Mon 5/13/13**	**Wed 5/22/13**	**Tue 12/10/13**	**Tue 12/10/13**	**Tue 12/10/13**	**0 days**	**0 days**
1.1. Market Research	**30 days**	**Mon 5/13/13**	**Mon 5/13/13**	**Wed 5/22/13**	**Fri 6/21/13**	**Fri 6/21/13**	**Tue 7/2/13**	**7 days**	**7 days**
1.1.1. Create Survey	7 days	Mon 5/13/13	Mon 5/13/13	Wed 5/22/13	Tue 5/21/13	Tue 5/21/13	Thu 5/30/13	0 days	7 days
1.1.2. Distribute Survey	2 days	Wed 5/22/13	Wed 5/22/13	Fri 5/31/13	Thu 5/23/13	Thu 5/23/13	Mon 6/3/13	0 days	7 days
1.1.3. Collect Responses	14 days	Fri 5/24/13	Fri 5/24/13	Tue 6/4/13	Wed 6/12/13	Wed 6/12/13	Fri 6/21/13	0 days	7 days
1.1.4. Analyze Data	7 days	Thu 6/13/13	Thu 6/13/13	Mon 6/24/13	Fri 6/21/13	Fri 6/21/13	Tue 7/2/13	0 days	7 days
1.2. Basic Research	**14 days**	**Mon 6/24/13**	**Mon 6/24/13**	**Wed 7/3/13**	**Thu 7/11/13**	**Thu 7/11/13**	**Mon 7/22/13**	**7 days**	**7 days**
1.2.1. Coral Spectrum Needs	7 days	Mon 6/24/13	Mon 6/24/13	Wed 7/3/13	Tue 7/2/13	Tue 7/2/13	Thu 7/11/13	0 days	7 days
1.2.2. Invertebrate Spectrum Needs	7 days	Mon 6/24/13	Mon 6/24/13	Wed 7/3/13	Tue 7/2/13	Tue 7/2/13	Thu 7/11/13	0 days	7 days
1.2.3. Coral Intensity Needs	7 days	Mon 6/24/13	Mon 6/24/13	Wed 7/3/13	Tue 7/2/13	Tue 7/2/13	Thu 7/11/13	0 days	7 days
1.2.4. Component Research	7 days	Wed 7/3/13	Wed 7/3/13	Fri 7/12/13	Thu 7/11/13	Thu 7/11/13	Mon 7/22/13	0 days	7 days
1.3. Definition	**10 days**	**Fri 7/12/13**	**Fri 7/12/13**	**Tue 7/23/13**	**Thu 7/25/13**	**Thu 7/25/13**	**Mon 8/5/13**	**7 days**	**7 days**
1.3.1. Needs/Goals/Objectives	3 days	Fri 7/12/13	Fri 7/12/13	Tue 7/23/13	Tue 7/16/13	Tue 7/16/13	Thu 7/25/13	0 days	7 days
1.3.2. Scope	2 days	Wed 7/17/13	Wed 7/17/13	Fri 7/26/13	Thu 7/18/13	Thu 7/18/13	Mon 7/29/13	0 days	7 days
1.3.3. Proposal	4 days	Fri 7/19/13	Fri 7/19/13	Tue 7/30/13	Wed 7/24/13	Wed 7/24/13	Fri 8/2/13	0 days	7 days
1.3.4. Charter	1 day	Thu 7/25/13	Thu 7/25/13	Mon 8/5/13	Thu 7/25/13	Thu 7/25/13	Mon 8/5/13	0 days	7 days
1.4. Conceptual Design	**11 days**	**Fri 7/26/13**	**Fri 7/26/13**	**Tue 8/6/13**	**Fri 8/9/13**	**Fri 8/9/13**	**Tue 8/20/13**	**7 days**	**7 days**
1.4.1. Problem Definition Revised	1 day	Fri 7/26/13	Fri 7/26/13	Tue 8/6/13	Fri 7/26/13	Fri 7/26/13	Tue 8/6/13	0 days	7 days
1.4.2. User Profiling	2 days	Mon 7/29/13	Mon 7/29/13	Wed 8/7/13	Tue 7/30/13	Tue 7/30/13	Thu 8/8/13	0 days	7 days
1.4.3. Requirements Summary	4 days	Wed 7/31/13	Wed 7/31/13	Fri 8/9/13	Mon 8/5/13	Mon 8/5/13	Wed 8/14/13	0 days	7 days
1.4.4. Functional Analysis	2 days	Tue 8/6/13	Tue 8/6/13	Thu 8/15/13	Wed 8/7/13	Wed 8/7/13	Fri 8/16/13	0 days	7 days
1.4.5. Evaluation	2 days	Thu 8/8/13	Thu 8/8/13	Mon 8/19/13	Fri 8/9/13	Fri 8/9/13	Tue 8/20/13	0 days	7 days
1.5. Preliminary System Design	**34 days**	**Mon 8/12/13**	**Mon 8/12/13**	**Wed 8/21/13**	**Thu 9/26/13**	**Thu 9/26/13**	**Mon 10/7/13**	**7 days**	**7 days**
1.5.1. Brainstorm Options	7 days	Mon 8/12/13	Mon 8/12/13	Wed 8/21/13	Tue 8/20/13	Tue 8/20/13	Thu 8/29/13	0 days	7 days
1.5.2. Design Alternatives	14 days	Wed 8/21/13	Wed 8/21/13	Fri 8/30/13	Mon 9/9/13	Mon 9/9/13	Wed 9/18/13	0 days	7 days
1.5.3. Select Best Design	2 days	Tue 9/10/13	Tue 9/10/13	Thu 9/19/13	Wed 9/11/13	Wed 9/11/13	Fri 9/20/13	0 days	7 days
1.5.4. Order Parts	4 days	Thu 9/12/13	Thu 9/12/13	Mon 9/23/13	Tue 9/17/13	Tue 9/17/13	Thu 9/26/13	0 days	7 days
1.5.5. Build	5 days	Wed 9/18/13	Wed 9/18/13	Fri 9/27/13	Tue 9/24/13	Tue 9/24/13	Thu 10/3/13	0 days	7 days
1.5.6. Recommendations for Improvement	2 days	Wed 9/25/13	Wed 9/25/13	Fri 10/4/13	Thu 9/26/13	Thu 9/26/13	Mon 10/7/13	0 days	7 days
1.6. Detail Design & Development	**37 days**	**Fri 9/27/13**	**Fri 9/27/13**	**Tue 10/8/13**	**Mon 11/18/13**	**Mon 11/18/13**	**Wed 11/27/13**	**7 days**	**7 days**
1.6.1. Interface Design	21 days	Fri 9/27/13	Fri 9/27/13	Tue 10/8/13	Fri 10/25/13	Fri 10/25/13	Tue 11/5/13	0 days	7 days
1.6.2. Usability Testing	7 days	Mon 10/28/13	Mon 10/28/13	Wed 11/6/13	Tue 11/5/13	Tue 11/5/13	Thu 11/14/13	0 days	7 days
1.6.3. Analyze Results	2 days	Wed 11/6/13	Wed 11/6/13	Fri 11/15/13	Thu 11/7/13	Thu 11/7/13	Mon 11/18/13	0 days	7 days
1.6.4. Final Product	7 days	Fri 11/8/13	Fri 11/8/13	Tue 11/19/13	Mon 11/18/13	Mon 11/18/13	Wed 11/27/13	0 days	7 days
1.7. T&E and Ver/Val	7 days	Tue 11/19/13	Tue 11/19/13	Thu 11/28/13	Wed 11/27/13	Wed 11/27/13	Fri 12/6/13	7 days	7 days
1.8. Project Closure	**2 days**	**Thu 11/28/13**	**Thu 11/28/13**	**Mon 12/9/13**	**Fri 11/29/13**	**Fri 11/29/13**	**Tue 12/10/13**	**7 days**	**7 days**
1.8.1. Solution Documentation	2 days	Mon 12/9/13	Mon 12/9/13	Mon 12/9/13	Tue 12/10/13	Tue 12/10/13	Tue 12/10/13	0 days	0 days

Table 4: 10% More/Less Time Sensitivity Analysis

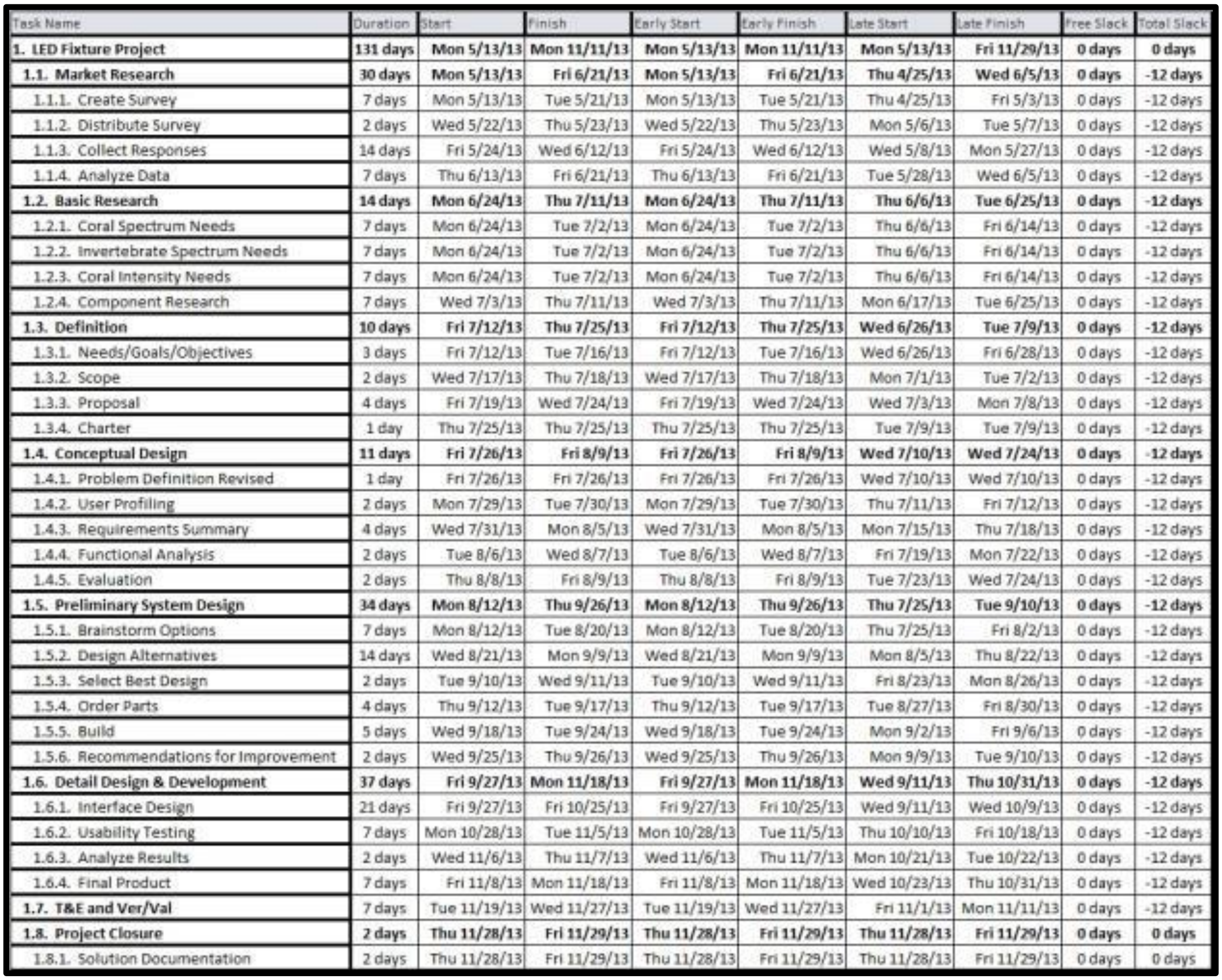
	Start Date	End Date	Duration	Delta	Critical Path
Original Schedule	5/13/2013	11/29/2013	145	N/A	All tasks are on critical path
10% Less Time	5/13/2013	11/11/2013	130.5	-14.5	All tasks are on critical path
10% More Time	5/13/2013	12/20/2013	159.5	14.5	All tasks are on critical path

Table 5: 10% More Time Sensitivity Analysis



Task Name	Duration	Start	Finish	Early Start	Early Finish	Late Start	Late Finish	Free Slack	Total Slack
1. LED Fixture Project	**159 days**	**Mon 5/13/13**	**Thu 12/19/13**	**Mon 5/13/13**	**Thu 12/19/13**	**Fri 5/31/13**	**Thu 12/19/13**	**0 days**	**0 days**
1.1. Market Research	**30 days**	**Mon 5/13/13**	**Fri 6/21/13**	**Mon 5/13/13**	**Fri 6/21/13**	**Fri 5/31/13**	**Thu 7/11/13**	**14 days**	**14 days**
1.1.1. Create Survey	7 days	Mon 5/13/13	Tue 5/21/13	Mon 5/13/13	Tue 5/21/13	Fri 5/31/13	Mon 6/10/13	0 days	14 days
1.1.2. Distribute Survey	2 days	Wed 5/22/13	Thu 5/23/13	Wed 5/22/13	Thu 5/23/13	Tue 6/11/13	Wed 6/12/13	0 days	14 days
1.1.3. Collect Responses	14 days	Fri 5/24/13	Wed 6/12/13	Fri 5/24/13	Wed 6/12/13	Thu 6/13/13	Tue 7/2/13	0 days	14 days
1.1.4. Analyze Data	7 days	Thu 6/13/13	Fri 6/21/13	Thu 6/13/13	Fri 6/21/13	Wed 7/3/13	Thu 7/11/13	0 days	14 days
1.2. Basic Research	**14 days**	**Mon 6/24/13**	**Thu 7/11/13**	**Mon 6/24/13**	**Thu 7/11/13**	**Fri 7/12/13**	**Wed 7/31/13**	**14 days**	**14 days**
1.2.1. Coral Spectrum Needs	7 days	Mon 6/24/13	Tue 7/2/13	Mon 6/24/13	Tue 7/2/13	Fri 7/12/13	Mon 7/22/13	0 days	14 days
1.2.2. Invertebrate Spectrum Needs	7 days	Mon 6/24/13	Tue 7/2/13	Mon 6/24/13	Tue 7/2/13	Fri 7/12/13	Mon 7/22/13	0 days	14 days
1.2.3. Coral Intensity Needs	7 days	Mon 6/24/13	Tue 7/2/13	Mon 6/24/13	Tue 7/2/13	Fri 7/12/13	Mon 7/22/13	0 days	14 days
1.2.4. Component Research	7 days	Wed 7/3/13	Thu 7/11/13	Wed 7/3/13	Thu 7/11/13	Tue 7/23/13	Wed 7/31/13	0 days	14 days
1.3. Definition	**10 days**	**Fri 7/12/13**	**Thu 7/25/13**	**Fri 7/12/13**	**Thu 7/25/13**	**Thu 8/1/13**	**Wed 8/14/13**	**14 days**	**14 days**
1.3.1. Needs/Goals/Objectives	3 days	Fri 7/12/13	Tue 7/16/13	Fri 7/12/13	Tue 7/16/13	Thu 8/1/13	Mon 8/5/13	0 days	14 days
1.3.2. Scope	2 days	Wed 7/17/13	Thu 7/18/13	Wed 7/17/13	Thu 7/18/13	Tue 8/6/13	Wed 8/7/13	0 days	14 days
1.3.3. Proposal	4 days	Fri 7/19/13	Wed 7/24/13	Fri 7/19/13	Wed 7/24/13	Thu 8/8/13	Tue 8/13/13	0 days	14 days
1.3.4. Charter	1 day	Thu 7/25/13	Thu 7/25/13	Thu 7/25/13	Thu 7/25/13	Wed 8/14/13	Wed 8/14/13	0 days	14 days
1.4. Conceptual Design	**11 days**	**Fri 7/26/13**	**Fri 8/9/13**	**Fri 7/26/13**	**Fri 8/9/13**	**Thu 8/15/13**	**Thu 8/29/13**	**14 days**	**14 days**
1.4.1. Problem Definition Revised	1 day	Fri 7/26/13	Fri 7/26/13	Fri 7/26/13	Fri 7/26/13	Thu 8/15/13	Thu 8/15/13	0 days	14 days
1.4.2. User Profiling	2 days	Mon 7/29/13	Tue 7/30/13	Mon 7/29/13	Tue 7/30/13	Fri 8/16/13	Mon 8/19/13	0 days	14 days
1.4.3. Requirements Summary	4 days	Wed 7/31/13	Mon 8/5/13	Wed 7/31/13	Mon 8/5/13	Tue 8/20/13	Fri 8/23/13	0 days	14 days
1.4.4. Functional Analysis	2 days	Tue 8/6/13	Wed 8/7/13	Tue 8/6/13	Wed 8/7/13	Mon 8/26/13	Tue 8/27/13	0 days	14 days
1.4.5. Evaluation	2 days	Thu 8/8/13	Fri 8/9/13	Thu 8/8/13	Fri 8/9/13	Wed 8/28/13	Thu 8/29/13	0 days	14 days
1.5. Preliminary System Design	**34 days**	**Mon 8/12/13**	**Thu 9/26/13**	**Mon 8/12/13**	**Thu 9/26/13**	**Fri 8/30/13**	**Wed 10/16/13**	**14 days**	**14 days**
1.5.1. Brainstorm Options	7 days	Mon 8/12/13	Tue 8/20/13	Mon 8/12/13	Tue 8/20/13	Fri 8/30/13	Mon 9/9/13	0 days	14 days
1.5.2. Design Alternatives	14 days	Wed 8/21/13	Mon 9/9/13	Wed 8/21/13	Mon 9/9/13	Tue 9/10/13	Fri 9/27/13	0 days	14 days
1.5.3. Select Best Design	2 days	Tue 9/10/13	Wed 9/11/13	Tue 9/10/13	Wed 9/11/13	Mon 9/30/13	Tue 10/1/13	0 days	14 days
1.5.4. Order Parts	4 days	Thu 9/12/13	Tue 9/17/13	Thu 9/12/13	Tue 9/17/13	Wed 10/2/13	Mon 10/7/13	0 days	14 days
1.5.5. Build	5 days	Wed 9/18/13	Tue 9/24/13	Wed 9/18/13	Tue 9/24/13	Tue 10/8/13	Mon 10/14/13	0 days	14 days
1.5.6. Recommendations for Improvement	2 days	Wed 9/25/13	Thu 9/26/13	Wed 9/25/13	Thu 9/26/13	Tue 10/15/13	Wed 10/16/13	0 days	14 days
1.6. Detail Design & Development	**37 days**	**Fri 9/27/13**	**Mon 11/18/13**	**Fri 9/27/13**	**Mon 11/18/13**	**Thu 10/17/13**	**Fri 12/6/13**	**14 days**	**14 days**
1.6.1. Interface Design	21 days	Fri 9/27/13	Fri 10/25/13	Fri 9/27/13	Fri 10/25/13	Thu 10/17/13	Thu 11/14/13	0 days	14 days
1.6.2. Usability Testing	7 days	Mon 10/28/13	Tue 11/5/13	Mon 10/28/13	Tue 11/5/13	Fri 11/15/13	Mon 11/25/13	0 days	14 days
1.6.3. Analyze Results	2 days	Wed 11/6/13	Thu 11/7/13	Wed 11/6/13	Thu 11/7/13	Tue 11/26/13	Wed 11/27/13	0 days	14 days
1.6.4. Final Product	7 days	Fri 11/8/13	Mon 11/18/13	Fri 11/8/13	Mon 11/18/13	Thu 11/28/13	Fri 12/6/13	0 days	14 days
1.7. T&E and Ver/Val	7 days	Tue 11/19/13	Wed 11/27/13	Tue 11/19/13	Wed 11/27/13	Mon 12/9/13	Tue 12/17/13	0 days	14 days
1.8. Project Closure	**2 days**	**Thu 11/28/13**	**Fri 11/29/13**	**Thu 11/28/13**	**Fri 11/29/13**	**Wed 12/18/13**	**Thu 12/19/13**	**14 days**	**14 days**
1.8.1. Solution Documentation	2 days	Thu 11/28/13	Fri 11/29/13	Thu 11/28/13	Fri 11/29/13	Wed 12/18/13	Thu 12/19/13	14 days	14 days

Table 6: 10% Less Time Sensitivity Analysis



Task Name	Duration	Start	Finish	Early Start	Early Finish	Late Start	Late Finish	Free Slack	Total Slack
1. LED Fixture Project	**131 days**	**Mon 5/13/13**	**Mon 11/11/13**	**Mon 5/13/13**	**Mon 11/11/13**	**Mon 5/13/13**	**Fri 11/29/13**	**0 days**	**0 days**
1.1. Market Research	**30 days**	**Mon 5/13/13**	**Fri 6/21/13**	**Mon 5/13/13**	**Fri 6/21/13**	**Thu 4/25/13**	**Wed 6/5/13**	**0 days**	**-12 days**
1.1.1. Create Survey	7 days	Mon 5/13/13	Tue 5/21/13	Mon 5/13/13	Tue 5/21/13	Thu 4/25/13	Fri 5/3/13	0 days	-12 days
1.1.2. Distribute Survey	2 days	Wed 5/22/13	Thu 5/23/13	Wed 5/22/13	Thu 5/23/13	Mon 5/6/13	Tue 5/7/13	0 days	-12 days
1.1.3. Collect Responses	14 days	Fri 5/24/13	Wed 6/12/13	Fri 5/24/13	Wed 6/12/13	Wed 5/8/13	Mon 5/27/13	0 days	-12 days
1.1.4. Analyze Data	7 days	Thu 6/13/13	Fri 6/21/13	Thu 6/13/13	Fri 6/21/13	Tue 5/28/13	Wed 6/5/13	0 days	-12 days
1.2. Basic Research	**14 days**	**Mon 6/24/13**	**Thu 7/11/13**	**Mon 6/24/13**	**Thu 7/11/13**	**Thu 6/6/13**	**Tue 6/25/13**	**0 days**	**-12 days**
1.2.1. Coral Spectrum Needs	7 days	Mon 6/24/13	Tue 7/2/13	Mon 6/24/13	Tue 7/2/13	Thu 6/6/13	Fri 6/14/13	0 days	-12 days
1.2.2. Invertebrate Spectrum Needs	7 days	Mon 6/24/13	Tue 7/2/13	Mon 6/24/13	Tue 7/2/13	Thu 6/6/13	Fri 6/14/13	0 days	-12 days
1.2.3. Coral Intensity Needs	7 days	Mon 6/24/13	Tue 7/2/13	Mon 6/24/13	Tue 7/2/13	Thu 6/6/13	Fri 6/14/13	0 days	-12 days
1.2.4. Component Research	7 days	Wed 7/3/13	Thu 7/11/13	Wed 7/3/13	Thu 7/11/13	Mon 6/17/13	Tue 6/25/13	0 days	-12 days
1.3. Definition	**10 days**	**Fri 7/12/13**	**Thu 7/25/13**	**Fri 7/12/13**	**Thu 7/25/13**	**Wed 6/26/13**	**Tue 7/9/13**	**0 days**	**-12 days**
1.3.1. Needs/Goals/Objectives	3 days	Fri 7/12/13	Tue 7/16/13	Fri 7/12/13	Tue 7/16/13	Wed 6/26/13	Fri 6/28/13	0 days	-12 days
1.3.2. Scope	2 days	Wed 7/17/13	Thu 7/18/13	Wed 7/17/13	Thu 7/18/13	Mon 7/1/13	Tue 7/2/13	0 days	-12 days
1.3.3. Proposal	4 days	Fri 7/19/13	Wed 7/24/13	Fri 7/19/13	Wed 7/24/13	Wed 7/3/13	Mon 7/8/13	0 days	-12 days
1.3.4. Charter	1 day	Thu 7/25/13	Thu 7/25/13	Thu 7/25/13	Thu 7/25/13	Tue 7/9/13	Tue 7/9/13	0 days	-12 days
1.4. Conceptual Design	**11 days**	**Fri 7/26/13**	**Fri 8/9/13**	**Fri 7/26/13**	**Fri 8/9/13**	**Wed 7/10/13**	**Wed 7/24/13**	**0 days**	**-12 days**
1.4.1. Problem Definition Revised	1 day	Fri 7/26/13	Fri 7/26/13	Fri 7/26/13	Fri 7/26/13	Wed 7/10/13	Wed 7/10/13	0 days	-12 days
1.4.2. User Profiling	2 days	Mon 7/29/13	Tue 7/30/13	Mon 7/29/13	Tue 7/30/13	Thu 7/11/13	Fri 7/12/13	0 days	-12 days
1.4.3. Requirements Summary	4 days	Wed 7/31/13	Mon 8/5/13	Wed 7/31/13	Mon 8/5/13	Mon 7/15/13	Thu 7/18/13	0 days	-12 days
1.4.4. Functional Analysis	2 days	Tue 8/6/13	Wed 8/7/13	Tue 8/6/13	Wed 8/7/13	Fri 7/19/13	Mon 7/22/13	0 days	-12 days
1.4.5. Evaluation	2 days	Thu 8/8/13	Fri 8/9/13	Thu 8/8/13	Fri 8/9/13	Tue 7/23/13	Wed 7/24/13	0 days	-12 days
1.5. Preliminary System Design	**34 days**	**Mon 8/12/13**	**Thu 9/26/13**	**Mon 8/12/13**	**Thu 9/26/13**	**Thu 7/25/13**	**Tue 9/10/13**	**0 days**	**-12 days**
1.5.1. Brainstorm Options	7 days	Mon 8/12/13	Tue 8/20/13	Mon 8/12/13	Tue 8/20/13	Thu 7/25/13	Fri 8/2/13	0 days	-12 days
1.5.2. Design Alternatives	14 days	Wed 8/21/13	Mon 9/9/13	Wed 8/21/13	Mon 9/9/13	Mon 8/5/13	Thu 8/22/13	0 days	-12 days
1.5.3. Select Best Design	2 days	Tue 9/10/13	Wed 9/11/13	Tue 9/10/13	Wed 9/11/13	Fri 8/23/13	Mon 8/26/13	0 days	-12 days
1.5.4. Order Parts	4 days	Thu 9/12/13	Tue 9/17/13	Thu 9/12/13	Tue 9/17/13	Tue 8/27/13	Fri 8/30/13	0 days	-12 days
1.5.5. Build	5 days	Wed 9/18/13	Tue 9/24/13	Wed 9/18/13	Tue 9/24/13	Mon 9/2/13	Fri 9/6/13	0 days	-12 days
1.5.6. Recommendations for Improvement	2 days	Wed 9/25/13	Thu 9/26/13	Wed 9/25/13	Thu 9/26/13	Mon 9/9/13	Tue 9/10/13	0 days	-12 days
1.6. Detail Design & Development	**37 days**	**Fri 9/27/13**	**Mon 11/18/13**	**Fri 9/27/13**	**Mon 11/18/13**	**Wed 9/11/13**	**Thu 10/31/13**	**0 days**	**-12 days**
1.6.1. Interface Design	21 days	Fri 9/27/13	Fri 10/25/13	Fri 9/27/13	Fri 10/25/13	Wed 9/11/13	Wed 10/9/13	0 days	-12 days
1.6.2. Usability Testing	7 days	Mon 10/28/13	Tue 11/5/13	Mon 10/28/13	Tue 11/5/13	Thu 10/10/13	Fri 10/18/13	0 days	-12 days
1.6.3. Analyze Results	2 days	Wed 11/6/13	Thu 11/7/13	Wed 11/6/13	Thu 11/7/13	Mon 10/21/13	Tue 10/22/13	0 days	-12 days
1.6.4. Final Product	7 days	Fri 11/8/13	Mon 11/18/13	Fri 11/8/13	Mon 11/18/13	Wed 10/23/13	Thu 10/31/13	0 days	-12 days
1.7. T&E and Ver/Val	7 days	Tue 11/19/13	Wed 11/27/13	Tue 11/19/13	Wed 11/27/13	Fri 11/1/13	Mon 11/11/13	0 days	-12 days
1.8. Project Closure	**2 days**	**Thu 11/28/13**	**Fri 11/29/13**	**Thu 11/28/13**	**Fri 11/29/13**	**Thu 11/28/13**	**Fri 11/29/13**	**0 days**	**0 days**
1.8.1. Solution Documentation	2 days	Thu 11/28/13	Fri 11/29/13	Thu 11/28/13	Fri 11/29/13	Thu 11/28/13	Fri 11/29/13	0 days	0 days

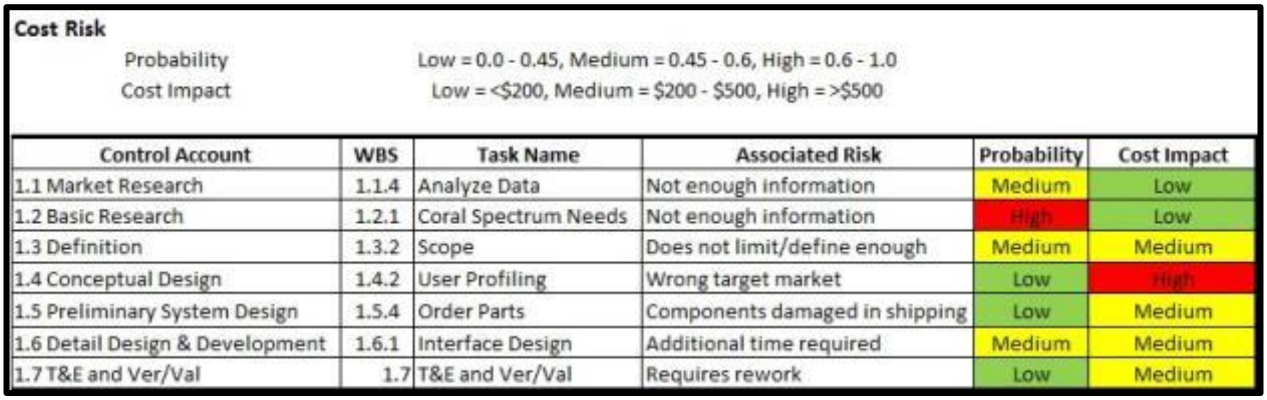
Risk Analysis

Three types of risks were analyzed: cost, schedule, and technical/performance. Based on the overall risk analysis, the majority of the project is medium to high risk, and little can be done to reduce or transfer the risk without affecting the cost and/or schedule. In order to reduce cost risk, additional time was allowed for research to ensure a solid design basis. This also helped reduced the schedule and technical/performance risk. However, most of the risk must be accepted.

Cost Risk

Table 7 depicts the costs risks to the project. The highest risk items were the results of the basic research (probability) and the conceptual design (cost impact). Although these had one component of high risk, the other component was low. The project definition and detail design and development both were medium for probability and cost impact. All of these items affect the scope, and scope creep is one of the most typical areas of cost increase. In order to mitigate the risk as much as possible, additional time was allowed for thorough research. However, not all risk can be mitigated, so some will have to be accepted.

Table 7: Cost Risks



Cost Risk

Probability Low = 0.0 - 0.45, Medium = 0.45 - 0.6, High = 0.6 - 1.0

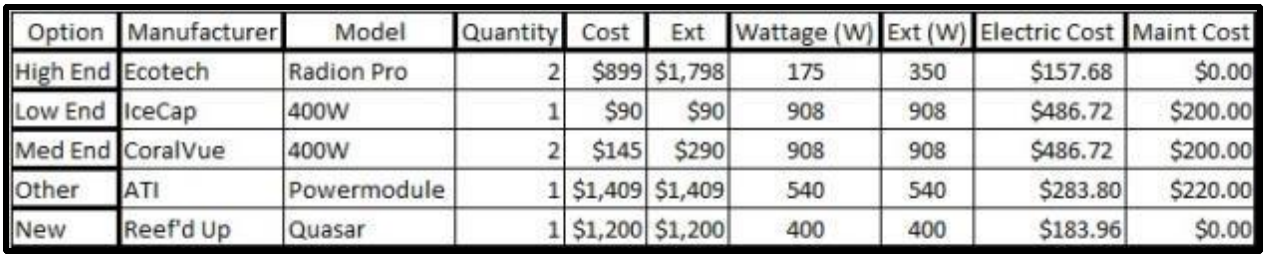
Cost Impact Low = <$200, Medium = $200 - $500, High = >$500

Control Account	WBS	Task Name	Associated Risk	Probability	Cost Impact
1.1 Market Research	1.1.4	Analyze Data	Not enough information	Medium	Low
1.2 Basic Research	1.2.1	Coral Spectrum Needs	Not enough information	High	Low
1.3 Definition	1.3.2	Scope	Does not limit/define enough	Medium	Medium
1.4 Conceptual Design	1.4.2	User Profiling	Wrong target market	Low	High
1.5 Preliminary System Design	1.5.4	Order Parts	Components damaged in shipping	Low	Medium
1.6 Detail Design & Development	1.6.1	Interface Design	Additional time required	Medium	Medium
1.7 T&E and Ver/Val	1.7	T&E and Ver/Val	Requires rework	Low	Medium

Another risk to cost was the cost effectiveness of the entire system. In order to be competitive, the LED lighting system has to have a threshold payback time of less than three years (per the requirements.) The options selected for this cost comparison (shown in Table 8) include the EcoTech Radion Pro, one of the leading LED lighting fixtures on the market for 2013, the ATI Powermodule, a high-end combination of T-5 lights and LEDs, the author's current metal halide system, and an upgrade to the author's metal halide system. The LED lighting fixture for this project was temporarily dubbed the "Quasar" for ease of comparison. The Quasar had an estimated payback of only 24 months, which met the threshold, as shown in Figure 8.

Each fixture had an initial purchase price (cost) (or overall budget for the project), a quantity required for the author's main display aquarium, an extended initial purchase price cost, the fixture wattage (ran at full power) to determine the yearly electrical cost. The maintenance cost is yearly and includes required bulb changes.

Table 8: Lighting Options Data



Option	Manufacturer	Model	Quantity	Cost	Ext	Wattage (W)	Ext (W)	Electric Cost	Maint Cost
High End	Ecotech	Radion Pro	2	$899	$1,798	175	350	$157.68	$0.00
Low End	IceCap	400W	1	$90	$90	908	908	$486.72	$200.00
Med End	CoralVue	400W	2	$145	$290	908	908	$486.72	$200.00
Other	ATI	Powermodule	1	$1,409	$1,409	540	540	$283.80	$220.00
New	Reef'd Up	Quasar	1	$1,200	$1,200	400	400	$183.96	$0.00

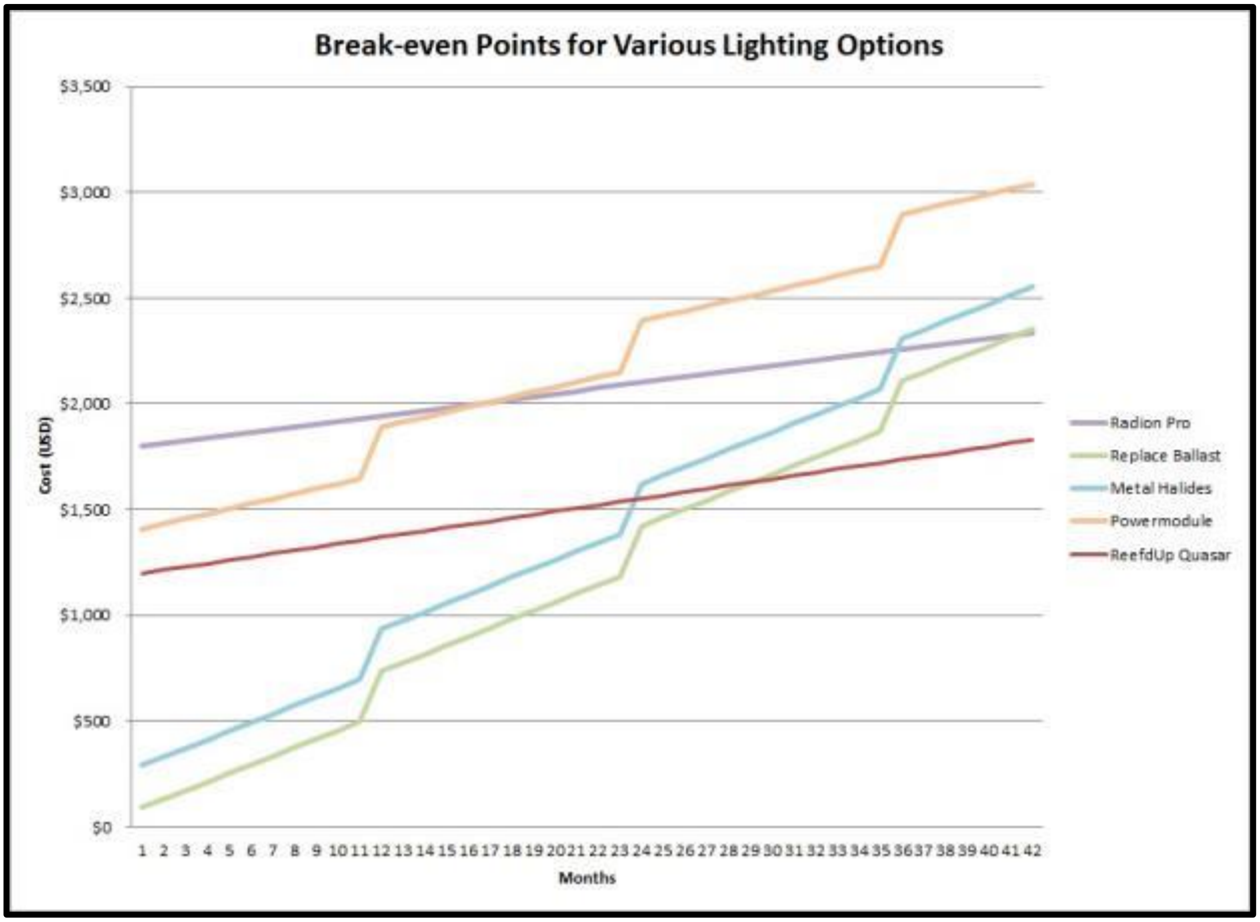
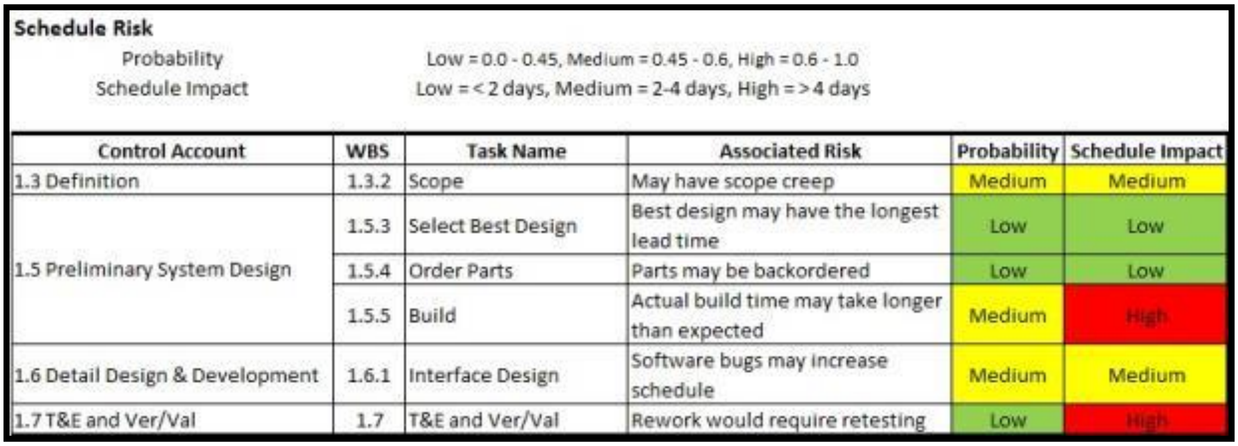


Figure 8: Break Even Points for Various Lighting Options

Schedule Risk

The schedule contains a fair amount of risk since nearly all items fall on the critical path (Table 9). Changes to the scope will affect the cost, as previously mentioned, but it will also have a medium schedule impact with medium probability. Of the highest concern is the build schedule. It is the item with the longest duration, has a medium probability, and it has a high schedule impact. In order to minimize the build duration, the author has contracted with several subject matter experts to provide assistance if required, but that option would increase the cost. Additionally, the software presents a medium probability of medium schedule impacts due to the non-commercial-off-the-shelf (COTS) code. If there is a mistake in the code, it is not easy to debug.

Table 9: Schedule Risks



Schedule Risk

Probability Low = 0.0 - 0.45, Medium = 0.45 - 0.6, High = 0.6 - 1.0

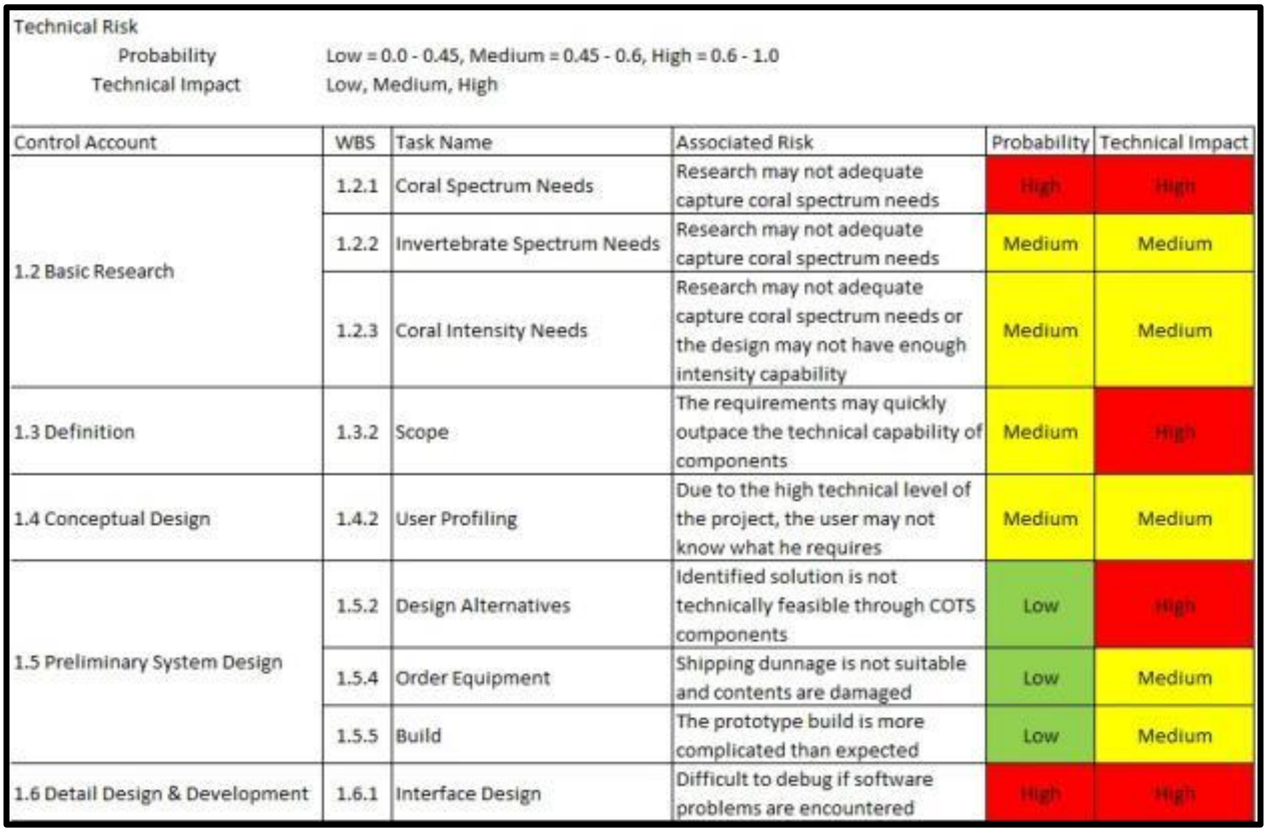
Schedule Impact Low = < 2 days, Medium = 2-4 days, High = > 4 days

Control Account	WBS	Task Name	Associated Risk	Probability	Schedule Impact
1.3 Definition	1.3.2	Scope	May have scope creep	Medium	Medium
1.5 Preliminary System Design	1.5.3	Select Best Design	Best design may have the longest lead time	Low	Low
	1.5.4	Order Parts	Parts may be backordered	Low	Low
	1.5.5	Build	Actual build time may take longer than expected	Medium	High
1.6 Detail Design & Development	1.6.1	Interface Design	Software bugs may increase schedule	Medium	Medium
1.7 T&E and Ver/Val	1.7	T&E and Ver/Val	Rework would require retesting	Low	High

Technical/Performance Risk

There is a significant amount of technical and performance risk to this project (Table 10) due to the limited availability of coral and other invertebrate photosynthetic research. These invertebrates vary widely in their requirements due to their geographic location (Great Barrier Reef, Indonesia, et cetera), the collection depth (light spectrum/intensity changes with depth), water turbidity (spectrum/intensity change with turbidity), species (not all species host the same symbiotic photosynthetic algae), and health history (past injury may cause the invertebrate to host the algae differently or even different species altogether.) Therefore, this item represents the highest risk due to probability and impact. Tying for the highest risk is the interface design. The LED fixture must interface with the Neptune Apex controller, which uses proprietary software. Although its software is somewhat intuitive, it is not easy to debug. The controller also controls two EcoTech MP-40 power heads, which simulate tidal effects, storms, lagoons, and other environmental conditions. The LED fixture must be able to tie in to the power heads to simulate the storms, sunrise/sunset, and other conditions simultaneously. To minimize the risk, several subject matter experts were identified that could assist, but this would influence the cost and schedule.

Table 10: Technical/Performance Risk



Technical Risk
Probability Low = 0.0 - 0.45, Medium = 0.45 - 0.6, High = 0.6 - 1.0
Technical Impact Low, Medium, High

Control Account	WBS	Task Name	Associated Risk	Probability	Technical Impact
1.2 Basic Research	1.2.1	Coral Spectrum Needs	Research may not adequate capture coral spectrum needs	High	High
	1.2.2	Invertebrate Spectrum Needs	Research may not adequate capture coral spectrum needs	Medium	Medium
	1.2.3	Coral Intensity Needs	Research may not adequate capture coral spectrum needs or the design may not have enough intensity capability	Medium	Medium
1.3 Definition	1.3.2	Scope	The requirements may quickly outpace the technical capability of components	Medium	High
1.4 Conceptual Design	1.4.2	User Profiling	Due to the high technical level of the project, the user may not know what he requires	Medium	Medium
1.5 Preliminary System Design	1.5.2	Design Alternatives	Identified solution is not technically feasible through COTS components	Low	High
	1.5.4	Order Equipment	Shipping dunnage is not suitable and contents are damaged	Low	Medium
	1.5.5	Build	The prototype build is more complicated than expected	Low	Medium
1.6 Detail Design & Development	1.6.1	Interface Design	Difficult to debug if software problems are encountered	High	High

Change Management and Control

All requests for project changes that lie outside of the approved project scope and deliverables must be submitted in writing to Reef'd Up Aquatics. Reef'd Up Aquatics will then evaluate the requested change and determine the impact to cost, schedule, and performance. If the change is approved, an amendment to the project scope will be issued along with a revised budget and schedule. The change in scope and/or deliverables will also be updated in the test and acceptance plan, if applicable.

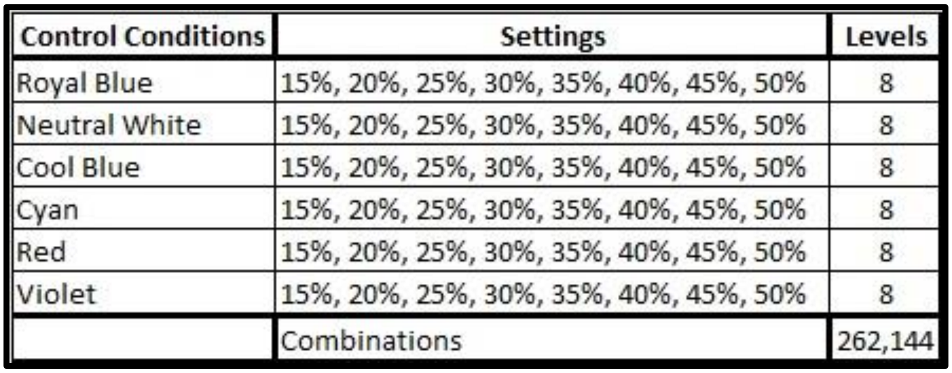
Test and Evaluation Methodology

Although the majority of test and evaluation will be performed in Phase 3 (outside the scope of ENM 590), the basic test methodology was developed. The objective of the test phase is to determine the optimal light spectrum(s) and intensity for invertebrate growth and color. The response variables (output) are mass growth and color. Mass growth is most easily determined subjectively (rating the growth rate) but is not accurate. Weighing the coral to determine mass growth is more accurate (objective test), but it involves removing the coral and killing it to weigh the skeletal mass. Initially a combination of the two tests was planned for use; however, a more representative measurement is to monitor the uptake of skeletal-building minerals. Expected consumption is resembles an exponential growth rate over time, but sudden changes in growth rates should be noticeable.

Color is also subjective and slightly objective to an extent. The basic coral pigments are visible to the human eye, so a rating system will be used to determine the quality of pigmentation display. Fluorescence is harder to observe with the human eye. Coral fluorescent proteins are excited at varying wavelengths and re-emit at others. The most fluorescent activity occurs when the coral is excited with blue light. However, very little fluorescence is noted without the use of a yellow filter to block the extraneous blue light from the viewer's eyes. In addition to coral growth and coloration, the photosynthetically active radiation (PAR), Lux, and Kelvin of the lighting beside each tested coral will be noted where possible.

Controllable factors for the experiments are extensive. Many factors affect coral growth and coloration (and many are likely still unknown). The most obvious controllable factors are the individual LED color strings (including royal blue, neutral white, cool blue, cyan/turquoise, red, and violet). The lowest setting for each color is 10% of the possible intensity (however, 15% is used to prevent inadvertent system shutoff due to low voltage). Due to coral acclimation to high light intensities, the highest intensity setting is limited to 50%. The number of combinations possible from these six control factors and eight levels is 262,144 (Table 11). Each test will take approximately two weeks to complete. At 262,144 combinations, a complete experiment would require several thousand years, which is not feasible.

Table 11: Controllable LED Component Combinations



Control Conditions	Settings	Levels
Royal Blue	15%, 20%, 25%, 30%, 35%, 40%, 45%, 50%	8
Neutral White	15%, 20%, 25%, 30%, 35%, 40%, 45%, 50%	8
Cool Blue	15%, 20%, 25%, 30%, 35%, 40%, 45%, 50%	8
Cyan	15%, 20%, 25%, 30%, 35%, 40%, 45%, 50%	8
Red	15%, 20%, 25%, 30%, 35%, 40%, 45%, 50%	8
Violet	15%, 20%, 25%, 30%, 35%, 40%, 45%, 50%	8
	Combinations	262,144

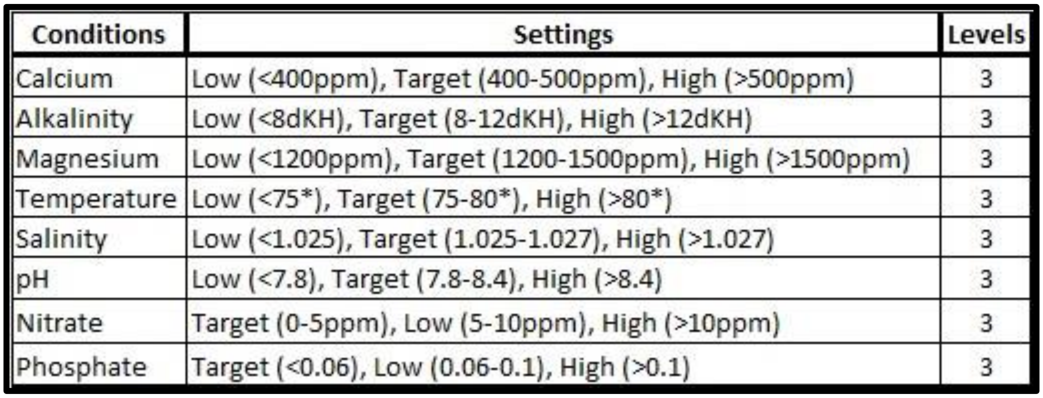
Instead, royal blue (RB) and neutral white (NW) are two separate factors. All other colors are combined into a third factor. The low level intensity is 15% and the high level is 30%. A high intensity of 50% is not used due to the acclimation time require from 15% to 50%. This results in a test matrix of only eight combinations (Table 12). With two weeks per test, a 16-week test run is feasible.

Table 12: Revised LED Component Combinations

Control Conditions	Settings	Levels
Royal Blue	15%, 30%	2
Neutral White	15%, 30%	2
Colors	15%, 30%	2
	Combinations	8

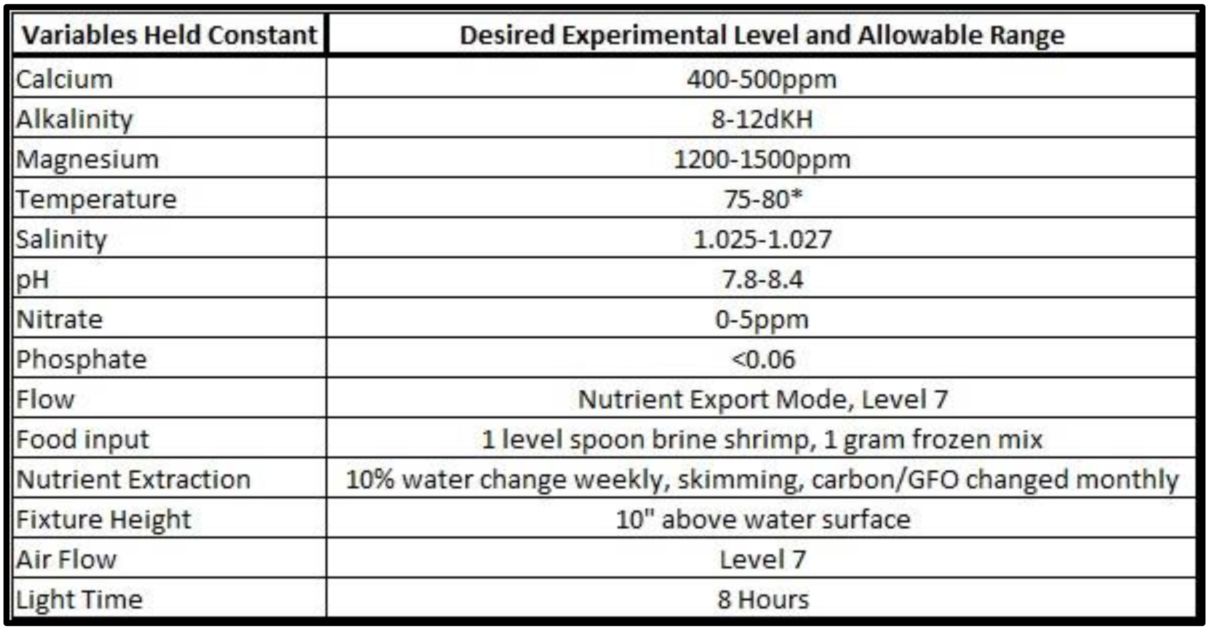
Other conditions are controllable, but they will be held as constant as possible for the duration of the tests (Table 13). A small target window will be allowed with most variables (Table 14). Corals cannot grow without alkalinity, magnesium, and calcium; therefore, a low range would inhibit their growth and negatively affect the test results if not quickly corrected. Although having other variables outside the "target" range is not ideal and can negatively affect the growth rates and/or coloration, their effects should be negligible compared to the effects of low alkalinity/magnesium/calcium.

Table 13: Controllable Constant Variables



Conditions	Settings	Levels
Calcium	Low (<400ppm), Target (400-500ppm), High (>500ppm)	3
Alkalinity	Low (<8dKH), Target (8-12dKH), High (>12dKH)	3
Magnesium	Low (<1200ppm), Target (1200-1500ppm), High (>1500ppm)	3
Temperature	Low (<75*), Target (75-80*), High (>80*)	3
Salinity	Low (<1.025), Target (1.025-1.027), High (>1.027)	3
pH	Low (<7.8), Target (7.8-8.4), High (>8.4)	3
Nitrate	Target (0-5ppm), Low (5-10ppm), High (>10ppm)	3
Phosphate	Target (<0.06), Low (0.06-0.1), High (>0.1)	3

Table 14: Constant Variables Experimental Levels



Variables Held Constant	Desired Experimental Level and Allowable Range
Calcium	400-500ppm
Alkalinity	8-12dKH
Magnesium	1200-1500ppm
Temperature	75-80*
Salinity	1.025-1.027
pH	7.8-8.4
Nitrate	0-5ppm
Phosphate	<0.06
Flow	Nutrient Export Mode, Level 7
Food input	1 level spoon brine shrimp, 1 gram frozen mix
Nutrient Extraction	10% water change weekly, skimming, carbon/GFO changed monthly
Fixture Height	10" above water surface
Air Flow	Level 7
Light Time	8 Hours

Food input can cause spikes in excess nutrient levels, so the amount and type of food is regulated. Each day a 0.1 gram sheet of seaweed (brown, red, or green) is provided. The nutritional analysis is 10.04% moisture, 46.32% protein, 3.9% fat, 1.9% fiber, and 9.17% ash. A 0.1 gram spoon of Brine Shrimp Direct Golden Pearl Reef & Larval Fish Diet (800-1000 micron size) is also fed, with a nutritional analysis of 50% crude protein, 18% crude fat, 15% crude ash, 2% fiber, 2% phosphorous, 15,000 IU/kg Vitamin A, 3,000 IU/kg Vitamin D, 350 ppm Vitamin E, 1,000 ppm Vitamin C, and 12 mg/g DHA. Its ingredients include hydrolyzed fish protein, crustacean meal, yeast, egg, soy, casein, fish oil, lecithin, cholesterol, vitamins and minerals, and antioxidants. Once each week, a 4.0-gram New Era tab is provided for grazing. Its nutritional analysis is 32% crude protein, 18% ash, 11% crude fat, 1.5% crude fiber, 23% moisture, 15,000 IU/kg Vitamin A, 2,000 IU/kg Vitamin D3, and 200 IU/kg Vitamin E. The ingredients are fish meal, dried seaweed meal, cornstarch, fish oil, krill, squid, mussel, shrimp, choline chloride, Vitamin A acetate, Cholecalciferol, dl-Alpha-Tocopherol acetate, Calcium-L-Ascorbyl-2-Monophosphate, Zinc Sulfate, Manganese Sulfate, Nicotinamide, Inositol, Copper Sulfate, d-Calcium Pantothenate, Ferrous Sulfate, Riboflavin, Calcium Iodate, Thiamine Mononitrate, Pyridoxine Hydrochloride, Menadione Sodium Bisulfite Complex, Folic Acid, Vitamin B12 Supplement, and Biotin.

Calcium, alkalinity, and magnesium are tested weekly with a Red Sea Reef Foundation Pro test kit (Figure 9). It is accurate to 5 ppm for calcium, 0.14 dKH (0.05 meq/l) for alkalinity, and 20 ppm for magnesium. (Red Sea, 2013) Calcium reagent lot numbers are 111 (part A), 191 (part B), and 331 (part C). The alkalinity reagent lot number is 321. The magnesium reagent lot numbers are 101 and 283 (part A), 303 and 531 (part B), and 141 and 953 (part C). (Bridges, 2013) These elements will be maintained within their target range using homemade additives. The recipe is located in APPENDIX D: Supplement Recipes. (Holmes-Farley, 2006)

Figure 9: Red Sea Reef Foundation Pro Test Kit

Temperature is measured nearly continuously with the Neptune AquaController Apex Temperature Probe (permanently calibrated and National Institute of Standards and Technology (NIST) certified) (Figure 10). The temperature is regulated with the Apex through a 300 W and a 400 W heater. If the temperature range exceeds predetermined limits, an audible warning will sound and the author will receive a warning text message and email (Figure 11).

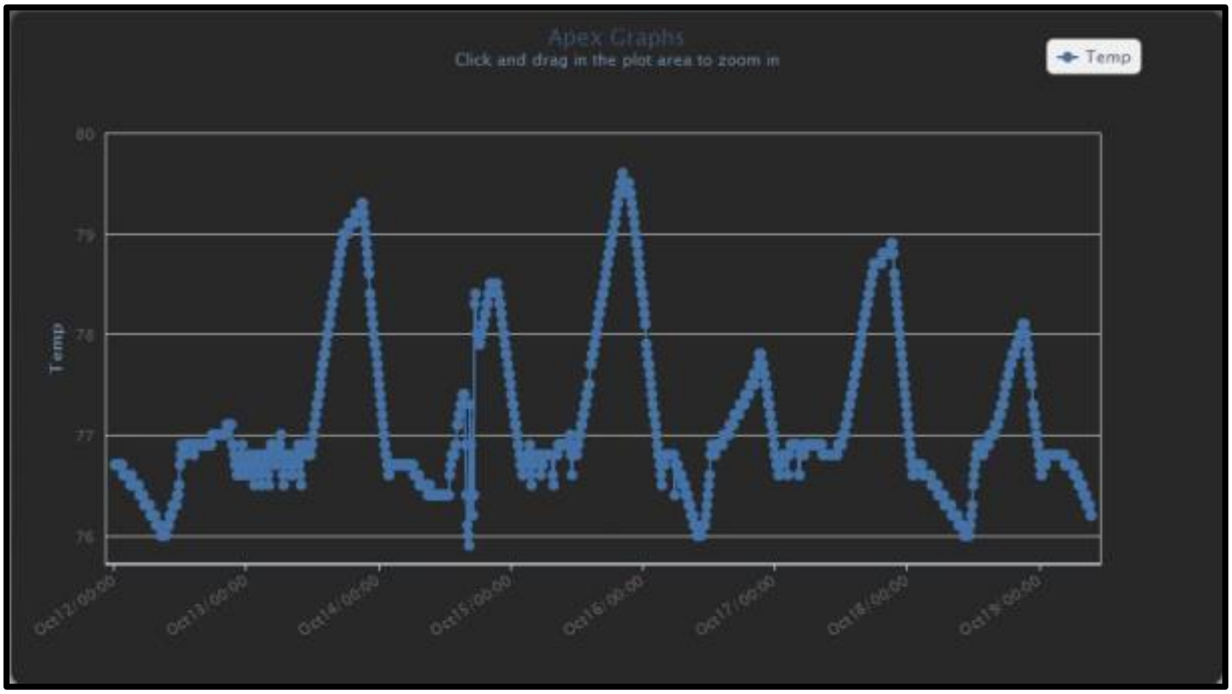
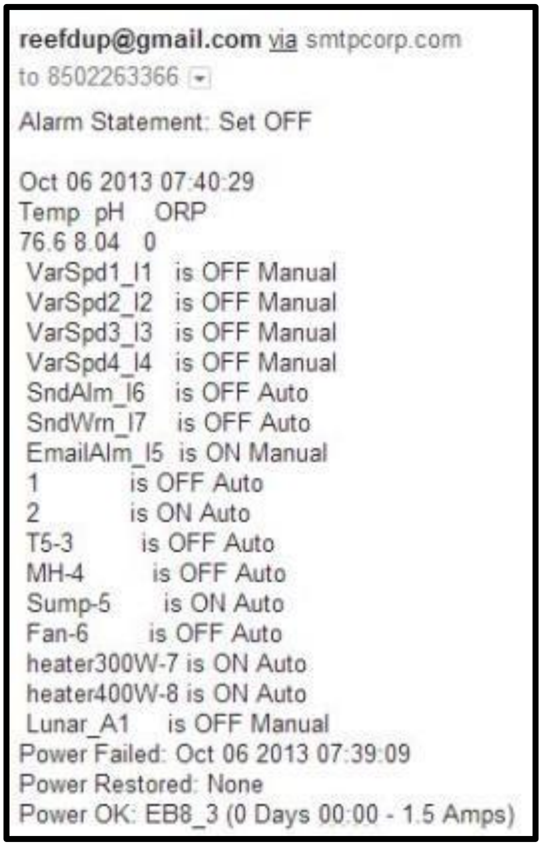


Figure 10: Temperature Monitoring via Neptune Apex



```
reefdup@gmail.com via smtpcorp.com
to 8502263366
Alarm Statement: Set OFF

Oct 06 2013 07:40:29
Temp  pH    ORP
76.6 8.04   0
 VarSpd1_I1   is OFF Manual
 VarSpd2_I2   is OFF Manual
 VarSpd3_I3   is OFF Manual
 VarSpd4_I4   is OFF Manual
 SndAlm_I6    is OFF Auto
 SndWrn_I7    is OFF Auto
 EmailAlm_I5  is ON Manual
 1            is OFF Auto
 2            is ON Auto
 T5-3         is OFF Auto
 MH-4         is OFF Auto
 Sump-5       is ON Auto
 Fan-6        is OFF Auto
 heater300W-7 is ON Auto
 heater400W-8 is ON Auto
 Lunar_A1     is OFF Manual
Power Failed: Oct 06 2013 07:39:09
Power Restored: None
Power OK: EB8_3 (0 Days 00:00 - 1.5 Amps)
```

Figure 11: Neptune Apex Warning Email Example

The Neptune Apex pH Probe will nearly continuously monitor pH and is accurate to 0.1 (Figure 12). However, it must be calibrated every six months with calibration fluid at 7.0 and 10.0 pH. If the measured pH range exceeds predetermined limits, an audible warning will sound and the author will receive a warning text message and email (Figure 11).

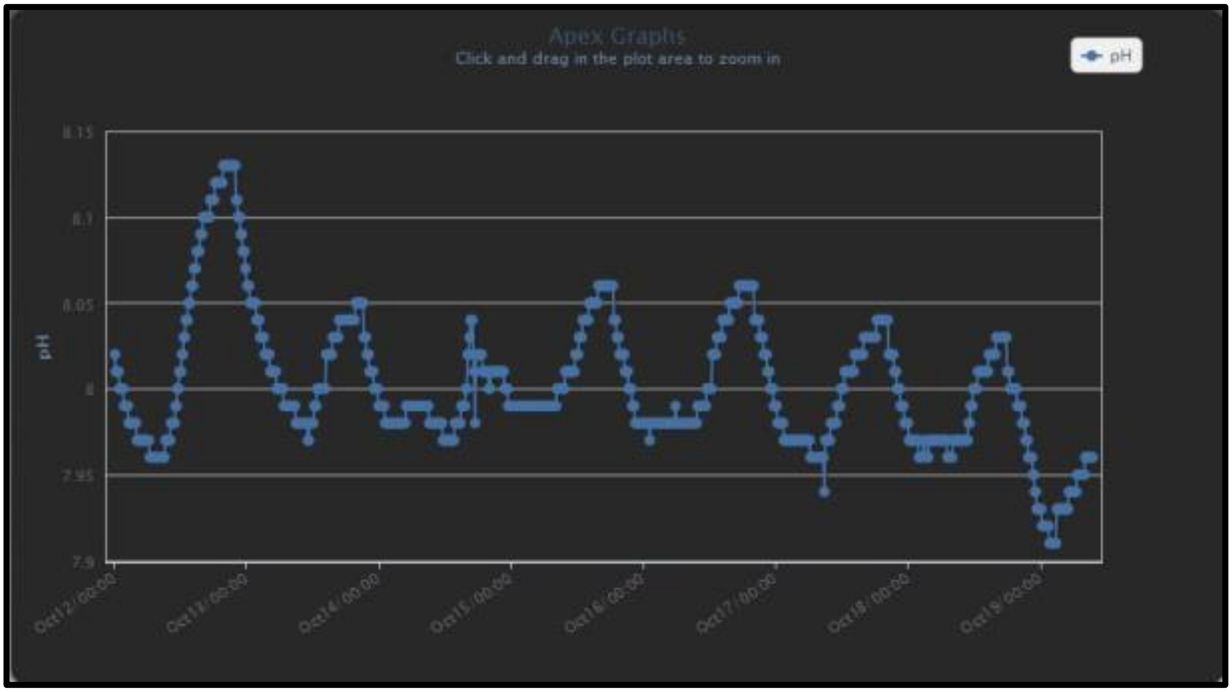


Figure 12: pH Monitoring via Neptune Apex

Salinity (measured in parts per thousand, ppt) or the specific gravity (measured as a ratio to pure water) is monitored during weekly testing with a Premium Blue Refractometer, RHS-10ATC (Figure 13). This refractometer is accurate to ±0.001 on the specific gravity scale. Calibration occurs weekly with zero total dissolved solids (TDS) reverse osmosis deionized (RO/DI) water. Proper salinity is maintained through the replacement of evaporated water with RO/DI water regulated with an automatic top-off system (homemade). Water changes (saltwater replacement) are performed weekly with RO/DI water and SeaChem Reef Salt mixed to the target salinity range.

Figure 13: Premium Blue Refractomer RHS-10ATC

Nitrate and phosphate testing occurs with a handheld Hanna Instruments meter (Figure 14). The Hanna Instruments 713 Phosphate Low Range Meter has a range of 0.00 to 2.50 parts per million (ppm), a resolution of 0.01 ppm, and is accurate to ±0.04 ppm or ±4% of the reading at 25 degrees Celsius. The reagent used is from lot number H059 and has an expiration date of 05/2016. Phosphate and nitrate levels are maintained through water changes, active skimming with a Reef Octopus Extreme 250, activated carbon in a media reactor, and granular ferric oxide in a media reactor. The activated carbon used is Bulk Reef Supply Rox 0.8, dosed at 20 tablespoons and changed monthly. The granular ferric oxide is Bulk Reef Supply, dosed at 25 tablespoons and changed monthly.

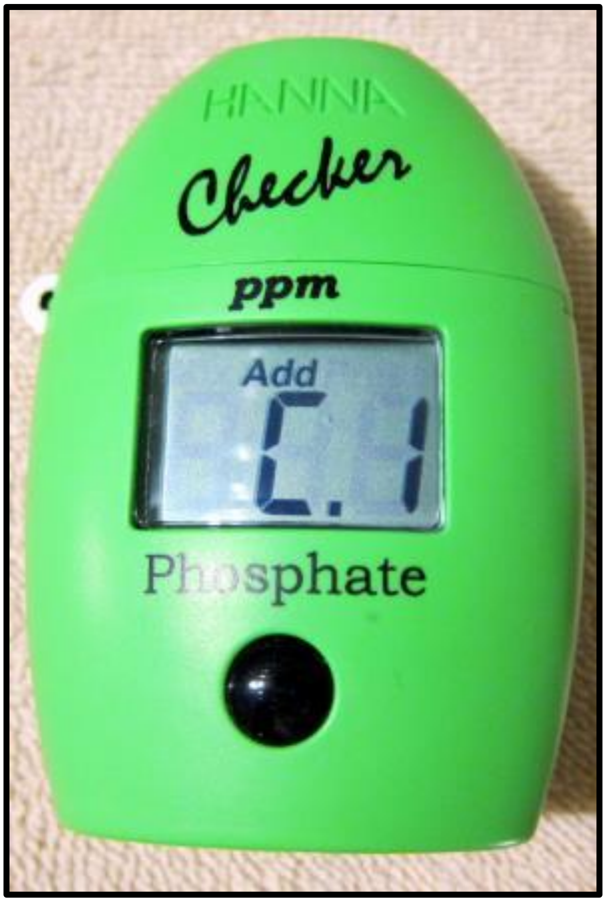


Figure 14: Hanna Phosphate Meter (Low-Range)

Free ammonia (NH3) and ammonium (NH4) are tested with the Seneye Reef Monitor (Figure 15). The range for NH3 is 0.000 to 0.500 ppm, and the resolution is 0.001 ppm. The accuracy is 0.005 ppm. Unfortunately, the accuracy of NH4 is not provided by the manufacturer. Regardless, NH4 is of little concern in a reef aquarium as it is a non-toxic salt, and its impacts are negated by higher pH systems.

Figure 15: Seneye Reef Monitor

Uncontrolled variables include the room lighting, sunlight exposure, unexpected livestock death and decay, and equipment failures. Artificial room lighting should have little to no impact on coral health or growth due to the low intensity. Sunlight exposure through uncovered windows could cause some coral bleaching due to excessive red light, or it could even wash out the LED intensity and cause the corals to turn brown (excessive population of the symbiotic algae, zooxanthallae.) Therefore, all windows in the room are covered with blinds that will be kept closed for the duration of the testing. Livestock death and subsequent decay could spike the ammonia, nitrite, nitrate, and phosphate levels. Depending on the level, the coral could bleach or turn brown. Therefore, ammonia and nitrite will be regularly tested (but uncontrolled) with a Seneye Reef Monitor (calibrated monthly). If they are detected, the test will be terminated. Lastly, equipment failures could result in diminished coral coloration or growth. For instance, if a skimmer pump quit, the corals may brown due to excessive nutrients. Or, if the chemical dosing pumps failed, the corals may stop growing due to limited minerals. Therefore, the equipment will be checked daily, and the chemicals will be tested weekly.

A three-factor design of experiment (DOE) results in the below matrix of eight tests (Table 15). The results of the tests (coral growth and coloration) will determine the main effects and interactions between the factors.

Table 15: Three-Factor Design of Experiments

	Run Order	RB	NW	Color	AxB	AxC	BxC	AxBxC
1	6	15	15	15	1	1	1	-1
2	8	15	15	30	1	-1	-1	1
3	1	15	30	15	-1	1	-1	1
4	4	15	30	30	-1	-1	1	-1
5	2	30	15	15	-1	-1	1	1
6	5	30	15	30	-1	1	-1	-1
7	3	30	30	15	1	-1	-1	-1
8	7	30	30	30	1	1	1	1

CHAPTER V – ANALYSIS AND RESULTS

Analysis

Environmental Analysis

Humidity

Exposed bodies of water evaporate toward equilibrium, and aquariums are no different. In humid environments (such as Florida), the excess humidity from an aquarium can cause mildew and rust problems. In dry environments (such as Utah), the humidity can be a welcome addition in a home. Regardless of the external environment, the evaporation from an aquarium can cause electrical problems in a lighting system if the airflow exchange rate is not sufficiently high. (Bridges, 2013)

Salt Creep

Salt creep is what results when water splashed out of the aquarium evaporates and leaves behind a trail of salt. Over time without good housekeeping, these salt deposits can grow quite extensive and infiltrate nearly every crack. It will corrode electrical components, fasteners, and damage unprotected light bulbs. Electrical and lighting components must be shielded, and all metals should be corrosion-resistant. (Bridges, 2013)

Temperature

Most reef aquariums are kept around 74-80 degrees Fahrenheit; operation outside this temperature range can have devastating results, to include coral bleaching and fish respiration difficulty. Metal halides are notorious for their heat output and usually require a chiller to counteract their output. This heat generation can also decrease the life of surrounding equipment. A lighting system should have a minimized heat output to keep the water temperature as stable as possible. Most LEDs have a maximum efficient temperature rating of only 120 degrees Fahrenheit and require a heat sink with a fan to maintain this temperature. (Bridges, 2013)

Intensity Analysis

Wattage per Surface Area

The amount of light that corals can receive is typically measured as photosynthetically available radiation and is measured in micromoles per square meter per second (μmol/m^2/s). Photosynthetically usable radiation (PUR) is a more valuable characteristic since it measures the intensity at the correct spectrum, but it is more expensive and difficult to measure, so it will not be included in this analysis. Coral needs vary by the individual coral species (various species host various zooxanthallae species and pigments), the coral's native location (Great Barrier Reef, Indonesia, et cetera), the coral's native depth (where it settled initially before collection), water turbidity (high turbulence can scatter light while calm waters allow greater penetration), and even the coral's health history. Therefore, even though basic PAR requirements are known for most coral species and can be measured, there is no guarantee that the coral will respond as expected. Additionally, PAR meters cost several hundred dollars for the entry-level models, which most hobbyists cannot afford. (Bridges, 2013)

In order to bridge this knowledge gap, a few "rules of thumb" were developed or modified. "Watts per gallon" was a standard entry-level guide for other lighting systems, and the recommendation was approximately three to five watts of lighting per gallon of the aquarium. Since light intensity and spectrum decreases with depth, the "watts per gallon" recommendation was imperfect at best. The "wattage per surface area" is no different. It simply provides a correlation where lighting wattage may affect aquarium health. Additionally, the starting parameter was determined by a survey with respondents from a wide range of experience levels. Although the baseline "wattage per surface area" is a starting point, the author has verified that it is a sufficient baseline to successfully grow SPS. (Bridges, 2013)

In order to determine a suitable baseline for "watts per surface area", a survey was created and placed on several online saltwater aquarium hobbyist forums, including the Wasatch Marine Aquarium Society, Reef Central, and Nano-Reefs. Each respondent was asked for their aquarium dimensions and their lighting wattage. The average respondent (n=85) had a "watts per surface area" of 0.22 for an LED system (Figure 16). This is much lower than for a typical metal halide system (0.4-1.0), which is reasonable, as LED systems are more efficient in their output for the wattage they consume. (Bridges, 2013)

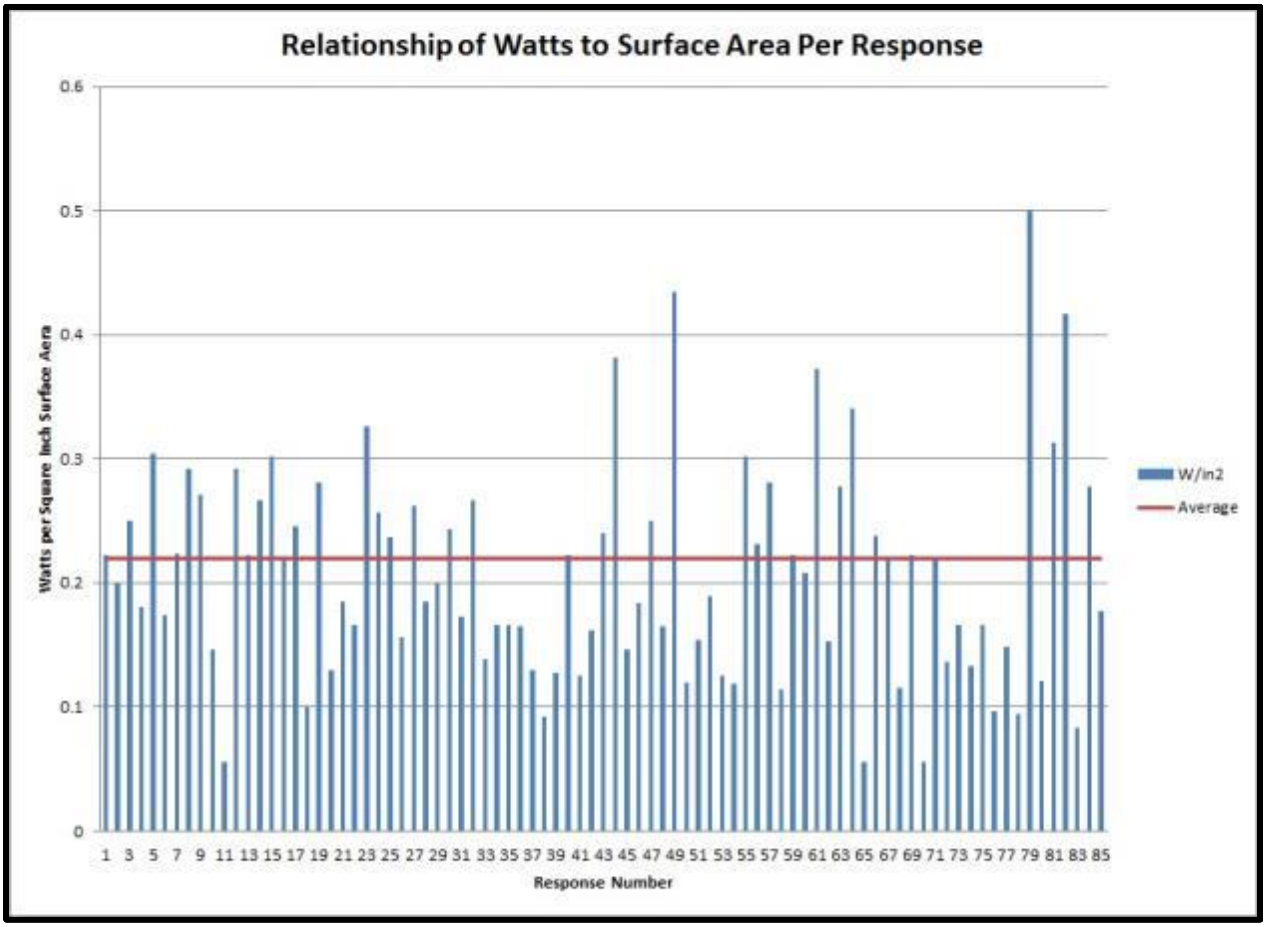


Figure 16: Watts to Surface Area Survey Response

Therefore, the "watts recommended" for an LED system can be determined:

$$SA = L * W$$

Where:

SA = Surface Area
L = Length
W = Width

$$WR = 3 * (CF * \sqrt{SA})$$

Where:

WR = Watts Recommended
CF = Conversion Factor (12 in^2)

Wattage per Depth

As previously mentioned, coral PAR requirements vastly differ due to numerous variables. However, certain species and groups of coral have similar saturation and photoinhibition points, which will allow wattage groupings. Saturation is essentially level of light required for optimal photosynthesis. Photoinhibition is beyond the saturation point, where light levels may be harmful. (Riddle, 2007)

Large polyp Scleractinian coral tolerate around 110-350 μmol/m^2/s, saturation and photoinhibition, respectively. Small polyp Scleractinian coral vary widely, but they generally have a safe point between 275-400 μmol/m^2/s, but some species' photoinhibition point may be up to 700 μmol/m^2/s or as low as 250 μmol/m^2/s. Soft corals have saturation and photoinhibition points around 200-400 μmol/m^2/s, respectively. Clams appear to have no known saturation or photoinhibition points. (Riddle, 2007)

With these light intensity variations in groups of coral, it is best to view an aquarium as a more compact version of the ocean. Light intensity on the sand bed should be 100-150 μmol/m^2/s, 150-300 μmol/m^2/s halfway up, and 300-400 μmol/m^2/s in the usable upper-half portion of the tank. (Bridges, 2013)

Optics Analysis

Most three-watt LED chips are manufactured with a 120-degree spread (60-degrees to each side), which is sufficient for most shallow tanks (under 24 inches deep). A tank from 24-30 inches may find that 80-degree optics will help prevent shadows, but they may cause a spotlighting effect. Deeper tanks may use 60-degree or more acute angles to help focus the light. (Bridges, 2013)

Spectral Analysis

For the past few decades, the consensus amongst the reefkeeping community is that only blue and white bulbs are of a concern. Although white bulbs contain the full visible spectrum, the ratio of blue to white light nearly negated the full spectrum effects of the white light. The rationale was that red (and amber, yellow, green, et cetera) did not penetrate to coral collection depths in the ocean. However, most coral in the hobby are collected by free-divers, who manually remove the coral from its base with a chisel and hammer. Therefore, most of these coral were collected within 30 feet (9.14 meters) of water, which is within the full-spectrum wavelength penetration (Figure 17). (Bridges, 2013; Karpenko, 2012)

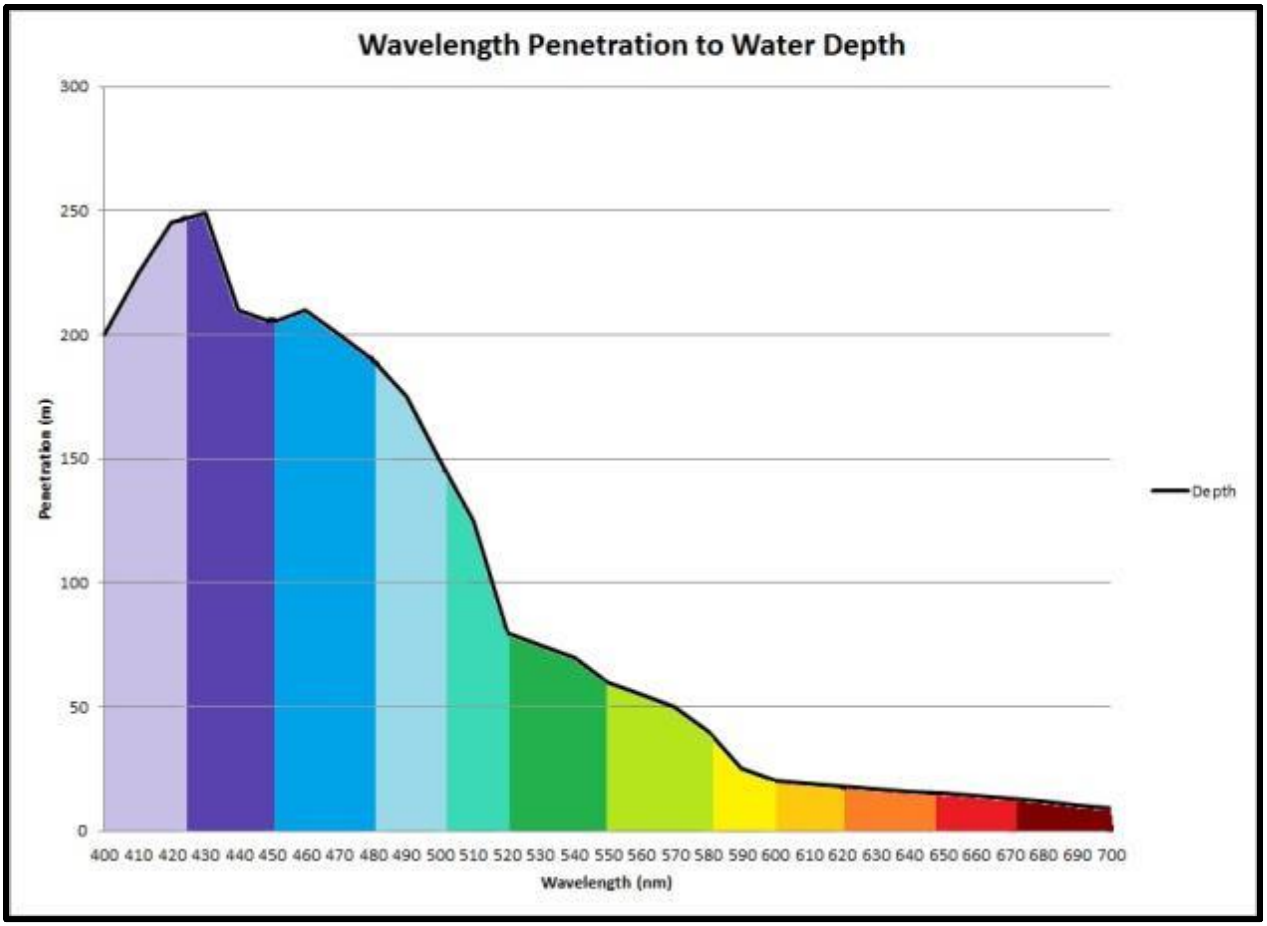


Figure 17: Wavelength Penetration to Water Depth
Source: Adapted from Karpenko, 2012

In addition to the spectrum the coral needs to survive and thrive, other spectrums are necessary for the aesthetic appeal. Coral fluorescence is important to many aquarists, and without the proper spectrum, the coral will not display its maximum coloration. Coral pigments can absorb light and reflect the light back in a longer wavelength as a form of luminescence. (Finet, 2005)

Infrared

Infrared wavelengths increase the temperature within the aquarium and are not known as part of the photosynthetically usable spectrum. Since a stable environment (including temperature) is ideal, it is recommended that wavelengths above 700 nm be excluded where possible. (Bridges, 2013)

Red Spectrum

The red portion of the visible light spectrum is one of the most debated wavelengths. Chlorophyll a (Chl a) is a photosynthetic pigment that has a major role in zooxanthallae, and it peaks around 685 nm. Corals also contain xanthophylls, a photoprotectant. However, these xanthophylls convert blue-spectrum light into non-radiant heat. Without a similar function for red-spectrum light, a coral may be overexposed and bleach. (Riddle, 2007) Therefore, the lighting should contain a dimmable red light source in order to provide the required red wavelength but prevent overexposure.

Yellow Spectrum

Although there are Yellow Fluorescent Proteins (YFP) that emit around 525-570 nm, they are quite uncommon and are not applicable. (Riddle, 2009)

Green Spectrum

Discosoma Red (DsRed) is one of the five major coral pigments, and it focuses its excitation and emission around 561 and 620 nm, respectively. (Riddle, 2009) Green Fluorescent Proteins (GFP) are the most numerous and are excited around 500 nm and emit around 510-520 nm. (Riddle, 2009)

Blue Spectrum

Cyan Fluorescent Proteins (CFP) excite around 450 nm and emit around 490 nm. (Riddle, 2009) This easily excited protein is a predominant reason behind the high actinic coloration of reef lighting, and it is likely a reason why full-spectrum LED systems are not in greater use.

Violet (and Ultraviolet) Spectrum

Blue Fluorescent Proteins absorb in UV (around 380 nm) and emit around 448 nm. (Cubitt, et al., 1999; Heim, et al., 1994) Violet/Blue excitation of 400-450 nm can emit cyan to green fluorescence of approximately 490-509 nm. (Gruber, et al., 2008)

Moon Phases

The moon has a 29.5-day cycle, is more red-shifted than sunlight, has an intensity under water of only approximately 0.5-1 μmol/m^2/s under a full moon, and drops to no intensity under a new moon. The moonlight spectrum is roughly composed of 55% red light, 30% green light, and 15% blue light. (Riddle, 2012) To simulate this effect, a 30-day cycle is easier to program into the LED controller. Cool blue light should ramp from 0-1% (off or on), green light from 0-2%, and red light from 0-4% over a 0-12 hour period each month. (Bridges, 2013)

Controllability Analysis

Dimming Function

LED dimming is controlled by two methods: pulse-width modulation (PWM) and analog. PWM provides more flexibility, but it is also more challenging to control and can cause an annoying flicker if not set to the appropriate frequency. Analog control is easier, but it can cause extraneous heat. (Bridges, 2013)

Channel Control

LEDs can be controlled on one or multiple channels, depending on the purpose. With multiple LED colors, each color can be individually controlled or grouped. The LEDs can also be controlled by location, but this will increase the amount of controller programming required. (Bridges, 2013)

Interoperability Analysis

Tidal Simulation

With a rudimentary moonlight cycle and a small water capacity, the tidal simulation capability is limited. Rather than programming a complex water movement cycle, variable rate power heads are sometimes preprogrammed. For instance, the EcoTech MP40 power head features (in addition to other programs) a “Tidal Swell Mode”. The flow starts in a left-to-right movement, calms down, switches to right-to-left flow, calms down, and then ends in a large surge (Figure 18). (EcoTech, 2013) The placement of these swells can be aligned with the moon cycle to reflect the higher tides around the full and new moon.

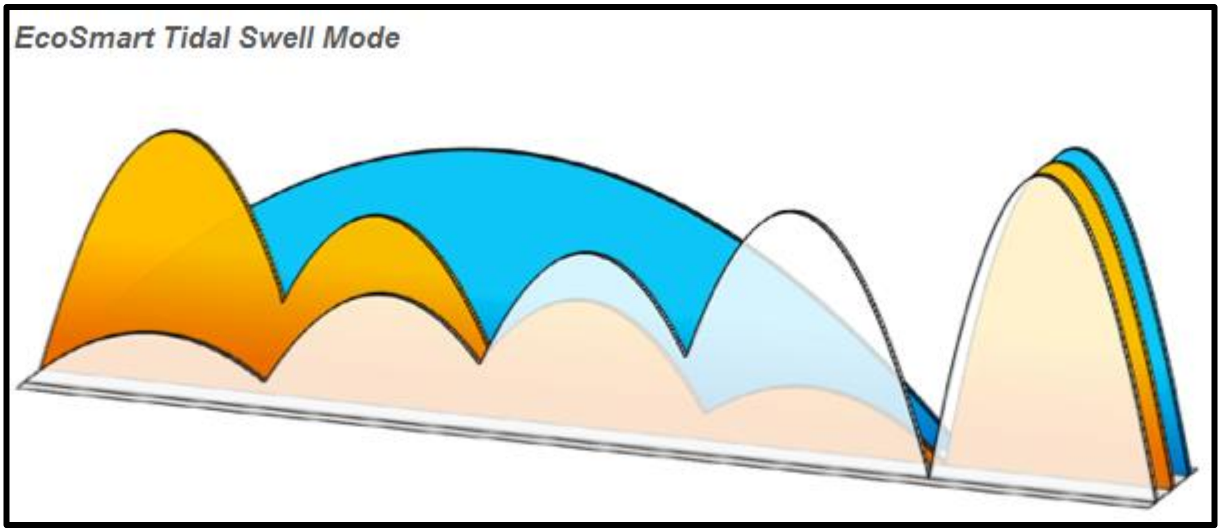


Figure 18: EcoTech MP40 Tidal Swell Mode
Source: EcoTech Marine, 2013

Weather Simulation

Although storms can leave negative lasting effects on a reef, they do help clean the area of trapped waste and debris. The same goes for an aquarium. Simulated cloud cover can provide coral photosynthesis relief, reduce cooling required, and save energy. LEDs and some drivers can produce simulated lightning effects (short bursts of high intensity light), but this is for no known purpose other than show. Combining cloud cover (and lightning effects if desired) with the EcoTech’s “Nutrient Transport Mode” through programming the controller will mimic the beneficial effects of storms (Figure 19). (EcoTech Marine, 2013)

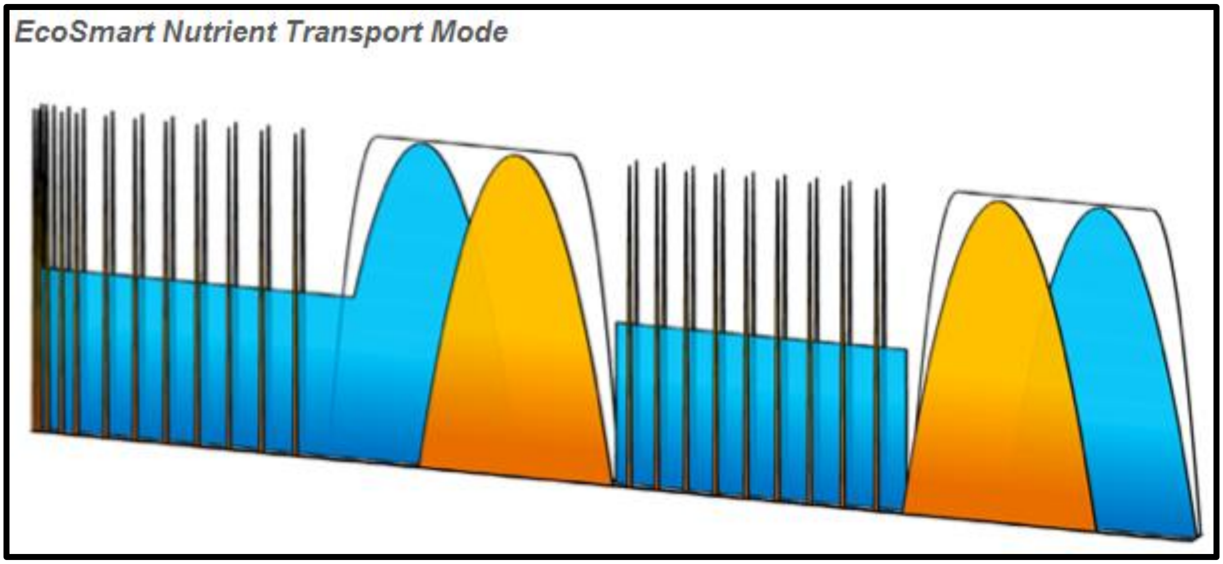


Figure 19: EcoTech MP40 Nutrient Transport Mode
Source: EcoTech Marine, 2013

Sunrise and Sunset Effects

The simplest simulation for sunrise and sunset is to simply dim the intensity across the spectrum used throughout the day. Aquarium lengths six feet and greater can simulate a true side-to-side sunrise and sunset effect, but this effect is lost on narrower tanks. (Bridges, 2013)

User Analysis

The aforementioned survey asked users why they chose LED lighting systems (Figure 20). The lack of heat produced and the low power consumption were the two most-cited reasons (16%). A long life expectancy (15%), low cost (14%), and color (11%) followed. High efficiency (6%), controllability (5%), and dimmability (4%) were other leading reasons. (Bridges, 2013)

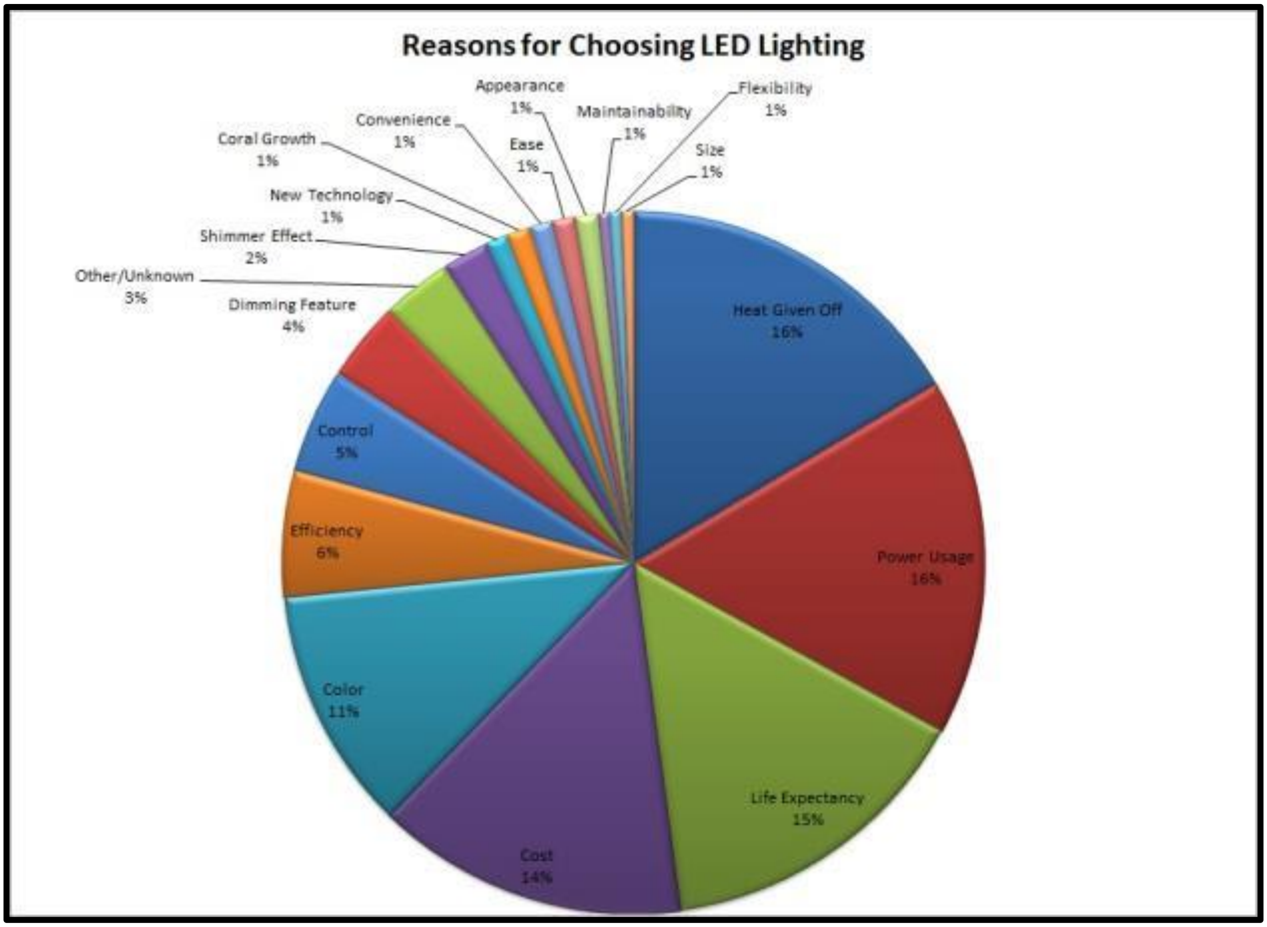


Figure 20: User Reasons for Choosing LED Lighting

Of a more technical nature is the light intensity and spectrum over each user's aquarium. Up until now, there has been very little correlation data between invertebrate health and LED fixture characteristics. Each user was asked for their tank dimensions and total lighting wattage. The aquarium surface area (length x width) was then calculated, and the total wattage was divided by the surface area. This is an imperfect characteristic as light intensity and spectrum quickly dissipate by depth. However, it is a start for correlations. The average user has 0.22 watts per square inch, but some users have as little as 0.05 and as high as 0.5 (Figure 21). The user with the highest wattage per square inch may have invertebrates with high photosynthetic demand while the user with the lowest may have invertebrates with nearly no photosynthetic demand. Without studying each aquarium's demand, it is difficult to develop a better correlation. However, the author has witnessed several healthy high-demand systems with approximately 0.22 watts per square inch, so this parameter is deemed feasible with some exceptions. Additionally, if this parameter is too high, then the light fixture can be dimmed to a more suitable number.

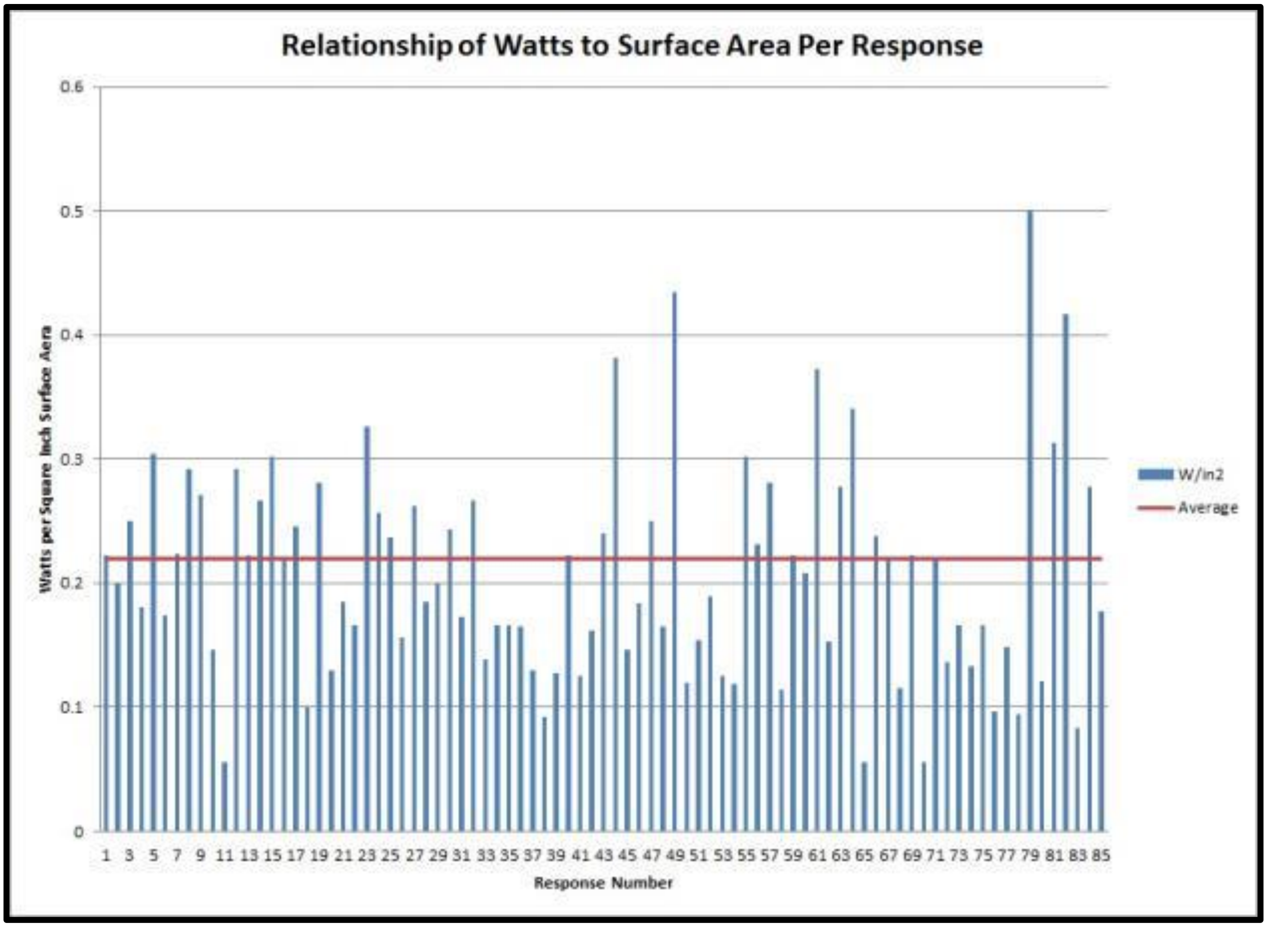


Figure 21: Relationship of Watts to Surface Area per Response

Out of 85 respondents, 29 respondents stated they had an adverse coral response to LEDs (although several responses sounded as though they did not understand the meaning of "adverse.") Nine reported a bleaching event. (A bleaching event is where a coral is stressed to the point where it releases its symbiotic photosynthetic algae (Figure 22).) Interestingly, those respondents who claimed their corals bleached after switching to LEDs had the same watts to surface area number, 0.22, on average as other users (Figure 23). This suggests another parameter may be at play, such as light spectrum. In fact, 66% of those who experienced a bleaching event used a full-spectrum light system.

Figure 22: A Bleached Coral (top) and Healing (bottom)

Increasing red light intensity and/or duration will cause corals to expel their symbiotic algae until they completely bleach. Photopigments within most coral do not absorb red wavelengths and have not developed protection against this exposure since approximately 40% of red wavelengths are attenuated within the first meter of water (Riddle, 2004). Therefore, it is possible that the users who reported bleaching may have exposed their coral to excess red light. However, red light does have a role in the captive reef environment as moonlight is composed of more red than blue wavelengths and may help signal vertebrate and invertebrate spawning (Riddle, 2012).

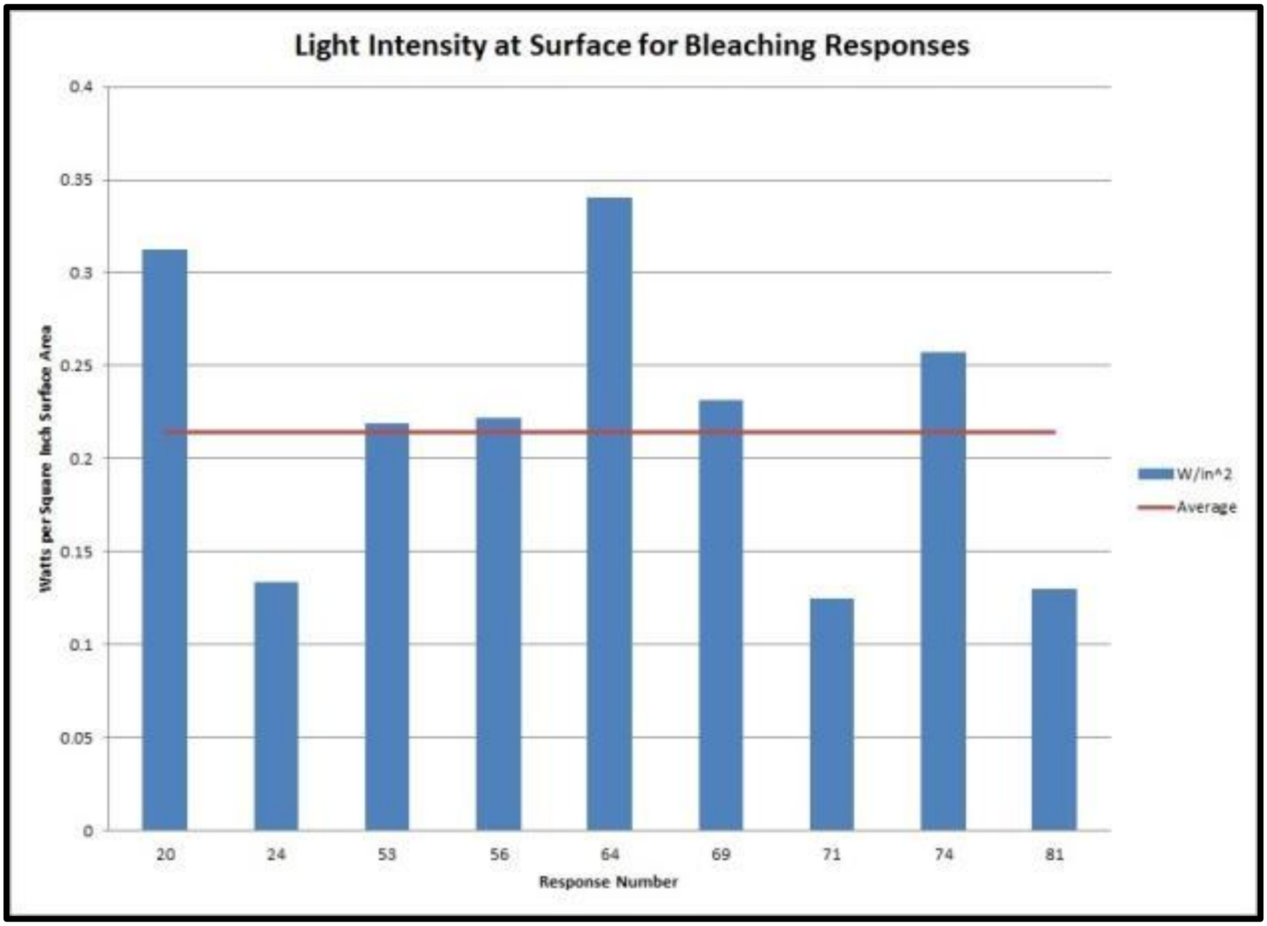


Figure 23: Light Intensity at Surface for Bleaching Responses

Requirements Analysis

<u>Goal A: Cost</u>
Objectives

A.1 The fixture shall reduce the electrical consumption from the lighting system by 50% from metal halide. This is traceable to user analysis.

A.2 The fixture shall have a reduced maintenance schedule of every five years compared to yearly of other systems. This is traceable to environmental and user analysis.

A.3 The fixture shall eliminate the requirement for active heat extraction (demonstrated by maintaining a constant set temperature, ±2 degree Fahrenheit) other than fan use. This is traceable to user analysis.

A.4 The fixture shall have a cost breakeven point of at most three years. This is traceable to user analysis.

<u>Goal B: Healthy Photosynthesis</u>
Objectives

B.1 The fixture shall provide adequate PAR for coral (to include various species of Montipora, Acropora, Favia, Acanthastrea, Scolymia, Acanthophyllia, Echinophyllia, et cetera), which is defined as a minimum of 100 PAR on the sandbed (approximately 30 inches below the water surface.) This is traceable to intensity analysis.

B.2 The fixture shall provide an adequate full-spectrum that closely replicates a various coral species' needs. With a lack of evidence, the sun's irradiance at various depths of water may be substituted. At a minimum, the light must be able to be varied for spectrum at 32.8 feet (10 meters), 65.6 feet (20 meters), and 98.4 feet (30 meters) for coastal waters (slightly turbulent). This is traceable to spectrum analysis.

B.3 The fixture shall not include any ultraviolet (UV) or infrared (IR) LEDs. These are defined for this project as less than 400 nanometers (UV) and greater than 700 nanometers (IR) peak. Detectable UV and IR shall be minimized. UV wavelengths shorter than 380 nm shall be shielded. This is traceable to spectrum analysis.

B.4 The fixture and individual LEDs shall be arranged to minimize the amount of shadows. This is traceable to intensity analysis.

Goal C: Control Parameters

Objectives

C.1 The fixture shall be dimmable, which means the user must be able to change the fixture's overall intensity, and the intensity of each individual color LED set, from 0-100% in 5% increments. This is traceable to intensity analysis, user analysis, spectrum analysis, and controllability analysis.

C.2 The fixture shall have a vast user-selectable color spectrum, through the use of dimmable LED combinations based on Objective C.1. This is traceable to user, spectrum, and controllability analysis.

C.3 The user shall be able to control the time (on/off) of the fixture locally or wirelessly through a distant computer, smartphone, and/or other electronically compatible device with an internet connection. This is traceable to user analysis.

C.4 The fixture shall be able to simulate the spectrum and phase (intensity) of the moon for a given location. This is traceable to spectrum, user, intensity, and controllability analysis.

C.5 The fixture shall be able to simulate a sunrise and sunset effect. This is traceable to user and interoperability analysis.

C.6 The fixture shall be able to simulate a cloudy day and increase water turbulence to mimic a storm. This is traceable to user and controllability analysis.

Preliminary System Design

The author's main display aquarium has a surface area of 1152 in^2, which requires at least 288 watts of LEDs, and results in a watts per surface area of 0.25 watts/in^2. This is slightly higher than the average watts per square inch in Figure 16, but the system is dimmable.

In addition to wattage, the color LED ratio will determine the spectrum. For every 14 LEDs, one red (660 nm) LED should be included. Two cool blue LEDs (475 nm) should accompany every five royal blue LEDs (450-455 nm). A cyan/turquoise LED (495 nm) should accompany every red LED. Two royal blue LEDs should match every one neutral white (4500 Kelvin) LED. A violet (430 nm) LED accompanies every four royal blue LEDs, and a violet (405 nm) accompanies every eight royal blue LEDs.

Lighting penetration is also of concern, so optics should be used for tank depths greater than 25 inches. 80-degree optics should be used for deeper tanks up to 30 inches deep. Deeper tanks, such as the author's 31 inch-deep tank should use 40-60 degree optics as well as higher wattage LEDs (such as 5W rather than the standard 3W).

Proper heat sink design is essential, as heat is one of the greatest enemies of electronics. Unfortunately, most easily available heat sinks do not provide specifications of thermal impedance or other characteristics. Instead, they provide a number of LEDs that the size heat sink can supposedly handle. This was used to determine a safety factor (SF), in addition to any that the heat sink manufacturer built in. Fans were not accounted for in the analysis, so the SF will only be improved with the use of fans.

$$SF = \frac{Watts\ the\ Heat\ Sink\ can\ Handle}{Watts\ Used}$$

Considered Designs

Two 18-inch Fixtures

The first design considered was two 6x18-inch heat sinks with 296 watts of LEDs (Figure 24). The LEDs used were in the following quantities:

- 24 x Royal Blue (450-455 nm), 5W each
- 16 x Neutral White (4500 K), 5W each
- 8 x Violet (420 nm), 3W each
- 8 x Cyan/Turquoise (495 nm), 3W each
- 8 x Red (660 nm), 3W each
- 8 x Cool Blue (475 nm), 3W each

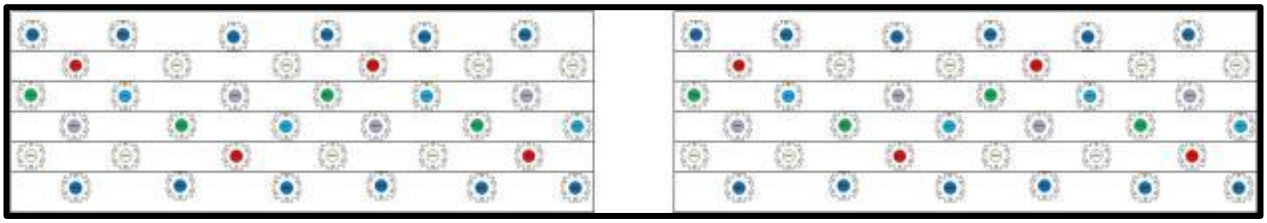


Figure 24: Two 6"x18" LED Fixtures

Depending on the LED source and heat sink design, the cost for this fixture design ranged from $693 to $713 (Table 16: **Bill of Materials for the Two 6"x18" Fixtures**Table 16). The higher-performance heat sink led to the higher cost, but its SF was only 1.01. The lower-performance heat sink could not handle this design since its SF was 0.44. Therefore, the $713 design was the only viable 18-inch option.

Table 16: Bill of Materials for the Two 6"x18" Fixtures

	Quantity	Cost Each	Extended	Source		Quantity	Cost Each	Extended	Source
Violet, 3W	8	$5.50	$44.00	RapidLed		$4.97	8	$39.76	LEDGroupBuy
Royal Blue, 5W	24	$4.00	$96.00	RapidLed		$3.25	24	$78.00	LEDGroupBuy
Blue, 3W	8	$4.25	$34.00	RapidLed		$3.60	8	$28.80	LEDGroupBuy
Cyan, 3W	8	$4.50	$36.00	RapidLed		$2.70	8	$21.60	LEDGroupBuy
Red, 3W	8	$3.50	$28.00	RapidLed		$3.50	8	$28.00	LEDGroupBuy
Neutral White, 5W	16	$5.00	$80.00	RapidLed		$3.70	16	$59.20	LEDGroupBuy
Heatsink	2	$74.88	$149.76	LEDGroupBuy		$37.05	2	$74.10	RapidLED
Fan	2	Incl		LEDGroupBuy		$10.00	2	$20.00	RapidLED
Splashguard		N/A				$3.00	2	$6.00	RapidLED
Hanging Kit		N/A					N/A		
Driver	7	$32.00	$224.00	RapidLed		$32.00	7	$224.00	RapidLED
Wiring	2	$5.75	$11.50	LEDGroupBuy		$5.75	2	$11.50	LEDGroupBuy
Thermal Grease	1	$10.00	$10.00	LEDGroupBuy		$10.00	1	$10.00	LEDGroupBuy
Lenses		Incl		RapidLed		$1.29	72	$92.88	LEDGroupBuy
		Total:	$713.26				Total:	$693.84	

Two 20-inch Fixtures

The second design considered was two 6x20-inch heat sinks with 300 watts of LEDs (Figure 25Figure 24). The LEDs used were in the following quantities:

- 28 x Royal Blue (450-455 nm), 5W each
- 14 x Neutral White (4500 K), 5W each
- 10 x Violet (420 nm), 3W each
- 6 x Cyan/Turquoise (495 nm), 3W each
- 6 x Red (660 nm), 3W each
- 8 x Cool Blue (475 nm), 3W each

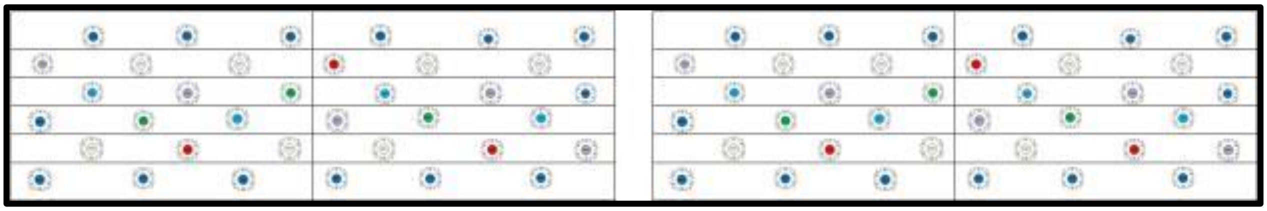


Figure 25: Two 6"x20" LED Fixtures

Depending on the LED source and heat sink design, the cost for this fixture design ranged from $651 to $753 (Table 16: **Bill of Materials for the Two 6"x18" Fixtures**Table 17). A high-end heat sink option was not available, so the SF was only 0.48. Therefore, this design was not feasible.

Table 17: Bill of Materials for Two 6"x20" Fixtures

	Quantity	Cost Each	Extended	Source		Quantity	Cost Each	Extended	Source
Violet, 3W	10	$5.50	$55.00	RapidLed		10	$4.97	$49.70	LEDGroupBuy
Royal Blue, 5W	28	$4.00	$112.00	RapidLed		28	$3.25	$91.00	LEDGroupBuy
Blue, 3W	8	$4.25	$34.00	RapidLed		8	$3.60	$28.80	LEDGroupBuy
Cyan, 3W	6	$4.50	$27.00	RapidLed		6	$2.70	$16.20	LEDGroupBuy
Red, 3W	6	$3.50	$21.00	RapidLed		6	$3.50	$21.00	LEDGroupBuy
Neutral White, 5W	14	$5.00	$70.00	RapidLed		14	$3.70	$51.80	LEDGroupBuy
Heatsink	2	$31.45	$62.90	LEDGroupBuy		2	$55.00	$110.00	RapidLED
Fan	4	$6.00	$24.00	LEDGroupBuy		4	$10.00	$40.00	RapidLED
Splashguard		N/A				2	$3.00	$6.00	RapidLED
Hanging Kit		N/A					N/A		
Driver	7	$32.00	$224.00	RapidLed		7	$32.00	$224.00	RapidLED
Wiring	2	$5.75	$11.50	LEDGroupBuy		2	$5.75	$11.50	LEDGroupBuy
Thermal Grease	1	$10.00	$10.00	LEDGroupBuy		1	$10.00	$10.00	LEDGroupBuy
Lenses		Incl		RapidLed		72	$1.29	$92.88	LEDGroupBuy
		Total:	$651.40				Total:	$752.88	

Two 24-inch Fixtures

The third design considered was two 6x24-inch heat sinks with 300 watts of LEDs (Figure 26Figure 24) in the same configuration as the second design in order to increase the SF. The LEDs used were in the following quantities:

- 28 x Royal Blue (450-455 nm), 5W each
- 14 x Neutral White (4500 K), 5W each
- 10 x Violet (420nm), 3W each
- 6 x Cyan/Turquoise (495 nm), 3W each
- 6 x Red (660 nm), 3W each
- 8 x Cool Blue (475 nm), 3W each

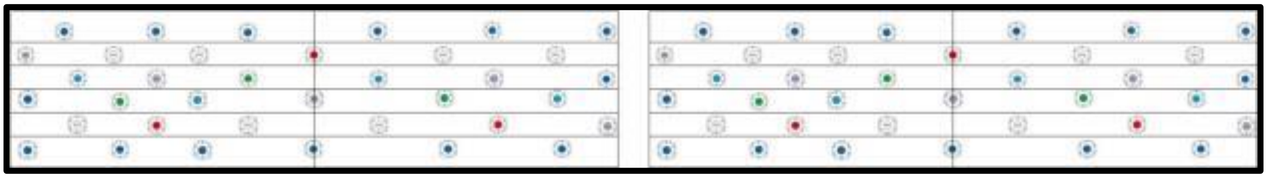


Figure 26: Two 6"x24" LED Fixtures

Depending on the LED source and heat sink design, the cost for this fixture design ranged from $760 to $764 (Table 16: **Bill of Materials for the Two 6"x18" Fixtures**Table 18). The higher-performance heat sink led to the slightly higher cost, and its safety factor was greatly improved to 1.33. The lower-performance heat sink could not handle this design since its SF was 0.58. Therefore, the $764 design was the only viable 24-inch option. However, a dual 24-inch fixture would cause interference with other equipment in the aquarium’s canopy, so this design was avoided to prevent further reconfigurations.

Table 18: Bill of Materials for 6"x24" LED Fixture

	Quantity	Cost Each	Extended	Source		Quantity	Cost Each	Extended	Source
Violet, 3W	10	$5.50	$55.00	RapidLed		10	$4.97	$49.70	LEDGroupBuy
Royal Blue, 5W	28	$4.00	$112.00	RapidLed		28	$3.25	$91.00	LEDGroupBuy
Blue, 3W	8	$4.25	$34.00	RapidLed		8	$3.60	$28.80	LEDGroupBuy
Cyan, 3W	6	$4.50	$27.00	RapidLed		6	$2.70	$16.20	LEDGroupBuy
Red, 3W	6	$3.50	$21.00	RapidLed		6	$3.50	$21.00	LEDGroupBuy
Neutral White, 5W	14	$5.00	$70.00	RapidLed		14	$3.70	$51.80	LEDGroupBuy
Heatsink	2	$99.84	$199.68	LEDGroupBuy		2	$58.75	$117.50	RapidLED
Fan	4	Incl		LEDGroupBuy		4	$10.00	$40.00	RapidLED
Splashguard		Incl		LEDGroupBuy		2	$3.00	$6.00	RapidLED
Hanging Kit		N/A					N/A		
Driver	7	$32.00	$224.00	RapidLed		7	$32.00	$224.00	RapidLED
Wiring	2	$5.75	$11.50	LEDGroupBuy		2	$5.75	$11.50	LEDGroupBuy
Thermal Grease	1	$10.00	$10.00	LEDGroupBuy		1	$10.00	$10.00	LEDGroupBuy
Lenses		Incl		RapidLed		72	$1.29	$92.88	LEDGroupBuy
		Total:	$764.18				Total:	$760.38	

Four 12-inch Fixtures

The fourth design considered was four 6x12-inch heat sinks with 312 watts of LEDs (Figure 27Figure 25Figure 24). The LEDs used were in the following quantities:

- 32 x Royal Blue (450-455 nm), 5W each
- 16 x Neutral White (4500 K), 5W each
- 8 x Violet (420 nm), 3W each
- 8 x Cool Blue (475 nm), 3W each
- 4 x Red (660 nm), 3W each
- 4 x Cyan/Turquoise (495 nm), 3W each

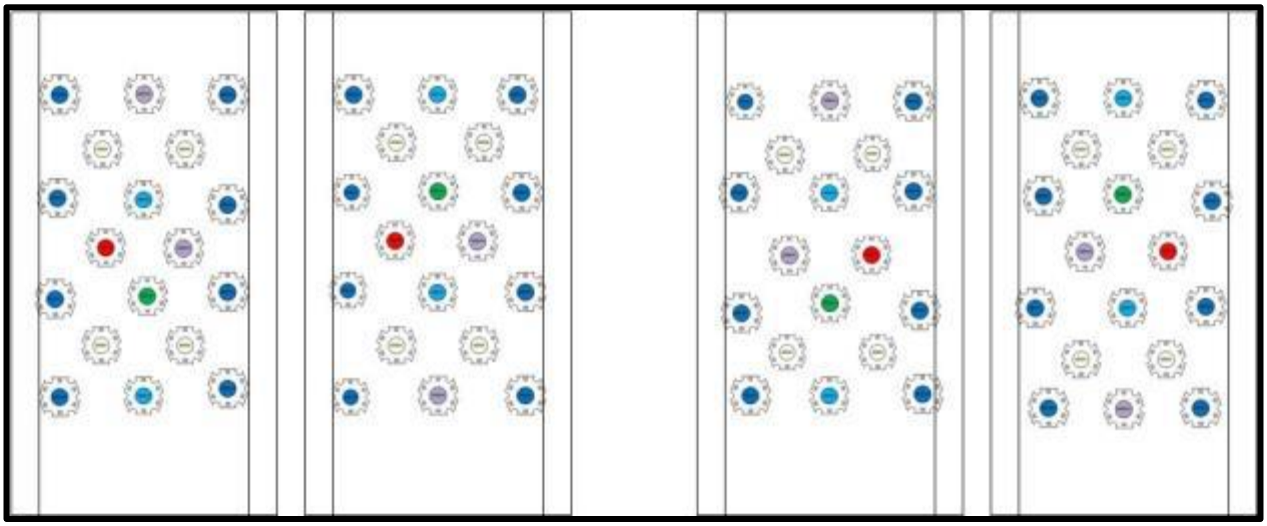


Figure 27: Four 6"x12" LED Fixtures

Depending on the LED source and heat sink design, the cost for this fixture design ranged from $737 to $795 (Table 16: **Bill of Materials for the Two 6"x18" Fixtures**Table 19). The higher-performance heat sink led to the higher cost, but its SF was 1.28. The lower-performance heat sink could not handle this design since its SF was 0.55. Therefore, the $795 design was the only viable 12-inch option.

Table 19: Bill of Materials for Four 6"x12" LED Fixtures

	Quantity	Cost Each	Extended	Source		Quantity	Cost Each	Extended	Source
Violet, 3W	8	$5.50	$44.00	RapidLed		8	$4.97	$39.76	LEDGroupBuy
Royal Blue, 5W	32	$4.00	$128.00	RapidLed		32	$3.25	$104.00	LEDGroupBuy
Blue, 3W	8	$4.25	$34.00	RapidLed		8	$3.60	$28.80	LEDGroupBuy
Cyan, 3W	4	$4.50	$18.00	RapidLed		4	$2.70	$10.80	LEDGroupBuy
Red, 3W	4	$3.50	$14.00	RapidLed		4	$3.50	$14.00	LEDGroupBuy
Neutral White, 5W	16	$5.00	$80.00	RapidLed		16	$3.70	$59.20	LEDGroupBuy
Heatsink	4	$25.35	$101.40	LEDGroupBuy		4	$49.92	$199.68	LEDGroupBuy
Fan	4	$6.00	$24.00	LEDGroupBuy		4	Incl		LEDGroupBuy
Splashguard		N/A				4	Incl		LEDGroupBuy
Hanging Kit	4	$12.00	$48.00	LEDGroupBuy			N/A		
Driver	7	$32.00	$224.00	RapidLed		7	$32.00	$224.00	LEDGroupBuy
Wiring	2	$5.75	$11.50	LEDGroupBuy		2	$5.75	$11.50	LEDGroupBuy
Thermal Grease	1	$10.00	$10.00	LEDGroupBuy		1	$10.00	$10.00	LEDGroupBuy
Lenses		Incl				72	$1.29	$92.88	LEDGroupBuy
		Total:	$736.90				Total:	$794.62	

With 60-degree optics on this fixture design, the aquarium should have sufficient light coverage with a peak intensity in the center of the tank (Figure 28 and Figure 29). To reduce the peak and increase the lighting along the perimeter of the tank, the fixtures could be spread further apart. However, this would increase the light spread outside of the tank, which is wasteful.

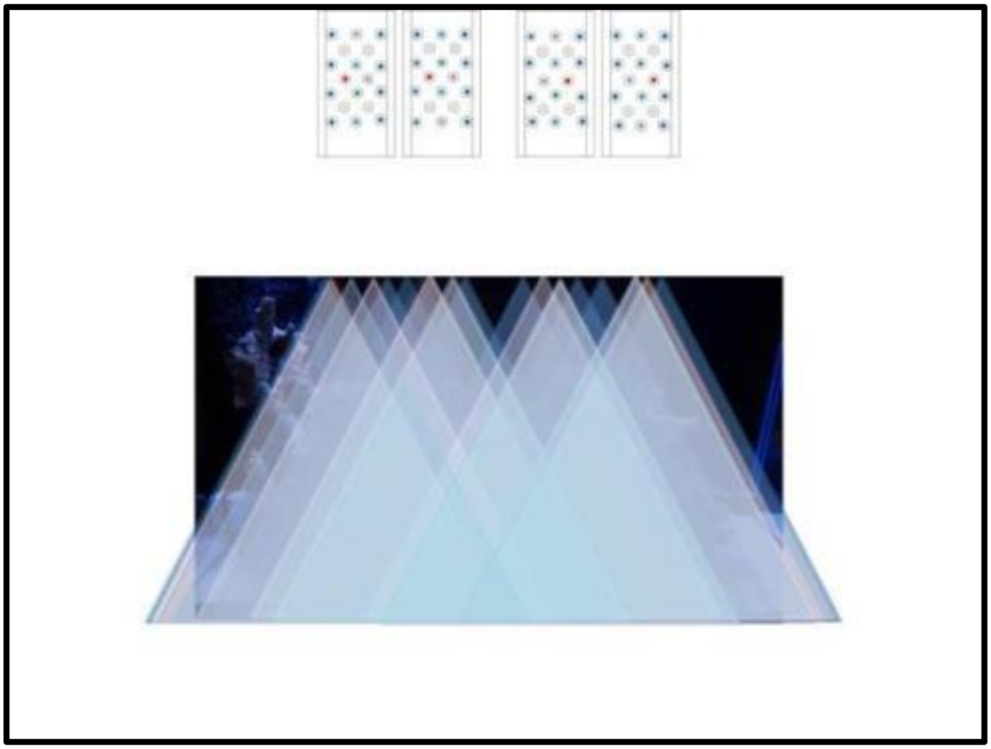


Figure 28: Light Coverage with 60 Degree Optics

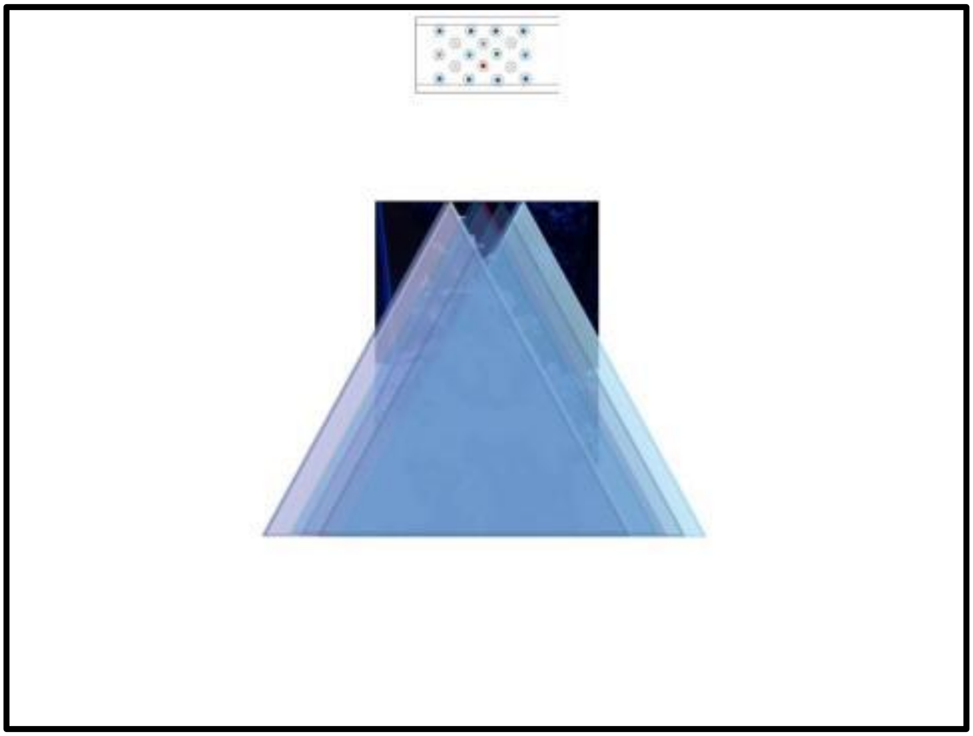


Figure 29: Light Coverage with 60 Degree Optics, Side View

Detail Design and Development

Detailed Interface Design

The LED lighting system interfaces with the Neptune Apex controller. As previously mentioned, the Apex uses proprietary software, but it is intuitive. Basic programs were developed and are located in APPENDIX F: Neptune Apex Code. This programming has a specified time when the individual LED strings (Neutral White, Royal Blue, et cetera) turn on and off. It also ramps the intensity throughout the day and night. If the temperature sensors in the aquarium get too hot, the Apex will turn the lights off but leave the fans on. If the aquarium gets too cold, it will turn the lights on as well as half the fans. It can also control the "storm" program where the EcoTech MP-40 power heads increase the water turbulence and create clouds/lightning with the LED fixture. It also simulates the sunrise/sunset feature of the LED system and can incorporate tidal patterns with the power heads.

Usability Testing

After the first build, the author tested each individual string of LEDs, combinations of LEDs, the intensity of the LED combinations, temperature variations, and controllability (see APPENDIX E: Fixture Build Documentation). The light fixture was initially dimmed over the aquarium at 15% and will be increased each week by 5% to meet the DOE. This intensity-ramping will occur during Phase 3, as corals and other invertebrates can take up to six months to adjust to their new surroundings.

Usability Test Participants and Location

The author and William Bridges (author's spouse) each individually tested the fixture, which is in operation on the author's 150-gallon main display aquarium, located in South Weber, Utah. Final test and evaluation will occur during Phase 3 over a six-month period.

Usability Results

The usability test and results will not be determined until Phase 3, which is outside the scope of this project. This is due to the long time that invertebrates take to produce a noticeable response to a change in their surroundings.

Results

Requirements Results

The new fixture uses 72 LEDs, and each individual LED is capable of running up to 3-5 watts. The fixture is currently consuming approximately 50 watts (not running at full capacity), including the fans, compared to almost 1000 watts of the previous metal halide fixture. However, the lack of heat output from the LEDs has caused the aquarium heaters to run more often, which raised the overall energy use. Figure 30 shows the current draw from both metal halides (on the left side) and LEDs (on the right side). Even with the heaters, the LED fixtures have an overall energy consumption 41% less than the metal halides. Therefore, the LED fixtures met Objective A.1.

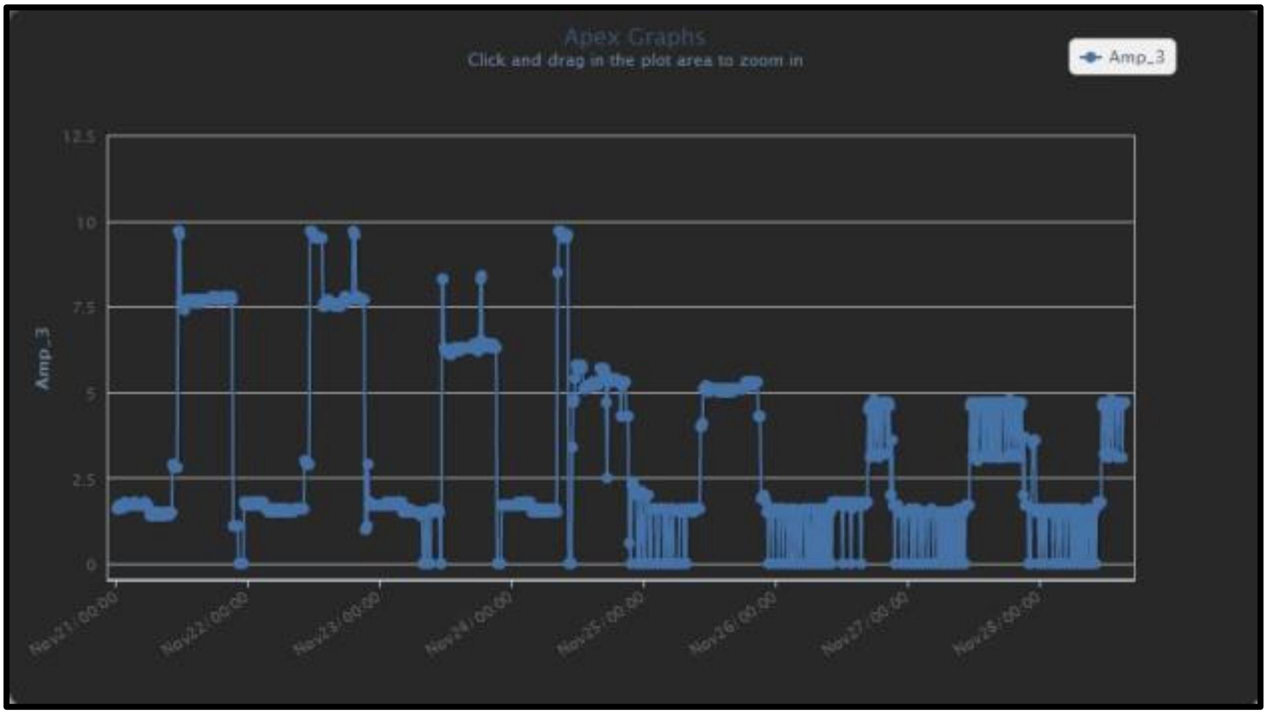


Figure 30: Current Draw from Metal Halides (Left) and LEDs (Right)

Objective A.2 required that the fixture have a reduced maintenance schedule to once every five years. LEDs have a life of 50,000 hours, and if they are run for eight hours each day, then their expected life is approximately 17 years. This gives a life safety factor of 3.42. The drivers are the highest risk, so additional fans were placed in the canopy to keep the drivers from overheating. Theoretically, Objective A.2 was met, although further testing is required.

Figure 31 shows the temperature variation over seven days, with the metal halide variation on the left and LED variation on the right. The sample standard deviation of the metal halide temperature was 0.53 degrees Fahrenheit while the sample standard deviation of the LEDs temperature was 0.15 degrees Fahrenheit. The metal halide system standard deviation is typically much greater in the summer since the ambient air temperature is warmer. Regardless, the LED system is influencing the aquariums temperature to within Objective A.3’s requirement.

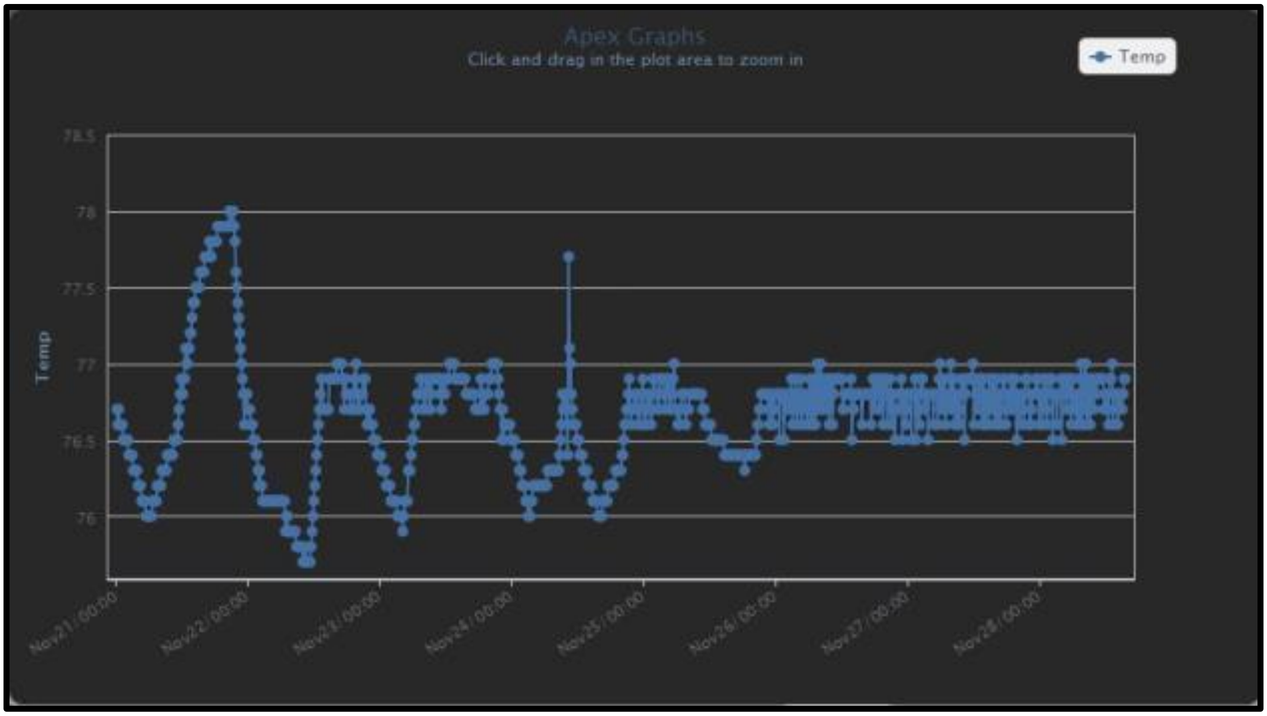


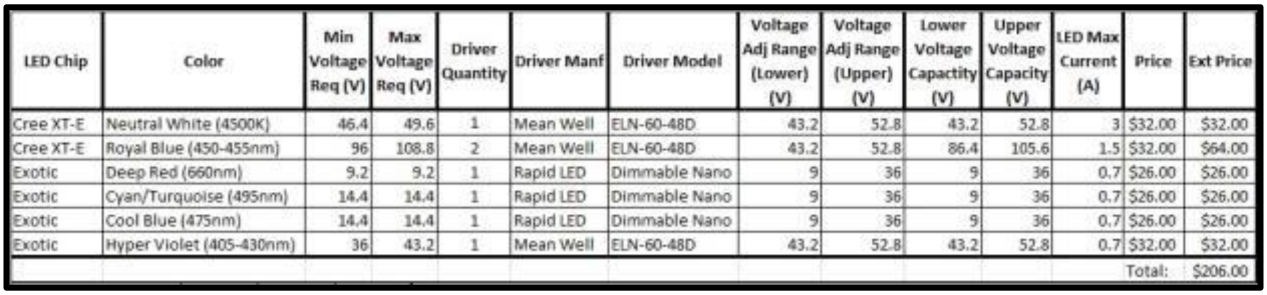
Figure 31: Temperature Variation with Metal Halides (Left) and LEDs (Right)

Actual LED lighting system costs came to a total of $1132.40. Table 20 shows a breakdown of the LED costs of $297.11, including spares. Driver costs are shown in Table 21, and miscellaneous supply costs are shown in Table 22. Driver costs were $206.00, and miscellaneous costs were $629.29. The total parts cost was $1132.40, which was 5.6% below the budget of $1200.00.

Table 20: LED Costs

LED Chip	Color	Power (W)	Current (A)	Max Current (A)	Forward Voltage (V)	Max Forward Voltage (V)	Power Total (W)	Quantity	Min Voltage Req (V)	Max Voltage Req (V)	Price	Spares	Total Order Quantity	Ext Price
Cree XT-E	Neutral White (5000K)	3	0.7	3	2.9	3.1	2.03	16	46.4	49.6	$3.52	2	18	$63.27
Cree XT-E	Royal Blue (450-455nm)	3	0.7	1.5	3	3.4	2.1	32	96	108.8	$3.09	3	36	$111.18
Exotic	Deep Red (660nm)	3	0.7	0.7	2.3	2.3	1.61	4	9.2	9.2	$2.24	1	6	$13.44
Exotic	Turquoise (495nm)	3	0.7	0.7	3.6	3.6	2.52	4	14.4	14.4	$2.70	1	6	$16.20
Exotic	Cool Blue (475nm)	3	0.7	0.7	3.6	3.6	2.52	4	14.4	14.4	$2.25	1	6	$13.50
Exotic	Hyper Violet (430nm)	3	0.7	0.7	3	3.6	2.1	8	24	28.8	$4.97	1	10	$49.70
Exotic	Hyper Violet (405nm)	3	0.7	0.7	3	3.6	2.1	4	12	14.4	$4.97	1	6	$29.82
													Total:	$297.11

Table 21: Driver Costs



LED Chip	Color	Min Voltage Req (V)	Max Voltage Req (V)	Driver Quantity	Driver Manf	Driver Model	Voltage Adj Range (Lower) (V)	Voltage Adj Range (Upper) (V)	Lower Voltage Capactity (V)	Upper Voltage Capacity (V)	LED Max Current (A)	Price	Ext Price
Cree XT-E	Neutral White (4500K)	46.4	49.6	1	Mean Well	ELN-60-48D	43.2	52.8	43.2	52.8	3	$32.00	$32.00
Cree XT-E	Royal Blue (450-455nm)	96	108.8	2	Mean Well	ELN-60-48D	43.2	52.8	86.4	105.6	1.5	$32.00	$64.00
Exotic	Deep Red (660nm)	9.2	9.2	1	Rapid LED	Dimmable Nano	9	36	9	36	0.7	$26.00	$26.00
Exotic	Cyan/Turquoise (495nm)	14.4	14.4	1	Rapid LED	Dimmable Nano	9	36	9	36	0.7	$26.00	$26.00
Exotic	Cool Blue (475nm)	14.4	14.4	1	Rapid LED	Dimmable Nano	9	36	9	36	0.7	$26.00	$26.00
Exotic	Hyper Violet (405-430nm)	36	43.2	1	Mean Well	ELN-60-48D	43.2	52.8	43.2	52.8	0.7	$32.00	$32.00
												Total:	$206.00

Table 22: Miscellaneous Supply Costs

Item	Quantity	Price	Ext Price
Neptune VDM	1	$99.95	$99.95
CAT 5e Cables	2	$19.27	$38.54
Power Cord	4	$3.00	$12.00
Terminal Strips	2	$3.14	$6.28
Heat Shrink Tubing	1	$15.73	$15.73
Heatsink (MakersLED)	4	$49.92	$199.68
Fan Power Supply	1	$19.50	$19.50
Fans	2	$10.00	$20.00
Thermal Adhesive	2	$6.99	$13.98
Black Stranded 24awg	3	$5.75	$17.25
White Stranded	3	$5.75	$17.25
Hanging Kit	4	$12.00	$48.00
Cree XT-E 60* Optics	72	$1.29	$92.88
Optic Adhesive	2	$3.50	$7.00
Shipping/Insurance	1	$21.25	$21.25
		Total:	$629.29

The breakeven point for the actual first article LED fixture build was 29 months, which met Objective A.4. However, the costs did not include labor, but they did include the initial purchase price, energy costs, and maintenance costs. Figure 32 shows the breakeven points for various lighting systems and shows that the breakeven cost was $1675. However, the breakeven point should be even sooner as Figure 32 assumes the light fixture is run at 100% capacity for a worst-case scenario.

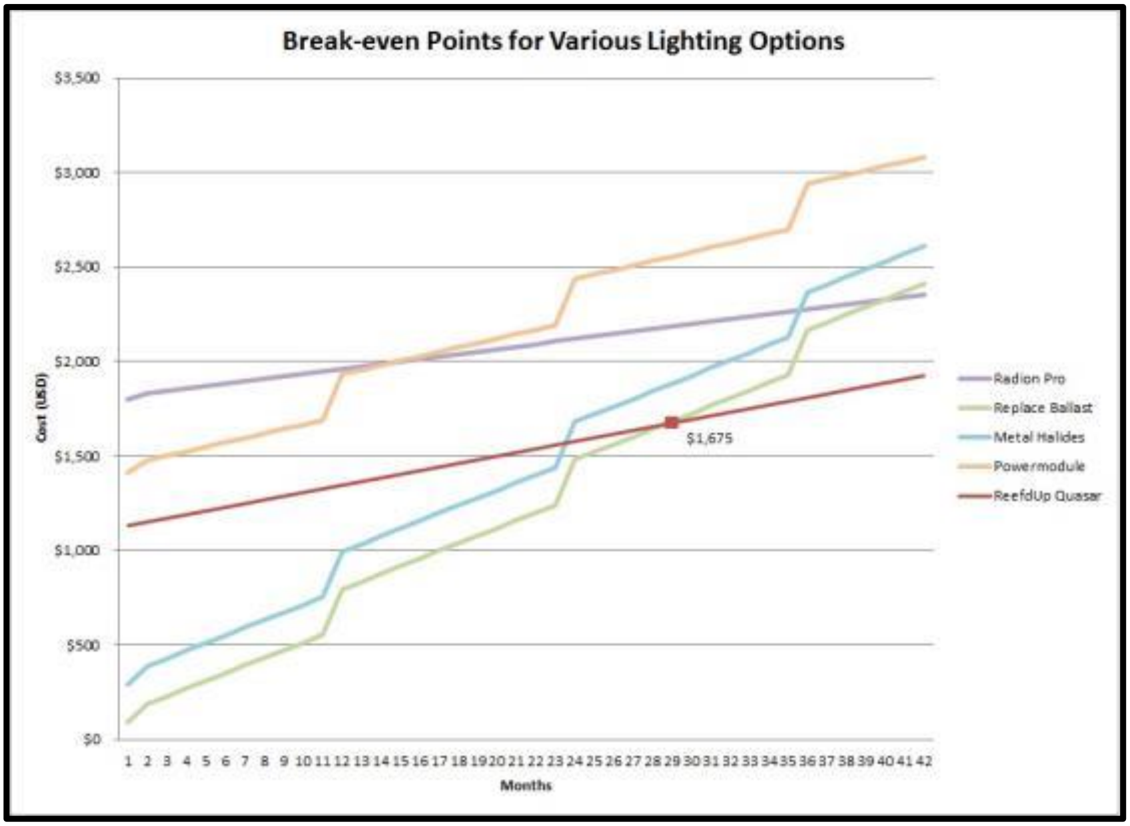


Figure 32: Breakeven Point for New LED System

Objective B.1 was met as the sand bed consistently measured 100-150 PAR with a Seneye Reef PAR meter. The middle of the aquarium had PAR values ranging from 200-300 PAR, and the uppermost corals had PAR values of 300 to over 400. Directly under the lights at the water surface, the PAR was 1300, which is comparable to high performance metal halide systems.

The spectrum analysis is not yet complete as tests are ongoing due to a faulty meter. However, this does not impact Phase 3 testing.

Objective B.3 was met as no dedicated UV or IR LEDs were included in the build. The 405 nm violet LED included does emit some UV radiation, but the amount is small (Figure 33). Emissions below 380 nm are negligible. Some IR radiation is emitted as well in the form of heat, but this was minimized by choosing the heat sinks with the highest safety factor.

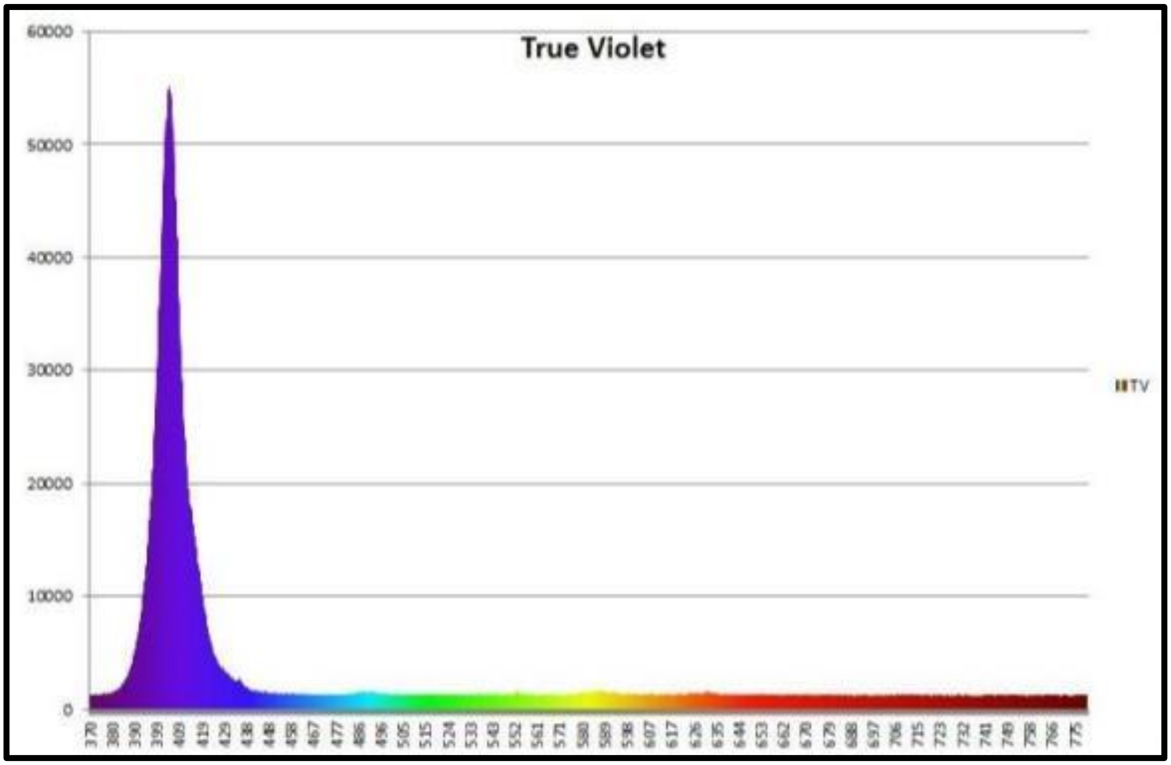


Figure 33: 405 nm Violet LED Spectrum
Source: LEDGroupBuy.com

Figure 34 shows the finished LED fixture hanging above the author's 150-gallon reef aquarium. The individual heatsink components are hung in a slight parabolic shape in order to minimize shadows. Some shadows could not be avoided due to the rock structure inside the aquarium.

Figure 34: LED Fixture over 150-gallon Aquarium

Objective C.1 required that the fixture be dimmable from 0-100%. At 0% intensity, the LEDs are off. Unfortunately, with an analog controller and dimmers, the LEDs do not respond from 1-9%. They turn on at 10% and are controllable from 10-100% in 1% increments. This was a trade-off as lower-end control was sacrificed for higher-end control. See APPENDIX F: Neptune Apex Code

APPENDIX for the code to control intensity.

Since all six colors of LEDs have intensity control from 10-100%, the number of color spectrum options available to the user is $5.3x10^{11}$. This is more than sufficient to meet Objective C.2. Standard color spectrums for user ease are still in development due to a faulty meter. In other words, settings will eventually be available for the user to choose a 10,000-Kelvin, 15,000-Kelvin, or a 20,000-Kelvin spectrum with little effort.

Figure 35 shows the computer interface with the Neptune Apex, accessed remotely via wireless internet. Figure 36 and Figure 37 show the cell phone interface on a Motorola smart phone. The interface was also tested on an HTC EVO 3D smart phone. From this dashboard, the user is able to see a snapshot of the temperature, pH, and current usage. Additionally, the user can control all the LEDs at once or individual LEDs to adjust the spectrum. The user also has control over the fans, heater, email alarms, and other parameters.

11/28/2013 15:22:45

EmailAlm_I5 OFF (OFF AUTO ON)

Temp 76.9

pH 8

Amp_3 4.8

Feed Cycle Cancel A B C D

LEDsPower ON (OFF AUTO ON)

Lunar_A1 OFF (OFF AUTO ON)

Sump-5 OFF (OFF AUTO ON)

NeutWhite ON (OFF AUTO ON)

RoyalBlue ON (OFF AUTO ON)

Violet_V7 OFF (OFF AUTO ON)

Red_V8 ON (OFF AUTO ON)

V1 OFF (OFF AUTO ON)

V2 OFF (OFF AUTO ON)

V3 OFF (OFF AUTO ON)

V4 OFF (OFF AUTO ON)

LEDFans ON (OFF AUTO ON)

Fan-6 OFF (OFF AUTO ON)

heater300W-7 ON (OFF AUTO ON)

heater400W-8 ON (OFF AUTO ON)

Figure 35: Remote Neptune Apex Control Panel

150 tank

Probes

Temp	76.2
pH	8.07
ORP	579
Amp_3	1.7

Outlets

Control

Status

Date	12/08/2013 21:07:12
P. Failed	12/07/2013 02:00:00
P.Restored	none
Serial #	AC4:06639
SW Version	4.20_1813
HW Version	1.0

Figure 36: Cell Phone Accessibility

V1 Auto [✓ Off] On
V2 Auto [✓ Off] On
V3 Auto [✓ Off] On
V4 Auto [✓ Off] On
SndAlm_I6 [✓ Auto] Off On
SndWrn_I7 [✓ Auto] Off On
EmailAlm_I5 [✓ Auto] Off On
1 [✓ Auto] Off On
2 [✓ Auto] Off On
LEDFans [✓ Auto] Off On
LEDsPower [✓ Auto] Off On
Sump-5 [✓ Auto] Off On
Fan-6 [✓ Auto] Off On

Figure 37: Cell Phone Control Panel

Objective C.4 (moonlight simulation) is still in development since low-end control was sacrificed for high-end performance.

Objective C.5 (sunrise and sunset simulation) was met as the fixture program ramps the colors and intensities up and down over an hour. The code is in APPENDIX F: Neptune Apex Code.

Objective C.6 was partially met as the fixture can simulate periods of high water flow with the Neptune Apex, but cloud cover is still in development due to the low-end intensity performance.

Test Results

Testing began on 9 November 2013 with the metal halide fixture and continued through 23 November 2013. The first LED test started 24 November 2013 and continued through 7 December 2013 with an intensity of 15% Royal Blue, 15% Neutral White, and 15% Other Colors. The subsequent weeks will consist of a ramping effect up to 15% Royal Blue, 15% Neutral White, and 30% Other Colors. At that point, the testing will be outside the scope of ENM 590 and into Phase 3.

Control Parameters

Specific gravity has stayed constant at 1.027 (Figure 38). The vertical green lines represent changes in the lighting, and error bars on each data point represent the test's accuracy. There is no known correlation between salt uptake and coral growth, so a stable specific gravity is expected.

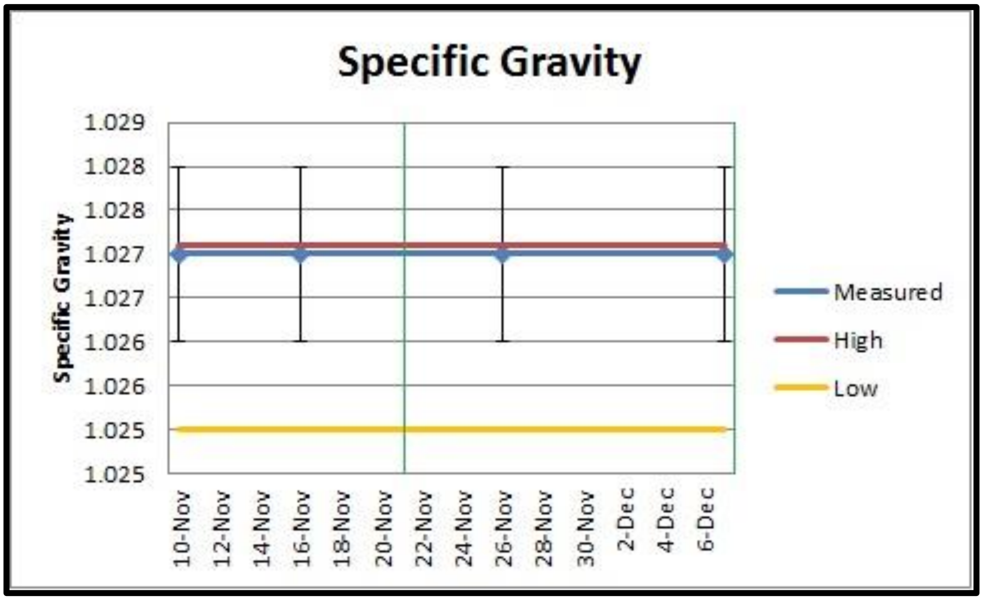


Figure 38: Specific Gravity

Alkalinity levels briefly dropped below target range (Figure 39), so the daily dosage was increased to compensate for the additional coral growth. The vertical green lines represent changes in the lighting, and error bars on each data point represent the test's accuracy. Although the daily alkalinity requirement increased, it did not appear to increase in relation to lighting changes. The alkalinity supplement was dosed at 70 ml per day and is now dosed at 100 ml per day (Figure 40).

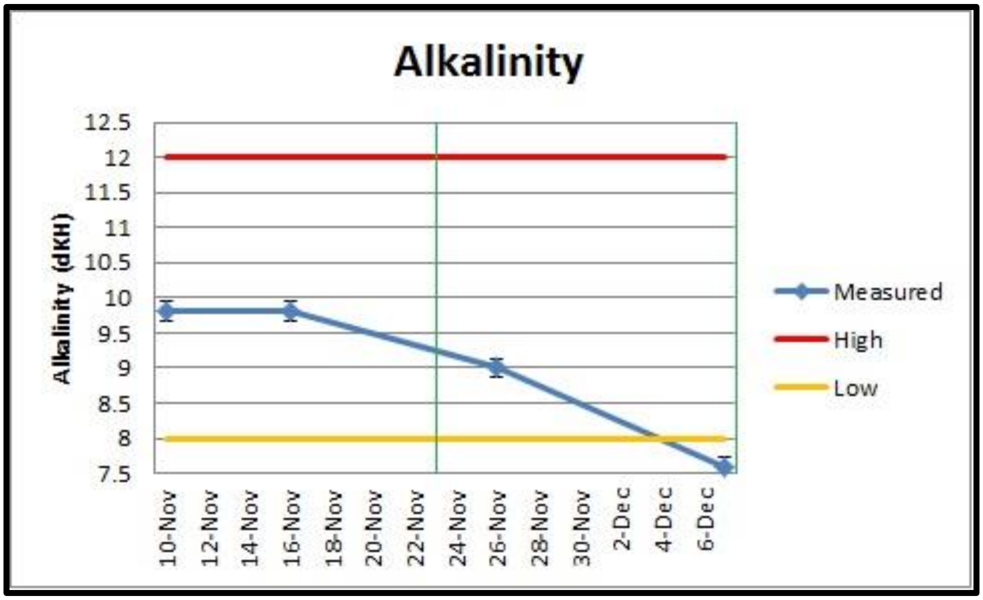


Figure 39: Alkalinity

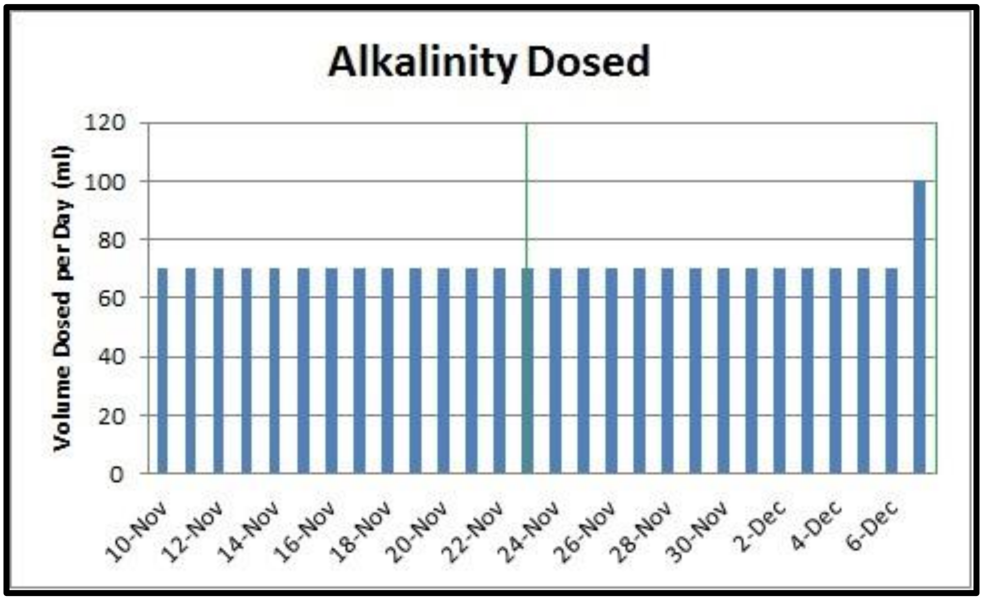


Figure 40: Daily Alkalinity Dosage Volume

The calcium level appeared to drop during one test with constant dosing (Figure 41), but a multitude of anomalies could have caused this. For instance, a new batch of calcium may not have been fully stirred, the tester may not have fully stirred the reagent or mixture, et cetera. The vertical green lines represent changes in the lighting, and error bars on each data point represent the test’s accuracy. The daily dosing level at 225 ml per day is currently sufficient to maintain coral growth.

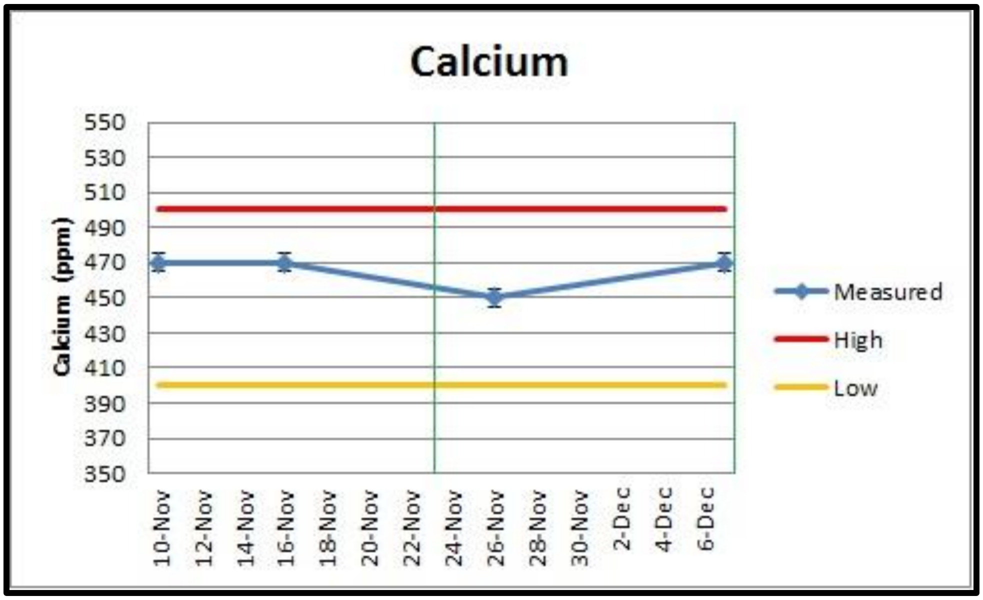


Figure 41: Calcium

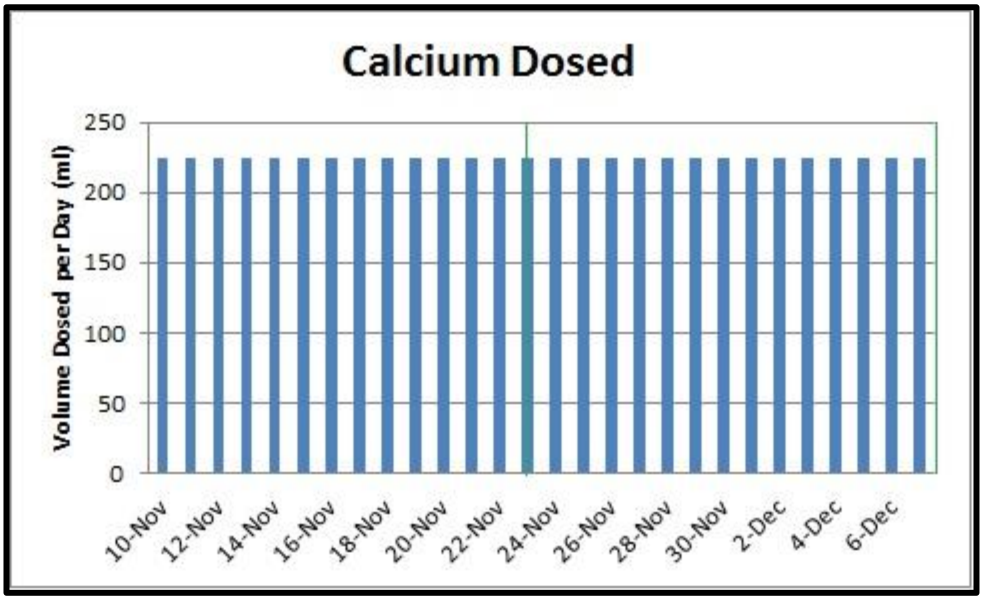


Figure 42: Daily Calcium Dosage Volume

Magnesium levels were maintained at 1360 ppm with 50 ml of supplementation per day until 7 December, where the levels reached down to 1200 ppm (Figure 43). The vertical green lines represent changes in the lighting, and error bars on each data point represent the test's accuracy. To compensate for the additional uptake, daily dosing was increased to 270 ml.

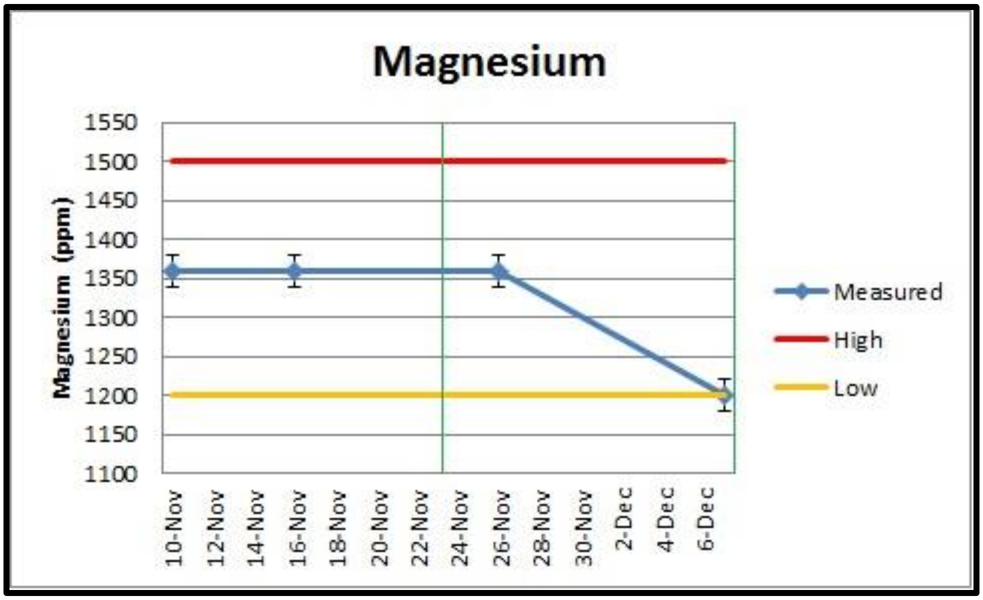


Figure 43: Magnesium

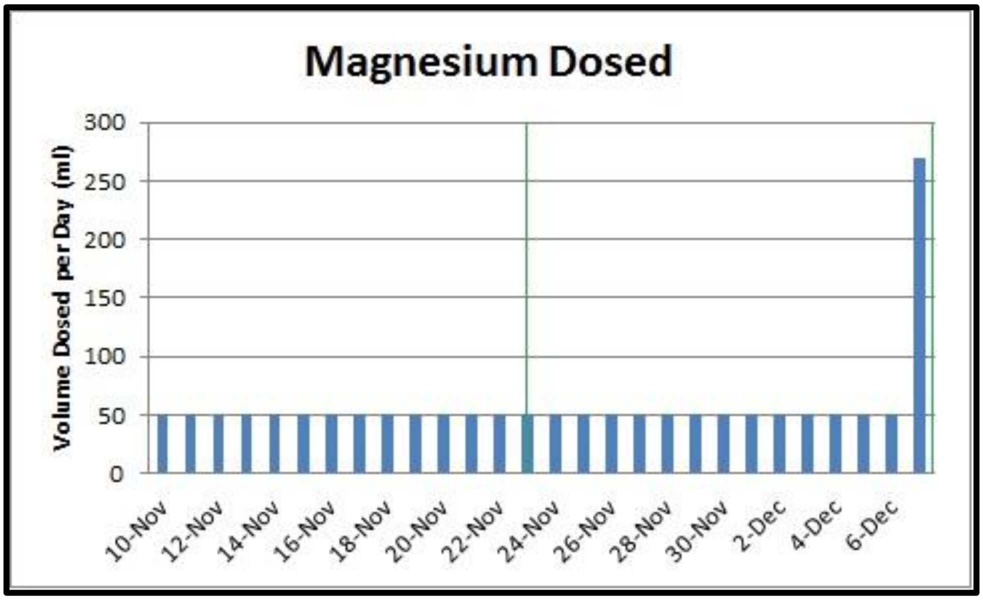


Figure 44: Daily Magnesium Dosage Volume

Temperature, as previously discussed in Requirements Results, now has a standard deviation of 0.15 and stays within the target range (Figure 31). pH is also within the target range (Figure 45). Phosphate is not within the target range, which could affect coral coloration and growth negatively (Figure 46). To correct this, additional skimming, water changes, and more frequent GFO changes will occur. Free ammonia has stayed constant at 0.001 ppm, which is negligible due to the accuracy of the tester. Ammonium varies throughout each day, but the average is around 13 ppm. This amount is negligible due to the pH.

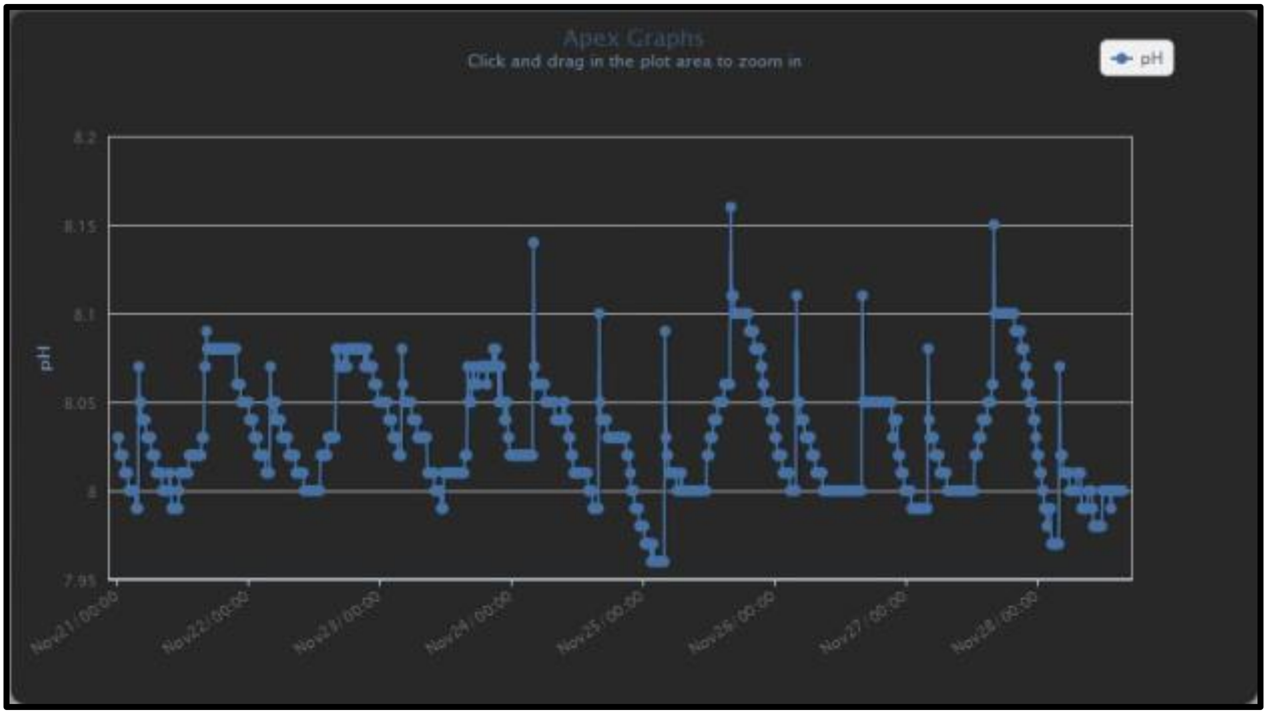


Figure 45: pH Variation

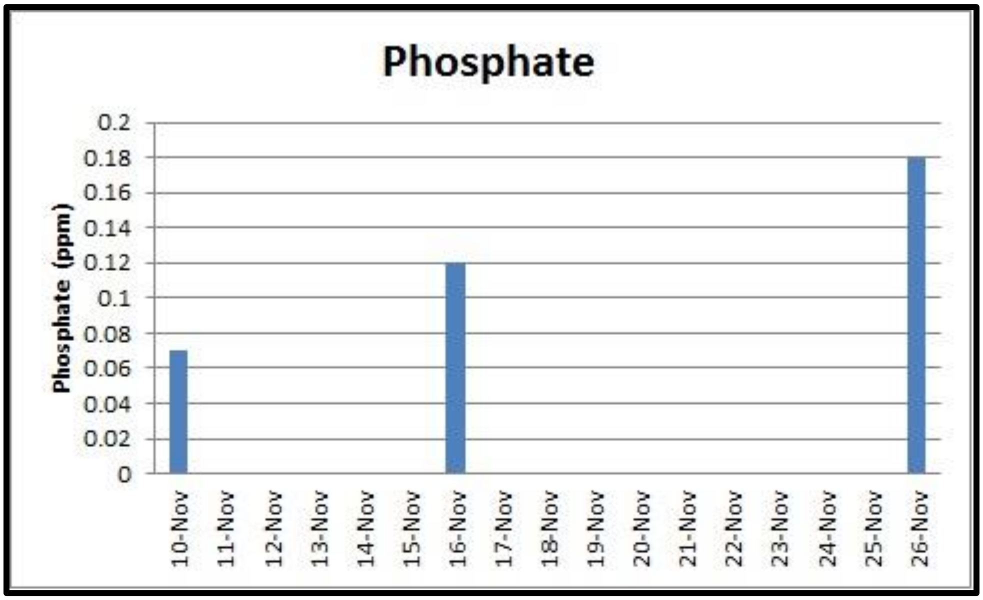


Figure 46: Phosphate Levels

Although the LED light system is entering Phase 3 test and evaluation, the results are extremely promising. At only 15% power, the LEDs are reaching equivalent metal halide performance at a much lower cost with more control.

CHAPTER VI – CONCLUSIONS

The LED fixture system has met nearly all of its requirements on schedule and below budget. It will enter Phase 3 on 10 December 2013, at which time the remaining requirements will be tested and verified. This system is cost-effective, meets user needs, and appears to meet coral requirements as well. A side-by-side comparison of an Acropora coral (Tyree Pink Lemonade) shows significant growth and coloration improvement (Figure 47). The photos were taken slightly over a month apart (3 November 2013 and 8 December 2013) with the left side under metal halides and the right side under LEDs. All other corals in the aquarium are responding similarly (Figure 48).

Figure 47: Acropora under Metal Halides (Left) and LEDs (Right) a Month Apart

Figure 48: Corals Successfully Growing under LED Light System after Two Weeks

In addition to coral health and coloration, the other invertebrates have responded well to the LED lighting. The Cerith snails have laid two batches of eggs during the two-week LED test period, which was typical for approximately every six months of metal halides. The Nerite and Collumbellid snails have also increased their egg-laying, but the exact increase is impossible to determine due to their egg-laying habits (they lay individual eggs sporadically across the landscape).

Future design improvement analysis will be completed after Phase 3 test and evaluation. However, initial test results suggest that less LEDs are required than initially believed. Less LEDs would significantly reduce the price and therefore, the breakeven point. This would make the fixture more competitive and/or more profitable. The fixture should also be designed for PWM controllers in order to expand the market. As power costs increase globally and the demand for efficient fixtures increases, this design should meet the user’s needs along with the aquarium inhabitant’s.

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29. Riddle, Dana, “Feature Article: How to Make Corals more Colorful, Part Two – New Information! Green Fluorescent Pigments, Pigment Clades, and Photoconversion from Green to Orange/Red,” *Advanced Aquarist*, February 2009.

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APPENDIX B: ACRONYMS

CAT5e	Category 5 cable
CF	Conversion Factor
CFP	Cyan Fluorescent Proteins
Chl a	Chlorophyll a
COTS	Commercial Off-The-Shelf
DIYers	Do-it-Yourself-ers
DNS	Dynamic Name Service
DOE	Design of Experiments
DOS	Disk Operating System
DsRed	Discosoma Red
FO	Fish Only
FOWLR	Fish Only With Live Rock
GFP	Green Fluorescent Proteins
HO	High Output fluorescent
IP	Internet Protocol
IR	Infrared
L	Length
LED	Light-Emitting Diode
LPS	Large Polyp Scleractinian
MTBF	Mean Time Between Failure
MTBR	Mean Time Between Repair
MH	Metal Halide
NIST	National Institute for Standards and Technology
NO	Normal Output fluorescent
NW	Neutral White
PAR	Photosynthetically Available Radiation
PC	Power Compacts
PUR	Photosynthetically Usable Radiation
PWM	Pulse Width Modulation
RB	Royal Blue
RO/DI	Reverse Osmosis Deionized
RTV	Room Temperature Vulcanizing
SA	Surface Area
SF	Safety Factor
SPS	Small Polyp Scleractinian
TDS	Total Dissolved Solids
UV	Ultra-Violet
VDM	Variable Dimming Module
VHO	Very High Output fluorescent
W	Width
WBS	Work Breakdown Structure
WMAS	Wasatch Marine Aquarium Society
WR	Watts Required
YFP	Yellow Fluorescent Proteins

APPENDIX C: LARGE FORMAT TABLES AND FIGURES

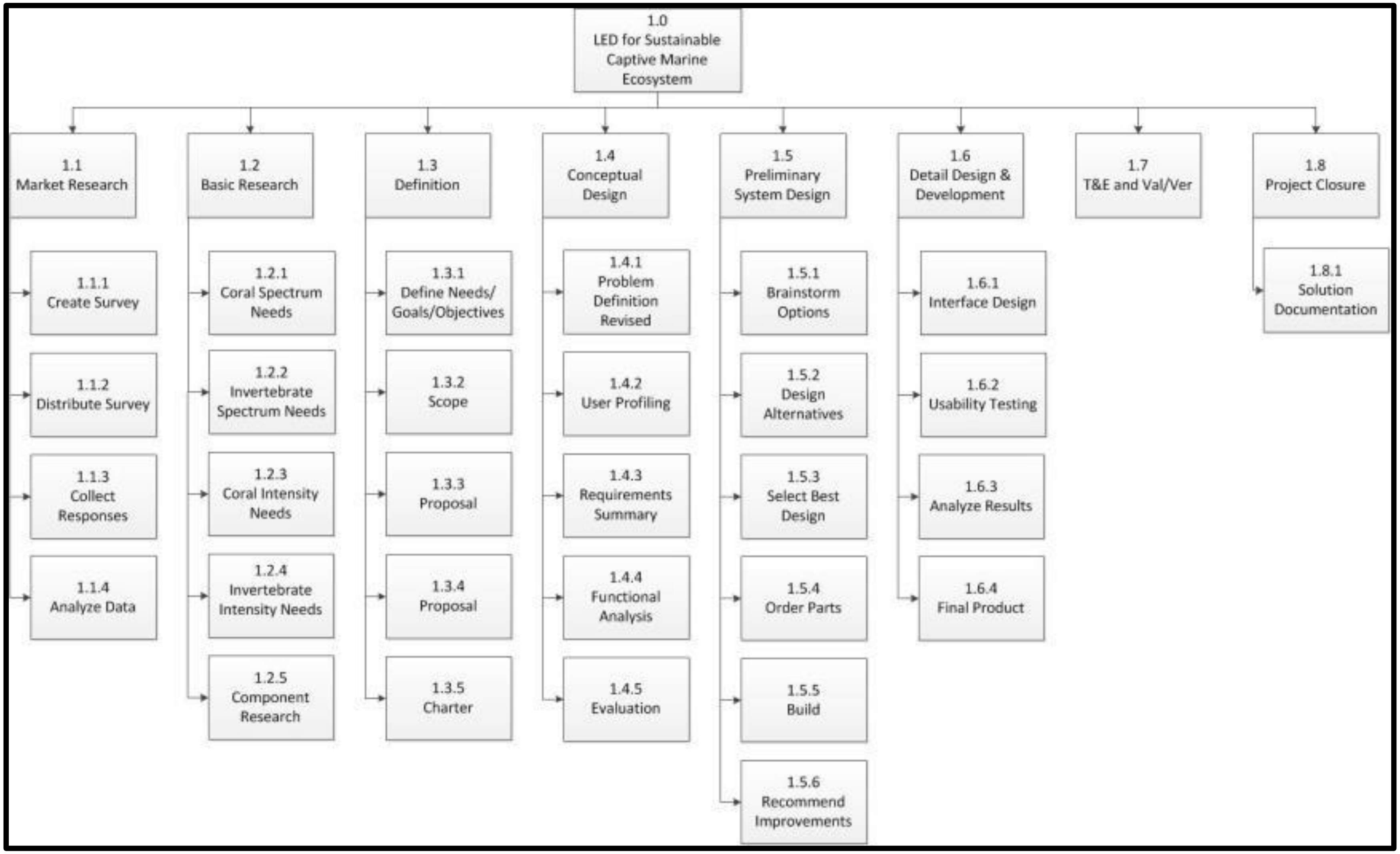
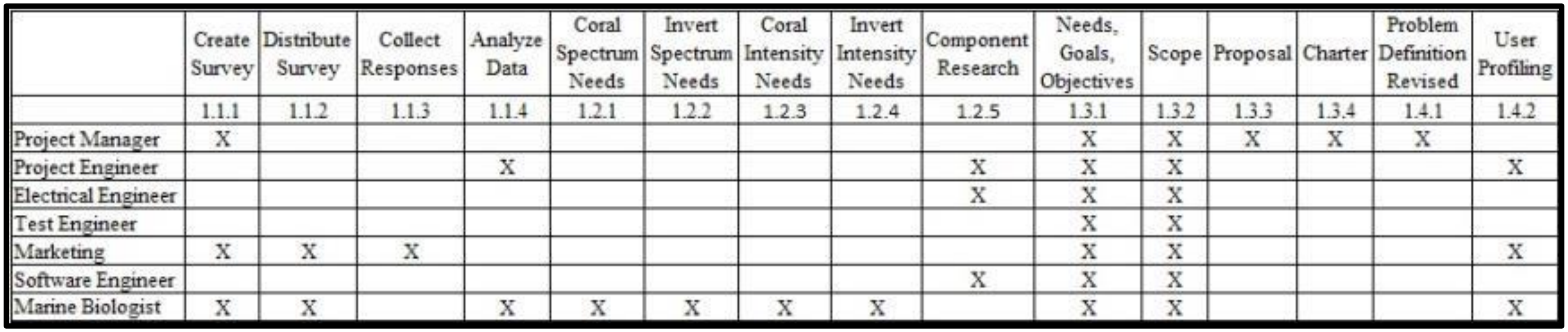
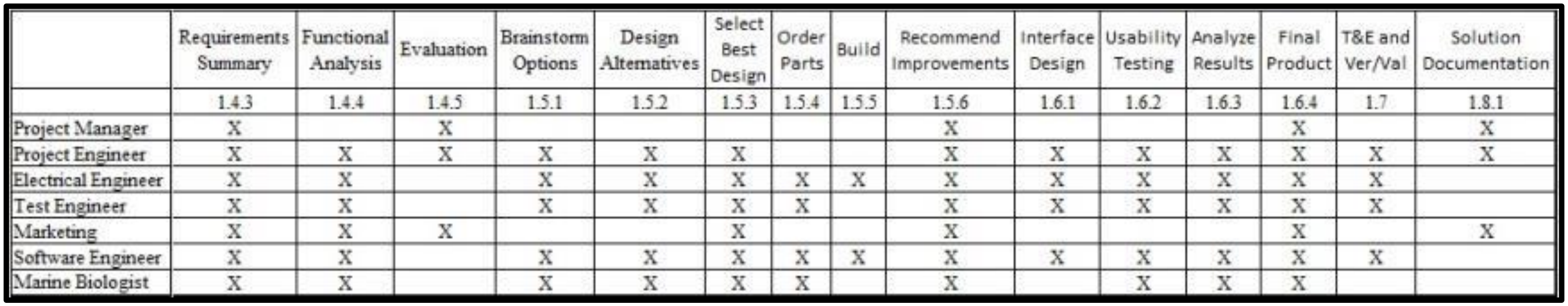


Figure 49: Enlarged Work Breakdown Structure



	Create Survey	Distribute Survey	Collect Responses	Analyze Data	Coral Spectrum Needs	Invert Spectrum Needs	Coral Intensity Needs	Invert Intensity Needs	Component Research	Needs, Goals, Objectives	Scope	Proposal	Charter	Problem Definition Revised	User Profiling
	1.1.1	1.1.2	1.1.3	1.1.4	1.2.1	1.2.2	1.2.3	1.2.4	1.2.5	1.3.1	1.3.2	1.3.3	1.3.4	1.4.1	1.4.2
Project Manager	X									X	X	X	X	X	
Project Engineer				X					X	X	X				X
Electrical Engineer									X	X	X				
Test Engineer										X	X				
Marketing	X	X	X							X	X				X
Software Engineer									X	X	X				
Marine Biologist	X	X		X	X	X	X	X		X	X				X

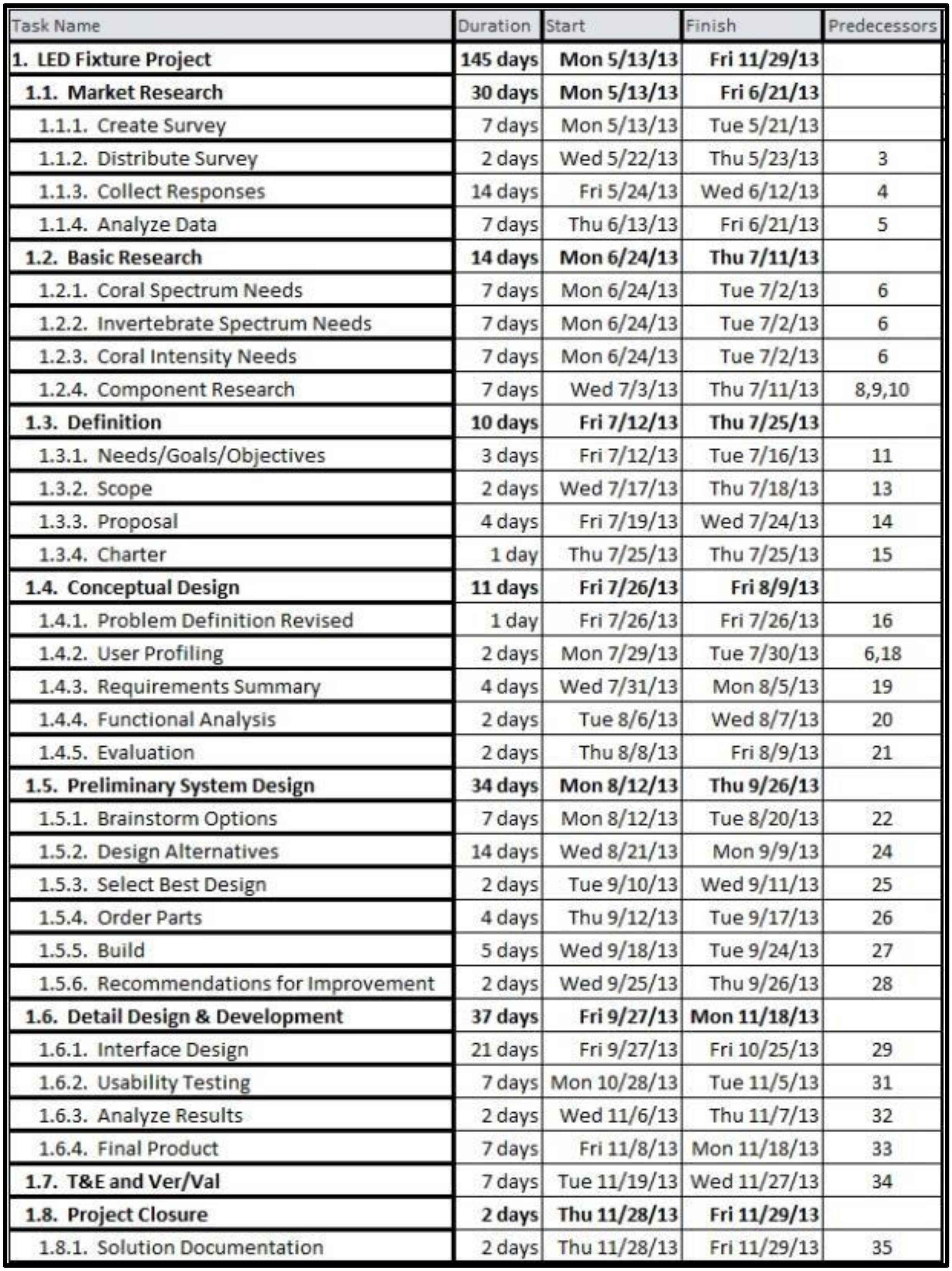
Figure 50: Enlarged Task Responsibility Matrix



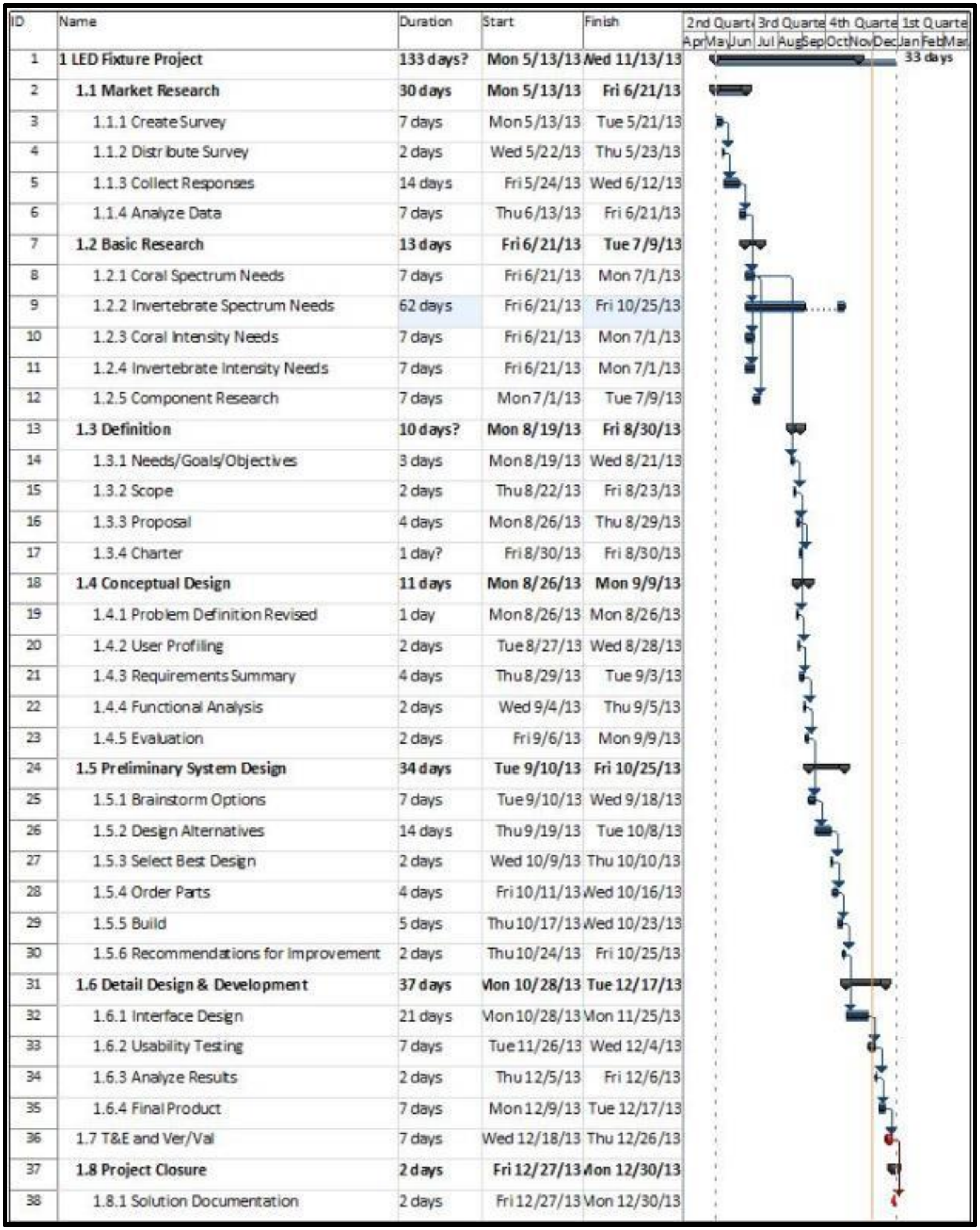
	Requirements Summary	Functional Analysis	Evaluation	Brainstorm Options	Design Alternatives	Select Best Design	Order Parts	Build	Recommend Improvements	Interface Design	Usability Testing	Analyze Results	Final Product	T&E and Ver/Val	Solution Documentation
	1.4.3	1.4.4	1.4.5	1.5.1	1.5.2	1.5.3	1.5.4	1.5.5	1.5.6	1.6.1	1.6.2	1.6.3	1.6.4	1.7	1.8.1
Project Manager	X		X						X				X		X
Project Engineer	X	X	X	X	X	X			X	X	X	X	X	X	X
Electrical Engineer	X	X		X	X	X	X	X	X	X	X	X	X	X	
Test Engineer	X	X		X	X	X	X		X	X	X	X	X	X	
Marketing	X	X	X			X			X				X		X
Software Engineer	X	X		X	X	X	X	X	X	X	X	X	X	X	
Marine Biologist	X	X		X	X	X	X		X		X	X	X		

Figure 51: Enlarged Task Responsibility Matrix, Continued

Table 23: Enlarged Project Schedule

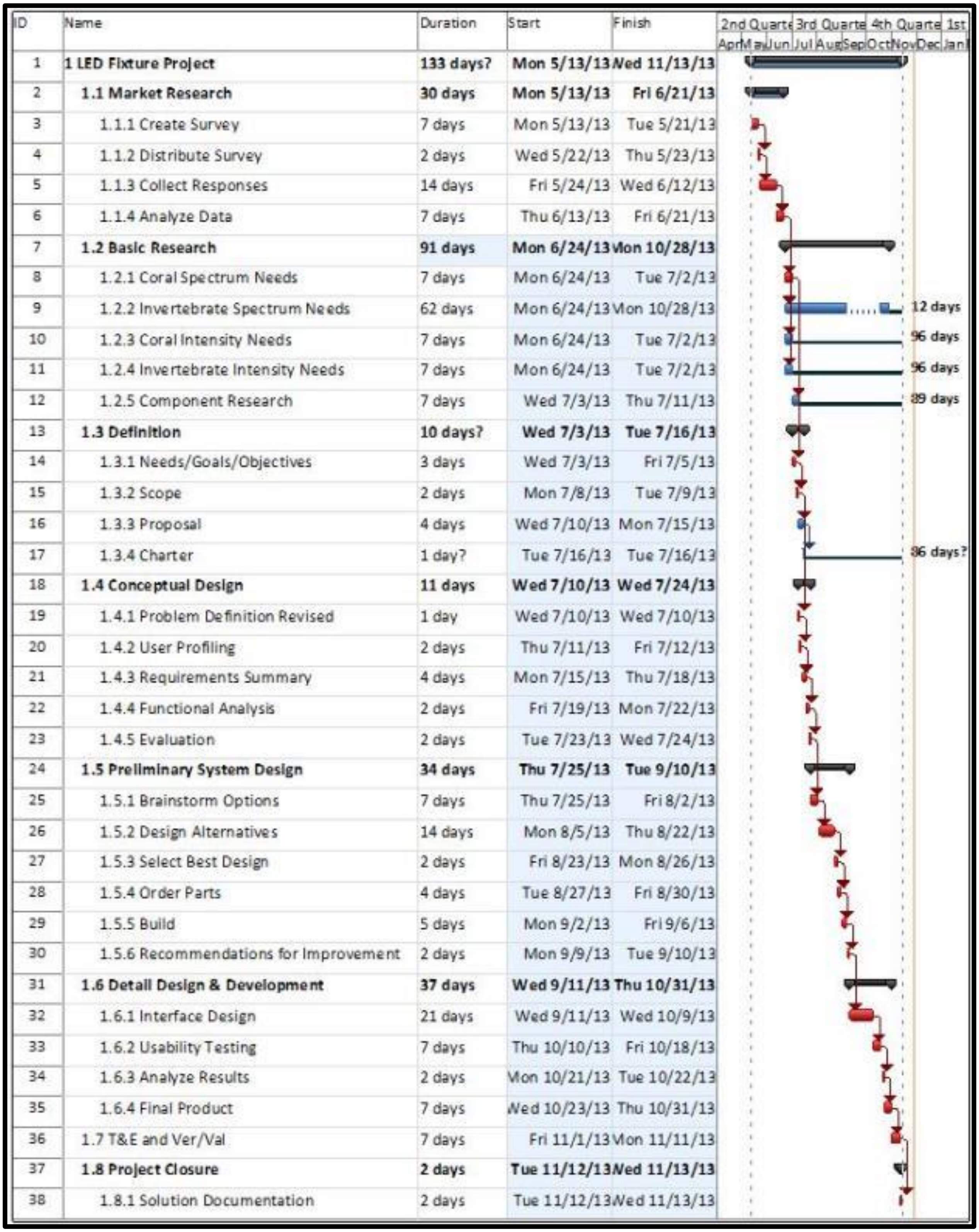


Task Name	Duration	Start	Finish	Predecessors
1. LED Fixture Project	**145 days**	**Mon 5/13/13**	**Fri 11/29/13**	
1.1. Market Research	**30 days**	**Mon 5/13/13**	**Fri 6/21/13**	
1.1.1. Create Survey	7 days	Mon 5/13/13	Tue 5/21/13	
1.1.2. Distribute Survey	2 days	Wed 5/22/13	Thu 5/23/13	3
1.1.3. Collect Responses	14 days	Fri 5/24/13	Wed 6/12/13	4
1.1.4. Analyze Data	7 days	Thu 6/13/13	Fri 6/21/13	5
1.2. Basic Research	**14 days**	**Mon 6/24/13**	**Thu 7/11/13**	
1.2.1. Coral Spectrum Needs	7 days	Mon 6/24/13	Tue 7/2/13	6
1.2.2. Invertebrate Spectrum Needs	7 days	Mon 6/24/13	Tue 7/2/13	6
1.2.3. Coral Intensity Needs	7 days	Mon 6/24/13	Tue 7/2/13	6
1.2.4. Component Research	7 days	Wed 7/3/13	Thu 7/11/13	8,9,10
1.3. Definition	**10 days**	**Fri 7/12/13**	**Thu 7/25/13**	
1.3.1. Needs/Goals/Objectives	3 days	Fri 7/12/13	Tue 7/16/13	11
1.3.2. Scope	2 days	Wed 7/17/13	Thu 7/18/13	13
1.3.3. Proposal	4 days	Fri 7/19/13	Wed 7/24/13	14
1.3.4. Charter	1 day	Thu 7/25/13	Thu 7/25/13	15
1.4. Conceptual Design	**11 days**	**Fri 7/26/13**	**Fri 8/9/13**	
1.4.1. Problem Definition Revised	1 day	Fri 7/26/13	Fri 7/26/13	16
1.4.2. User Profiling	2 days	Mon 7/29/13	Tue 7/30/13	6,18
1.4.3. Requirements Summary	4 days	Wed 7/31/13	Mon 8/5/13	19
1.4.4. Functional Analysis	2 days	Tue 8/6/13	Wed 8/7/13	20
1.4.5. Evaluation	2 days	Thu 8/8/13	Fri 8/9/13	21
1.5. Preliminary System Design	**34 days**	**Mon 8/12/13**	**Thu 9/26/13**	
1.5.1. Brainstorm Options	7 days	Mon 8/12/13	Tue 8/20/13	22
1.5.2. Design Alternatives	14 days	Wed 8/21/13	Mon 9/9/13	24
1.5.3. Select Best Design	2 days	Tue 9/10/13	Wed 9/11/13	25
1.5.4. Order Parts	4 days	Thu 9/12/13	Tue 9/17/13	26
1.5.5. Build	5 days	Wed 9/18/13	Tue 9/24/13	27
1.5.6. Recommendations for Improvement	2 days	Wed 9/25/13	Thu 9/26/13	28
1.6. Detail Design & Development	**37 days**	**Fri 9/27/13**	**Mon 11/18/13**	
1.6.1. Interface Design	21 days	Fri 9/27/13	Fri 10/25/13	29
1.6.2. Usability Testing	7 days	Mon 10/28/13	Tue 11/5/13	31
1.6.3. Analyze Results	2 days	Wed 11/6/13	Thu 11/7/13	32
1.6.4. Final Product	7 days	Fri 11/8/13	Mon 11/18/13	33
1.7. T&E and Ver/Val	7 days	Tue 11/19/13	Wed 11/27/13	34
1.8. Project Closure	**2 days**	**Thu 11/28/13**	**Fri 11/29/13**	
1.8.1. Solution Documentation	2 days	Thu 11/28/13	Fri 11/29/13	35



ID	Name	Duration	Start	Finish
1	**1 LED Fixture Project**	**133 days?**	**Mon 5/13/13**	**Wed 11/13/13**
2	**1.1 Market Research**	**30 days**	**Mon 5/13/13**	**Fri 6/21/13**
3	1.1.1 Create Survey	7 days	Mon 5/13/13	Tue 5/21/13
4	1.1.2 Distribute Survey	2 days	Wed 5/22/13	Thu 5/23/13
5	1.1.3 Collect Responses	14 days	Fri 5/24/13	Wed 6/12/13
6	1.1.4 Analyze Data	7 days	Thu 6/13/13	Fri 6/21/13
7	**1.2 Basic Research**	**13 days**	**Fri 6/21/13**	**Tue 7/9/13**
8	1.2.1 Coral Spectrum Needs	7 days	Fri 6/21/13	Mon 7/1/13
9	1.2.2 Invertebrate Spectrum Needs	62 days	Fri 6/21/13	Fri 10/25/13
10	1.2.3 Coral Intensity Needs	7 days	Fri 6/21/13	Mon 7/1/13
11	1.2.4 Invertebrate Intensity Needs	7 days	Fri 6/21/13	Mon 7/1/13
12	1.2.5 Component Research	7 days	Mon 7/1/13	Tue 7/9/13
13	**1.3 Definition**	**10 days?**	**Mon 8/19/13**	**Fri 8/30/13**
14	1.3.1 Needs/Goals/Objectives	3 days	Mon 8/19/13	Wed 8/21/13
15	1.3.2 Scope	2 days	Thu 8/22/13	Fri 8/23/13
16	1.3.3 Proposal	4 days	Mon 8/26/13	Thu 8/29/13
17	1.3.4 Charter	1 day?	Fri 8/30/13	Fri 8/30/13
18	**1.4 Conceptual Design**	**11 days**	**Mon 8/26/13**	**Mon 9/9/13**
19	1.4.1 Problem Definition Revised	1 day	Mon 8/26/13	Mon 8/26/13
20	1.4.2 User Profiling	2 days	Tue 8/27/13	Wed 8/28/13
21	1.4.3 Requirements Summary	4 days	Thu 8/29/13	Tue 9/3/13
22	1.4.4 Functional Analysis	2 days	Wed 9/4/13	Thu 9/5/13
23	1.4.5 Evaluation	2 days	Fri 9/6/13	Mon 9/9/13
24	**1.5 Preliminary System Design**	**34 days**	**Tue 9/10/13**	**Fri 10/25/13**
25	1.5.1 Brainstorm Options	7 days	Tue 9/10/13	Wed 9/18/13
26	1.5.2 Design Alternatives	14 days	Thu 9/19/13	Tue 10/8/13
27	1.5.3 Select Best Design	2 days	Wed 10/9/13	Thu 10/10/13
28	1.5.4 Order Parts	4 days	Fri 10/11/13	Wed 10/16/13
29	1.5.5 Build	5 days	Thu 10/17/13	Wed 10/23/13
30	1.5.6 Recommendations for Improvement	2 days	Thu 10/24/13	Fri 10/25/13
31	**1.6 Detail Design & Development**	**37 days**	**Mon 10/28/13**	**Tue 12/17/13**
32	1.6.1 Interface Design	21 days	Mon 10/28/13	Mon 11/25/13
33	1.6.2 Usability Testing	7 days	Tue 11/26/13	Wed 12/4/13
34	1.6.3 Analyze Results	2 days	Thu 12/5/13	Fri 12/6/13
35	1.6.4 Final Product	7 days	Mon 12/9/13	Tue 12/17/13
36	1.7 T&E and Ver/Val	7 days	Wed 12/18/13	Thu 12/26/13
37	**1.8 Project Closure**	**2 days**	**Fri 12/27/13**	**Mon 12/30/13**
38	1.8.1 Solution Documentation	2 days	Fri 12/27/13	Mon 12/30/13

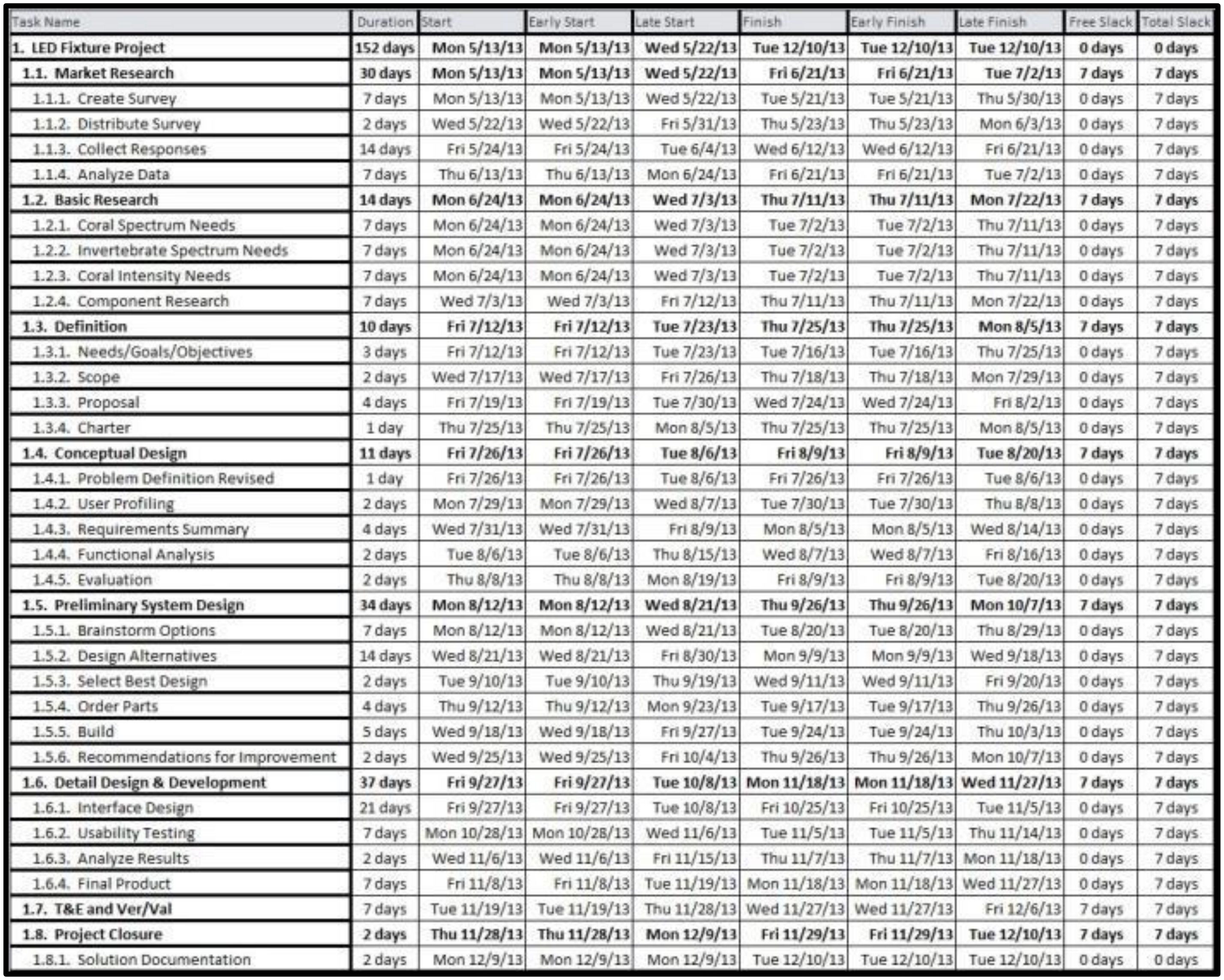
Figure 52: Enlarged Project Schedule Detail



ID	Name	Duration	Start	Finish
1	**1 LED Fixture Project**	**133 days?**	**Mon 5/13/13**	**Wed 11/13/13**
2	**1.1 Market Research**	**30 days**	**Mon 5/13/13**	**Fri 6/21/13**
3	1.1.1 Create Survey	7 days	Mon 5/13/13	Tue 5/21/13
4	1.1.2 Distribute Survey	2 days	Wed 5/22/13	Thu 5/23/13
5	1.1.3 Collect Responses	14 days	Fri 5/24/13	Wed 6/12/13
6	1.1.4 Analyze Data	7 days	Thu 6/13/13	Fri 6/21/13
7	**1.2 Basic Research**	**91 days**	**Mon 6/24/13**	**Mon 10/28/13**
8	1.2.1 Coral Spectrum Needs	7 days	Mon 6/24/13	Tue 7/2/13
9	1.2.2 Invertebrate Spectrum Needs	62 days	Mon 6/24/13	Mon 10/28/13
10	1.2.3 Coral Intensity Needs	7 days	Mon 6/24/13	Tue 7/2/13
11	1.2.4 Invertebrate Intensity Needs	7 days	Mon 6/24/13	Tue 7/2/13
12	1.2.5 Component Research	7 days	Wed 7/3/13	Thu 7/11/13
13	**1.3 Definition**	**10 days?**	**Wed 7/3/13**	**Tue 7/16/13**
14	1.3.1 Needs/Goals/Objectives	3 days	Wed 7/3/13	Fri 7/5/13
15	1.3.2 Scope	2 days	Mon 7/8/13	Tue 7/9/13
16	1.3.3 Proposal	4 days	Wed 7/10/13	Mon 7/15/13
17	1.3.4 Charter	1 day?	Tue 7/16/13	Tue 7/16/13
18	**1.4 Conceptual Design**	**11 days**	**Wed 7/10/13**	**Wed 7/24/13**
19	1.4.1 Problem Definition Revised	1 day	Wed 7/10/13	Wed 7/10/13
20	1.4.2 User Profiling	2 days	Thu 7/11/13	Fri 7/12/13
21	1.4.3 Requirements Summary	4 days	Mon 7/15/13	Thu 7/18/13
22	1.4.4 Functional Analysis	2 days	Fri 7/19/13	Mon 7/22/13
23	1.4.5 Evaluation	2 days	Tue 7/23/13	Wed 7/24/13
24	**1.5 Preliminary System Design**	**34 days**	**Thu 7/25/13**	**Tue 9/10/13**
25	1.5.1 Brainstorm Options	7 days	Thu 7/25/13	Fri 8/2/13
26	1.5.2 Design Alternatives	14 days	Mon 8/5/13	Thu 8/22/13
27	1.5.3 Select Best Design	2 days	Fri 8/23/13	Mon 8/26/13
28	1.5.4 Order Parts	4 days	Tue 8/27/13	Fri 8/30/13
29	1.5.5 Build	5 days	Mon 9/2/13	Fri 9/6/13
30	1.5.6 Recommendations for Improvement	2 days	Mon 9/9/13	Tue 9/10/13
31	**1.6 Detail Design & Development**	**37 days**	**Wed 9/11/13**	**Thu 10/31/13**
32	1.6.1 Interface Design	21 days	Wed 9/11/13	Wed 10/9/13
33	1.6.2 Usability Testing	7 days	Thu 10/10/13	Fri 10/18/13
34	1.6.3 Analyze Results	2 days	Mon 10/21/13	Tue 10/22/13
35	1.6.4 Final Product	7 days	Wed 10/23/13	Thu 10/31/13
36	1.7 T&E and Ver/Val	7 days	Fri 11/1/13	Mon 11/11/13
37	**1.8 Project Closure**	**2 days**	**Tue 11/12/13**	**Wed 11/13/13**
38	1.8.1 Solution Documentation	2 days	Tue 11/12/13	Wed 11/13/13

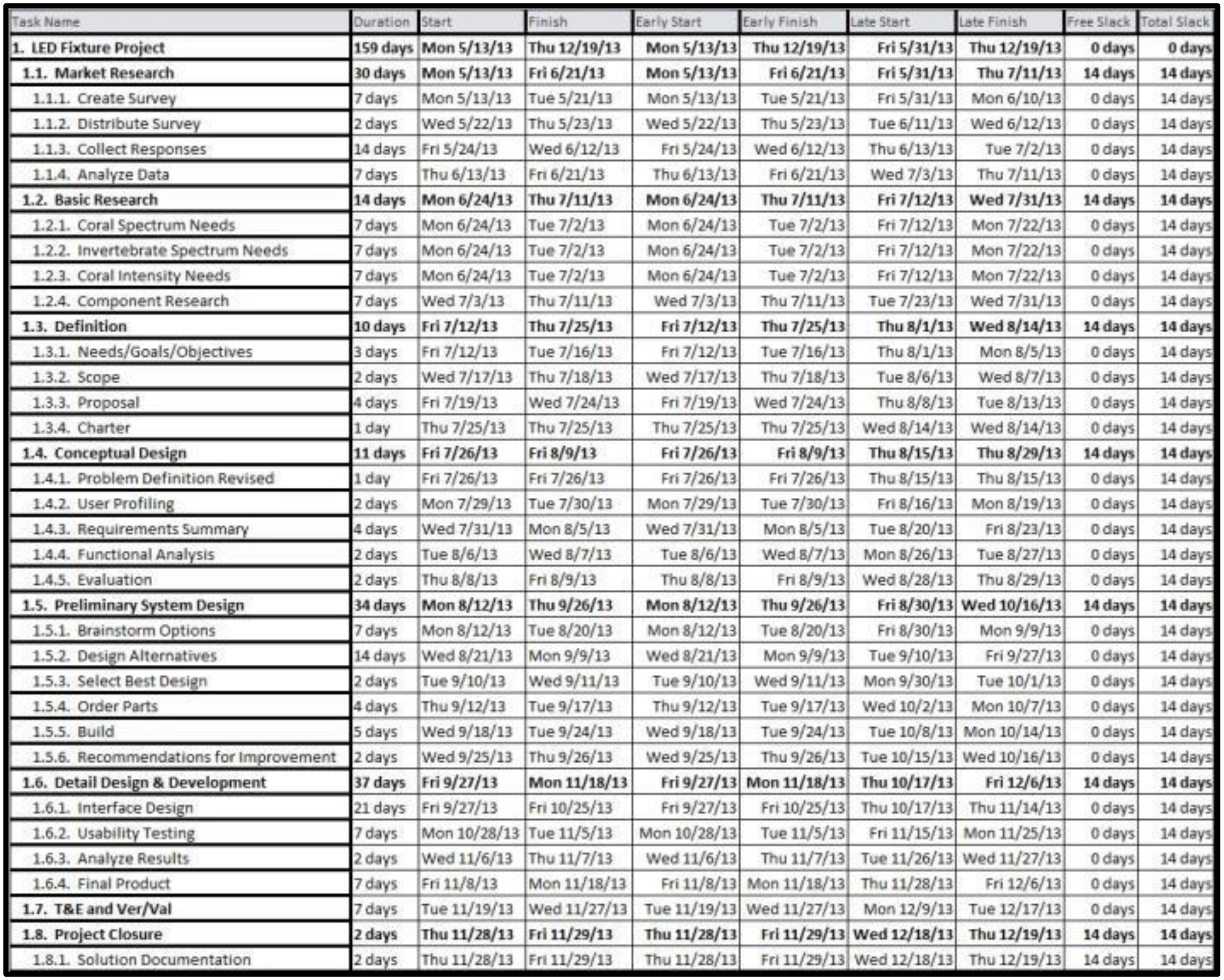
Figure 53: Enlarged Project Schedule with Critical Path

Table 24: Enlarged Baseline Sensitivity Analysis



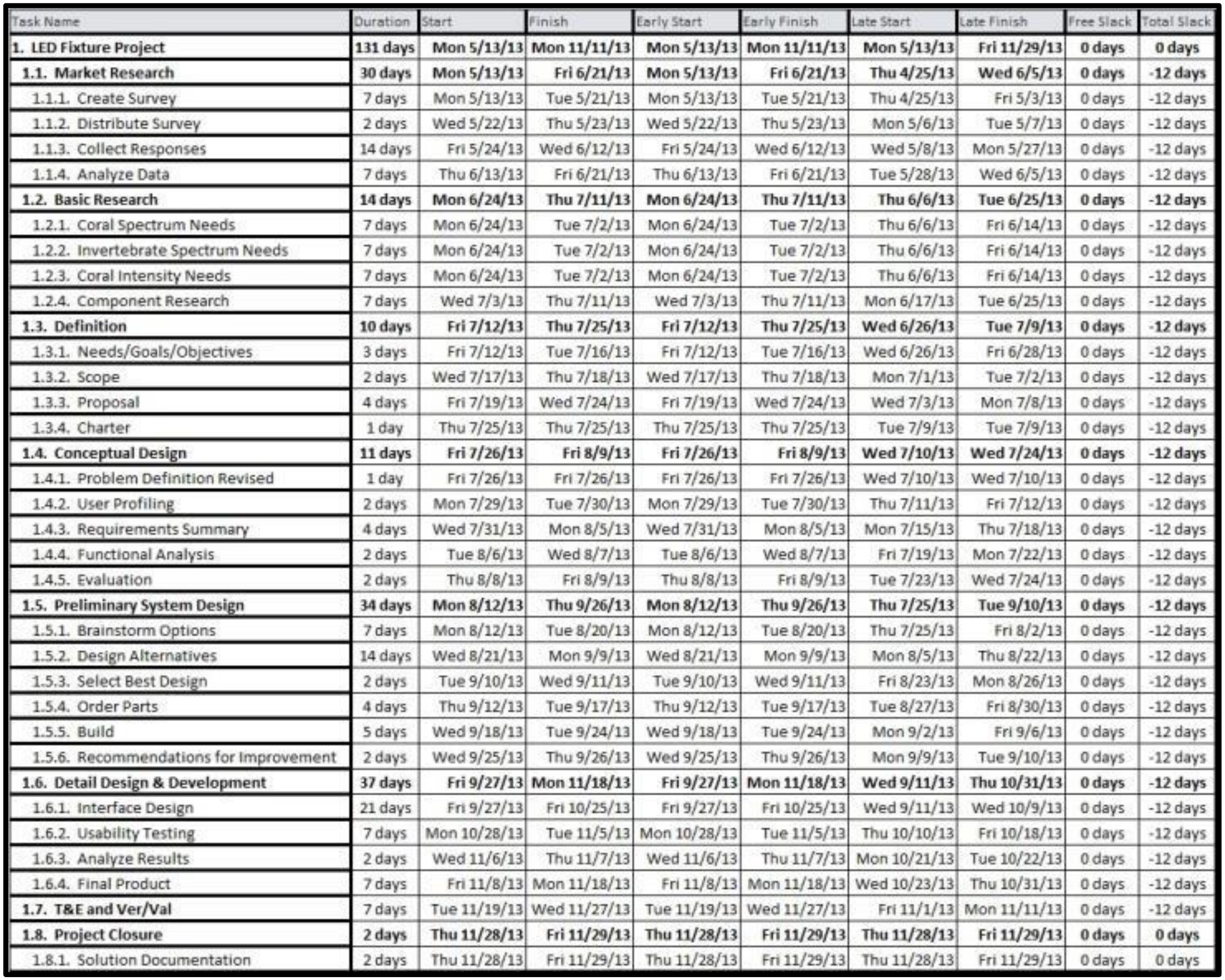
Task Name	Duration	Start	Early Start	Late Start	Finish	Early Finish	Late Finish	Free Slack	Total Slack
1. LED Fixture Project	**152 days**	**Mon 5/13/13**	**Mon 5/13/13**	**Wed 5/22/13**	**Tue 12/10/13**	**Tue 12/10/13**	**Tue 12/10/13**	**0 days**	**0 days**
1.1. Market Research	**30 days**	**Mon 5/13/13**	**Mon 5/13/13**	**Wed 5/22/13**	**Fri 6/21/13**	**Fri 6/21/13**	**Tue 7/2/13**	**7 days**	**7 days**
1.1.1. Create Survey	7 days	Mon 5/13/13	Mon 5/13/13	Wed 5/22/13	Tue 5/21/13	Tue 5/21/13	Thu 5/30/13	0 days	7 days
1.1.2. Distribute Survey	2 days	Wed 5/22/13	Wed 5/22/13	Fri 5/31/13	Thu 5/23/13	Thu 5/23/13	Mon 6/3/13	0 days	7 days
1.1.3. Collect Responses	14 days	Fri 5/24/13	Fri 5/24/13	Tue 6/4/13	Wed 6/12/13	Wed 6/12/13	Fri 6/21/13	0 days	7 days
1.1.4. Analyze Data	7 days	Thu 6/13/13	Thu 6/13/13	Mon 6/24/13	Fri 6/21/13	Fri 6/21/13	Tue 7/2/13	0 days	7 days
1.2. Basic Research	**14 days**	**Mon 6/24/13**	**Mon 6/24/13**	**Wed 7/3/13**	**Thu 7/11/13**	**Thu 7/11/13**	**Mon 7/22/13**	**7 days**	**7 days**
1.2.1. Coral Spectrum Needs	7 days	Mon 6/24/13	Mon 6/24/13	Wed 7/3/13	Tue 7/2/13	Tue 7/2/13	Thu 7/11/13	0 days	7 days
1.2.2. Invertebrate Spectrum Needs	7 days	Mon 6/24/13	Mon 6/24/13	Wed 7/3/13	Tue 7/2/13	Tue 7/2/13	Thu 7/11/13	0 days	7 days
1.2.3. Coral Intensity Needs	7 days	Mon 6/24/13	Mon 6/24/13	Wed 7/3/13	Tue 7/2/13	Tue 7/2/13	Thu 7/11/13	0 days	7 days
1.2.4. Component Research	7 days	Wed 7/3/13	Wed 7/3/13	Fri 7/12/13	Thu 7/11/13	Thu 7/11/13	Mon 7/22/13	0 days	7 days
1.3. Definition	**10 days**	**Fri 7/12/13**	**Fri 7/12/13**	**Tue 7/23/13**	**Thu 7/25/13**	**Thu 7/25/13**	**Mon 8/5/13**	**7 days**	**7 days**
1.3.1. Needs/Goals/Objectives	3 days	Fri 7/12/13	Fri 7/12/13	Tue 7/23/13	Tue 7/16/13	Tue 7/16/13	Thu 7/25/13	0 days	7 days
1.3.2. Scope	2 days	Wed 7/17/13	Wed 7/17/13	Fri 7/26/13	Thu 7/18/13	Thu 7/18/13	Mon 7/29/13	0 days	7 days
1.3.3. Proposal	4 days	Fri 7/19/13	Fri 7/19/13	Tue 7/30/13	Wed 7/24/13	Wed 7/24/13	Fri 8/2/13	0 days	7 days
1.3.4. Charter	1 day	Thu 7/25/13	Thu 7/25/13	Mon 8/5/13	Thu 7/25/13	Thu 7/25/13	Mon 8/5/13	0 days	7 days
1.4. Conceptual Design	**11 days**	**Fri 7/26/13**	**Fri 7/26/13**	**Tue 8/6/13**	**Fri 8/9/13**	**Fri 8/9/13**	**Tue 8/20/13**	**7 days**	**7 days**
1.4.1. Problem Definition Revised	1 day	Fri 7/26/13	Fri 7/26/13	Tue 8/6/13	Fri 7/26/13	Fri 7/26/13	Tue 8/6/13	0 days	7 days
1.4.2. User Profiling	2 days	Mon 7/29/13	Mon 7/29/13	Wed 8/7/13	Tue 7/30/13	Tue 7/30/13	Thu 8/8/13	0 days	7 days
1.4.3. Requirements Summary	4 days	Wed 7/31/13	Wed 7/31/13	Fri 8/9/13	Mon 8/5/13	Mon 8/5/13	Wed 8/14/13	0 days	7 days
1.4.4. Functional Analysis	2 days	Tue 8/6/13	Tue 8/6/13	Thu 8/15/13	Wed 8/7/13	Wed 8/7/13	Fri 8/16/13	0 days	7 days
1.4.5. Evaluation	2 days	Thu 8/8/13	Thu 8/8/13	Mon 8/19/13	Fri 8/9/13	Fri 8/9/13	Tue 8/20/13	0 days	7 days
1.5. Preliminary System Design	**34 days**	**Mon 8/12/13**	**Mon 8/12/13**	**Wed 8/21/13**	**Thu 9/26/13**	**Thu 9/26/13**	**Mon 10/7/13**	**7 days**	**7 days**
1.5.1. Brainstorm Options	7 days	Mon 8/12/13	Mon 8/12/13	Wed 8/21/13	Tue 8/20/13	Tue 8/20/13	Thu 8/29/13	0 days	7 days
1.5.2. Design Alternatives	14 days	Wed 8/21/13	Wed 8/21/13	Fri 8/30/13	Mon 9/9/13	Mon 9/9/13	Wed 9/18/13	0 days	7 days
1.5.3. Select Best Design	2 days	Tue 9/10/13	Tue 9/10/13	Thu 9/19/13	Wed 9/11/13	Wed 9/11/13	Fri 9/20/13	0 days	7 days
1.5.4. Order Parts	4 days	Thu 9/12/13	Thu 9/12/13	Mon 9/23/13	Tue 9/17/13	Tue 9/17/13	Thu 9/26/13	0 days	7 days
1.5.5. Build	5 days	Wed 9/18/13	Wed 9/18/13	Fri 9/27/13	Tue 9/24/13	Tue 9/24/13	Thu 10/3/13	0 days	7 days
1.5.6. Recommendations for Improvement	2 days	Wed 9/25/13	Wed 9/25/13	Fri 10/4/13	Thu 9/26/13	Thu 9/26/13	Mon 10/7/13	0 days	7 days
1.6. Detail Design & Development	**37 days**	**Fri 9/27/13**	**Fri 9/27/13**	**Tue 10/8/13**	**Mon 11/18/13**	**Mon 11/18/13**	**Wed 11/27/13**	**7 days**	**7 days**
1.6.1. Interface Design	21 days	Fri 9/27/13	Fri 9/27/13	Tue 10/8/13	Fri 10/25/13	Fri 10/25/13	Tue 11/5/13	0 days	7 days
1.6.2. Usability Testing	7 days	Mon 10/28/13	Mon 10/28/13	Wed 11/6/13	Tue 11/5/13	Tue 11/5/13	Thu 11/14/13	0 days	7 days
1.6.3. Analyze Results	2 days	Wed 11/6/13	Wed 11/6/13	Fri 11/15/13	Thu 11/7/13	Thu 11/7/13	Mon 11/18/13	0 days	7 days
1.6.4. Final Product	7 days	Fri 11/8/13	Fri 11/8/13	Tue 11/19/13	Mon 11/18/13	Mon 11/18/13	Wed 11/27/13	0 days	7 days
1.7. T&E and Ver/Val	7 days	Tue 11/19/13	Tue 11/19/13	Thu 11/28/13	Wed 11/27/13	Wed 11/27/13	Fri 12/6/13	7 days	7 days
1.8. Project Closure	**2 days**	**Thu 11/28/13**	**Thu 11/28/13**	**Mon 12/9/13**	**Fri 11/29/13**	**Fri 11/29/13**	**Tue 12/10/13**	**7 days**	**7 days**
1.8.1. Solution Documentation	2 days	Mon 12/9/13	Mon 12/9/13	Mon 12/9/13	Tue 12/10/13	Tue 12/10/13	Tue 12/10/13	0 days	0 days

Table 25: Enlarged 10% More Time Sensitivity Analysis



Task Name	Duration	Start	Finish	Early Start	Early Finish	Late Start	Late Finish	Free Slack	Total Slack
1. LED Fixture Project	**159 days**	**Mon 5/13/13**	**Thu 12/19/13**	**Mon 5/13/13**	**Thu 12/19/13**	**Fri 5/31/13**	**Thu 12/19/13**	**0 days**	**0 days**
1.1. Market Research	**30 days**	**Mon 5/13/13**	**Fri 6/21/13**	**Mon 5/13/13**	**Fri 6/21/13**	**Fri 5/31/13**	**Thu 7/11/13**	**14 days**	**14 days**
1.1.1. Create Survey	7 days	Mon 5/13/13	Tue 5/21/13	Mon 5/13/13	Tue 5/21/13	Fri 5/31/13	Mon 6/10/13	0 days	14 days
1.1.2. Distribute Survey	2 days	Wed 5/22/13	Thu 5/23/13	Wed 5/22/13	Thu 5/23/13	Tue 6/11/13	Wed 6/12/13	0 days	14 days
1.1.3. Collect Responses	14 days	Fri 5/24/13	Wed 6/12/13	Fri 5/24/13	Wed 6/12/13	Thu 6/13/13	Tue 7/2/13	0 days	14 days
1.1.4. Analyze Data	7 days	Thu 6/13/13	Fri 6/21/13	Thu 6/13/13	Fri 6/21/13	Wed 7/3/13	Thu 7/11/13	0 days	14 days
1.2. Basic Research	**14 days**	**Mon 6/24/13**	**Thu 7/11/13**	**Mon 6/24/13**	**Thu 7/11/13**	**Fri 7/12/13**	**Wed 7/31/13**	**14 days**	**14 days**
1.2.1. Coral Spectrum Needs	7 days	Mon 6/24/13	Tue 7/2/13	Mon 6/24/13	Tue 7/2/13	Fri 7/12/13	Mon 7/22/13	0 days	14 days
1.2.2. Invertebrate Spectrum Needs	7 days	Mon 6/24/13	Tue 7/2/13	Mon 6/24/13	Tue 7/2/13	Fri 7/12/13	Mon 7/22/13	0 days	14 days
1.2.3. Coral Intensity Needs	7 days	Mon 6/24/13	Tue 7/2/13	Mon 6/24/13	Tue 7/2/13	Fri 7/12/13	Mon 7/22/13	0 days	14 days
1.2.4. Component Research	7 days	Wed 7/3/13	Thu 7/11/13	Wed 7/3/13	Thu 7/11/13	Tue 7/23/13	Wed 7/31/13	0 days	14 days
1.3. Definition	**10 days**	**Fri 7/12/13**	**Thu 7/25/13**	**Fri 7/12/13**	**Thu 7/25/13**	**Thu 8/1/13**	**Wed 8/14/13**	**14 days**	**14 days**
1.3.1. Needs/Goals/Objectives	3 days	Fri 7/12/13	Tue 7/16/13	Fri 7/12/13	Tue 7/16/13	Thu 8/1/13	Mon 8/5/13	0 days	14 days
1.3.2. Scope	2 days	Wed 7/17/13	Thu 7/18/13	Wed 7/17/13	Thu 7/18/13	Tue 8/6/13	Wed 8/7/13	0 days	14 days
1.3.3. Proposal	4 days	Fri 7/19/13	Wed 7/24/13	Fri 7/19/13	Wed 7/24/13	Thu 8/8/13	Tue 8/13/13	0 days	14 days
1.3.4. Charter	1 day	Thu 7/25/13	Thu 7/25/13	Thu 7/25/13	Thu 7/25/13	Wed 8/14/13	Wed 8/14/13	0 days	14 days
1.4. Conceptual Design	**11 days**	**Fri 7/26/13**	**Fri 8/9/13**	**Fri 7/26/13**	**Fri 8/9/13**	**Thu 8/15/13**	**Thu 8/29/13**	**14 days**	**14 days**
1.4.1. Problem Definition Revised	1 day	Fri 7/26/13	Fri 7/26/13	Fri 7/26/13	Fri 7/26/13	Thu 8/15/13	Thu 8/15/13	0 days	14 days
1.4.2. User Profiling	2 days	Mon 7/29/13	Tue 7/30/13	Mon 7/29/13	Tue 7/30/13	Fri 8/16/13	Mon 8/19/13	0 days	14 days
1.4.3. Requirements Summary	4 days	Wed 7/31/13	Mon 8/5/13	Wed 7/31/13	Mon 8/5/13	Tue 8/20/13	Fri 8/23/13	0 days	14 days
1.4.4. Functional Analysis	2 days	Tue 8/6/13	Wed 8/7/13	Tue 8/6/13	Wed 8/7/13	Mon 8/26/13	Tue 8/27/13	0 days	14 days
1.4.5. Evaluation	2 days	Thu 8/8/13	Fri 8/9/13	Thu 8/8/13	Fri 8/9/13	Wed 8/28/13	Thu 8/29/13	0 days	14 days
1.5. Preliminary System Design	**34 days**	**Mon 8/12/13**	**Thu 9/26/13**	**Mon 8/12/13**	**Thu 9/26/13**	**Fri 8/30/13**	**Wed 10/16/13**	**14 days**	**14 days**
1.5.1. Brainstorm Options	7 days	Mon 8/12/13	Tue 8/20/13	Mon 8/12/13	Tue 8/20/13	Fri 8/30/13	Mon 9/9/13	0 days	14 days
1.5.2. Design Alternatives	14 days	Wed 8/21/13	Mon 9/9/13	Wed 8/21/13	Mon 9/9/13	Tue 9/10/13	Fri 9/27/13	0 days	14 days
1.5.3. Select Best Design	2 days	Tue 9/10/13	Wed 9/11/13	Tue 9/10/13	Wed 9/11/13	Mon 9/30/13	Tue 10/1/13	0 days	14 days
1.5.4. Order Parts	4 days	Thu 9/12/13	Tue 9/17/13	Thu 9/12/13	Tue 9/17/13	Wed 10/2/13	Mon 10/7/13	0 days	14 days
1.5.5. Build	5 days	Wed 9/18/13	Tue 9/24/13	Wed 9/18/13	Tue 9/24/13	Tue 10/8/13	Mon 10/14/13	0 days	14 days
1.5.6. Recommendations for Improvement	2 days	Wed 9/25/13	Thu 9/26/13	Wed 9/25/13	Thu 9/26/13	Tue 10/15/13	Wed 10/16/13	0 days	14 days
1.6. Detail Design & Development	**37 days**	**Fri 9/27/13**	**Mon 11/18/13**	**Fri 9/27/13**	**Mon 11/18/13**	**Thu 10/17/13**	**Fri 12/6/13**	**14 days**	**14 days**
1.6.1. Interface Design	21 days	Fri 9/27/13	Fri 10/25/13	Fri 9/27/13	Fri 10/25/13	Thu 10/17/13	Thu 11/14/13	0 days	14 days
1.6.2. Usability Testing	7 days	Mon 10/28/13	Tue 11/5/13	Mon 10/28/13	Tue 11/5/13	Fri 11/15/13	Mon 11/25/13	0 days	14 days
1.6.3. Analyze Results	2 days	Wed 11/6/13	Thu 11/7/13	Wed 11/6/13	Thu 11/7/13	Tue 11/26/13	Wed 11/27/13	0 days	14 days
1.6.4. Final Product	7 days	Fri 11/8/13	Mon 11/18/13	Fri 11/8/13	Mon 11/18/13	Thu 11/28/13	Fri 12/6/13	0 days	14 days
1.7. T&E and Ver/Val	7 days	Tue 11/19/13	Wed 11/27/13	Tue 11/19/13	Wed 11/27/13	Mon 12/9/13	Tue 12/17/13	0 days	14 days
1.8. Project Closure	**2 days**	**Thu 11/28/13**	**Fri 11/29/13**	**Thu 11/28/13**	**Fri 11/29/13**	**Wed 12/18/13**	**Thu 12/19/13**	**14 days**	**14 days**
1.8.1. Solution Documentation	2 days	Thu 11/28/13	Fri 11/29/13	Thu 11/28/13	Fri 11/29/13	Wed 12/18/13	Thu 12/19/13	14 days	14 days

Table 26: Enlarged 10% Less Time Sensitivity Analysis



Task Name	Duration	Start	Finish	Early Start	Early Finish	Late Start	Late Finish	Free Slack	Total Slack
1. LED Fixture Project	**131 days**	**Mon 5/13/13**	**Mon 11/11/13**	**Mon 5/13/13**	**Mon 11/11/13**	**Mon 5/13/13**	**Fri 11/29/13**	**0 days**	**0 days**
1.1. Market Research	**30 days**	**Mon 5/13/13**	**Fri 6/21/13**	**Mon 5/13/13**	**Fri 6/21/13**	**Thu 4/25/13**	**Wed 6/5/13**	**0 days**	**-12 days**
1.1.1. Create Survey	7 days	Mon 5/13/13	Tue 5/21/13	Mon 5/13/13	Tue 5/21/13	Thu 4/25/13	Fri 5/3/13	0 days	-12 days
1.1.2. Distribute Survey	2 days	Wed 5/22/13	Thu 5/23/13	Wed 5/22/13	Thu 5/23/13	Mon 5/6/13	Tue 5/7/13	0 days	-12 days
1.1.3. Collect Responses	14 days	Fri 5/24/13	Wed 6/12/13	Fri 5/24/13	Wed 6/12/13	Wed 5/8/13	Mon 5/27/13	0 days	-12 days
1.1.4. Analyze Data	7 days	Thu 6/13/13	Fri 6/21/13	Thu 6/13/13	Fri 6/21/13	Tue 5/28/13	Wed 6/5/13	0 days	-12 days
1.2. Basic Research	**14 days**	**Mon 6/24/13**	**Thu 7/11/13**	**Mon 6/24/13**	**Thu 7/11/13**	**Thu 6/6/13**	**Tue 6/25/13**	**0 days**	**-12 days**
1.2.1. Coral Spectrum Needs	7 days	Mon 6/24/13	Tue 7/2/13	Mon 6/24/13	Tue 7/2/13	Thu 6/6/13	Fri 6/14/13	0 days	-12 days
1.2.2. Invertebrate Spectrum Needs	7 days	Mon 6/24/13	Tue 7/2/13	Mon 6/24/13	Tue 7/2/13	Thu 6/6/13	Fri 6/14/13	0 days	-12 days
1.2.3. Coral Intensity Needs	7 days	Mon 6/24/13	Tue 7/2/13	Mon 6/24/13	Tue 7/2/13	Thu 6/6/13	Fri 6/14/13	0 days	-12 days
1.2.4. Component Research	7 days	Wed 7/3/13	Thu 7/11/13	Wed 7/3/13	Thu 7/11/13	Mon 6/17/13	Tue 6/25/13	0 days	-12 days
1.3. Definition	**10 days**	**Fri 7/12/13**	**Thu 7/25/13**	**Fri 7/12/13**	**Thu 7/25/13**	**Wed 6/26/13**	**Tue 7/9/13**	**0 days**	**-12 days**
1.3.1. Needs/Goals/Objectives	3 days	Fri 7/12/13	Tue 7/16/13	Fri 7/12/13	Tue 7/16/13	Wed 6/26/13	Fri 6/28/13	0 days	-12 days
1.3.2. Scope	2 days	Wed 7/17/13	Thu 7/18/13	Wed 7/17/13	Thu 7/18/13	Mon 7/1/13	Tue 7/2/13	0 days	-12 days
1.3.3. Proposal	4 days	Fri 7/19/13	Wed 7/24/13	Fri 7/19/13	Wed 7/24/13	Wed 7/3/13	Mon 7/8/13	0 days	-12 days
1.3.4. Charter	1 day	Thu 7/25/13	Thu 7/25/13	Thu 7/25/13	Thu 7/25/13	Tue 7/9/13	Tue 7/9/13	0 days	-12 days
1.4. Conceptual Design	**11 days**	**Fri 7/26/13**	**Fri 8/9/13**	**Fri 7/26/13**	**Fri 8/9/13**	**Wed 7/10/13**	**Wed 7/24/13**	**0 days**	**-12 days**
1.4.1. Problem Definition Revised	1 day	Fri 7/26/13	Fri 7/26/13	Fri 7/26/13	Fri 7/26/13	Wed 7/10/13	Wed 7/10/13	0 days	-12 days
1.4.2. User Profiling	2 days	Mon 7/29/13	Tue 7/30/13	Mon 7/29/13	Tue 7/30/13	Thu 7/11/13	Fri 7/12/13	0 days	-12 days
1.4.3. Requirements Summary	4 days	Wed 7/31/13	Mon 8/5/13	Wed 7/31/13	Mon 8/5/13	Mon 7/15/13	Thu 7/18/13	0 days	-12 days
1.4.4. Functional Analysis	2 days	Tue 8/6/13	Wed 8/7/13	Tue 8/6/13	Wed 8/7/13	Fri 7/19/13	Mon 7/22/13	0 days	-12 days
1.4.5. Evaluation	2 days	Thu 8/8/13	Fri 8/9/13	Thu 8/8/13	Fri 8/9/13	Tue 7/23/13	Wed 7/24/13	0 days	-12 days
1.5. Preliminary System Design	**34 days**	**Mon 8/12/13**	**Thu 9/26/13**	**Mon 8/12/13**	**Thu 9/26/13**	**Thu 7/25/13**	**Tue 9/10/13**	**0 days**	**-12 days**
1.5.1. Brainstorm Options	7 days	Mon 8/12/13	Tue 8/20/13	Mon 8/12/13	Tue 8/20/13	Thu 7/25/13	Fri 8/2/13	0 days	-12 days
1.5.2. Design Alternatives	14 days	Wed 8/21/13	Mon 9/9/13	Wed 8/21/13	Mon 9/9/13	Mon 8/5/13	Thu 8/22/13	0 days	-12 days
1.5.3. Select Best Design	2 days	Tue 9/10/13	Wed 9/11/13	Tue 9/10/13	Wed 9/11/13	Fri 8/23/13	Mon 8/26/13	0 days	-12 days
1.5.4. Order Parts	4 days	Thu 9/12/13	Tue 9/17/13	Thu 9/12/13	Tue 9/17/13	Tue 8/27/13	Fri 8/30/13	0 days	-12 days
1.5.5. Build	5 days	Wed 9/18/13	Tue 9/24/13	Wed 9/18/13	Tue 9/24/13	Mon 9/2/13	Fri 9/6/13	0 days	-12 days
1.5.6. Recommendations for Improvement	2 days	Wed 9/25/13	Thu 9/26/13	Wed 9/25/13	Thu 9/26/13	Mon 9/9/13	Tue 9/10/13	0 days	-12 days
1.6. Detail Design & Development	**37 days**	**Fri 9/27/13**	**Mon 11/18/13**	**Fri 9/27/13**	**Mon 11/18/13**	**Wed 9/11/13**	**Thu 10/31/13**	**0 days**	**-12 days**
1.6.1. Interface Design	21 days	Fri 9/27/13	Fri 10/25/13	Fri 9/27/13	Fri 10/25/13	Wed 9/11/13	Wed 10/9/13	0 days	-12 days
1.6.2. Usability Testing	7 days	Mon 10/28/13	Tue 11/5/13	Mon 10/28/13	Tue 11/5/13	Thu 10/10/13	Fri 10/18/13	0 days	-12 days
1.6.3. Analyze Results	2 days	Wed 11/6/13	Thu 11/7/13	Wed 11/6/13	Thu 11/7/13	Mon 10/21/13	Tue 10/22/13	0 days	-12 days
1.6.4. Final Product	7 days	Fri 11/8/13	Mon 11/18/13	Fri 11/8/13	Mon 11/18/13	Wed 10/23/13	Thu 10/31/13	0 days	-12 days
1.7. T&E and Ver/Val	7 days	Tue 11/19/13	Wed 11/27/13	Tue 11/19/13	Wed 11/27/13	Fri 11/1/13	Mon 11/11/13	0 days	-12 days
1.8. Project Closure	**2 days**	**Thu 11/28/13**	**Fri 11/29/13**	**Thu 11/28/13**	**Fri 11/29/13**	**Thu 11/28/13**	**Fri 11/29/13**	**0 days**	**0 days**
1.8.1. Solution Documentation	2 days	Thu 11/28/13	Fri 11/29/13	Thu 11/28/13	Fri 11/29/13	Thu 11/28/13	Fri 11/29/13	0 days	0 days

APPENDIX D: SUPPLEMENT RECIPES

Calcium:

Ingredients:

- 1 gallon RO/DI water
- 2 ½ cups calcium chloride dihydrate OR 2 cups anhydrous calcium chloride

Directions:

1. Add about half a gallon of the RO/DI water to a mixing or storing jug.
2. Add the calcium chloride through a funnel.
3. Cap the jug and mix carefully as the mixture will become very hot.
4. Add the remaining RO/DI water until the jug is full. Mix again.

Alkalinity:

Ingredients:

- 1 gallon RO/DI water
- 2 ¼ cups baked food grade baking soda (baked at 300°F for one hour)

Directions:

1. Add about half a gallon of the RO/DI water to a mixing or storing jug.
2. Add the sodium carbonate (baked baking soda) through a funnel.
3. Cap the jug and mix carefully.
4. Add the remaining RO/DI water until the jug is full. Mix again.

Magnesium:

Ingredients:

- 1 gallon RO/DI water
- 5 cups magnesium chloride
- 3 cups magnesium sulfate

Directions:

1. Add about half a gallon of the RO/DI water to a mixing or storing jug.
2. Add the magnesium chloride and magnesium sulfate through a funnel.
3. Cap the jug and mix carefully.
4. Add the remaining RO/DI water until the jug is full. Mix again.

APPENDIX E: FIXTURE BUILD DOCUMENTATION

Before starting the build, all the necessary supplies and equipment were gathered, including the items in Table 20, Table 21, and Table 22. Other supplies included a Sparkfun Electronics 937b electrostatic discharge (ESD) safe soldering iron, various wire strippers, nippers, pliers, screwdrivers, a soldering wire holder, and a heat gun (Figure 54, Figure 55, and Figure 56).

Figure 54: LED Build Workstation

Figure 55: LED Build Supplies

Figure 56: Nippers and Wire Strippers

The four heat sinks in Figure 57 are MakersLED heat sinks from RapidLED.com. These heat sinks had the best safety factor out of the ones analyzed. The faces shown are where the LEDs will be mounted.

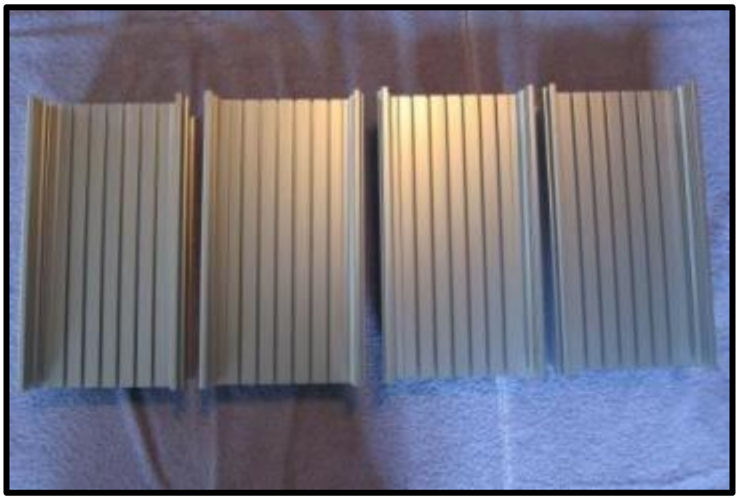


Figure 57: MakersLED Heat Sinks

The LEDs were joined together and were separated up front to speed production later (Figure 58, Figure 59, and Figure 60). All LEDs were kept in their packaging as much as possible to prevent damage.

Figure 58: Royal Blue LEDs

Figure 59: 430 nm Violet LEDs

Figure 60: Red LEDs

In order to pre-tin the LEDs, the soldering iron was turned on to 350 degrees Fahrenheit and preheated (Figure 61). The LED was place in the soldering wire holder for easier access to the soldering pads (Figure 62).

Figure 61: Sparkfun Electronics 937b ESD-Safe Soldering Iron

Figure 62: LED in the Soldering Wire Holder

The tip of the soldering iron was placed on each LED pad for two seconds before the solder was touched to the iron. This allowed the solder to flow properly on to each LED pad with no overruns or splatters (Figure 63).

Figure 63: Tinned LED Solder Points

After the LEDs were pre-tinned, they were laid out according to the design in 1.5 inch increments (Figure 64). They were also tested with a multi-meter to ensure connectivity.

Figure 64: LED Placement on the Heat Sink

Next, 144 bolt sets were made by sliding the nylon washer onto the bolt and barely threading on the nut (Figure 65).

Figure 65: Adding Nylon Washers and Nuts to the Bolts

Two bolts were required to secure each LED, so four bolts were added to the outside races and seven bolts to each of the four inside races (Figure 66 and Figure 67).

Figure 66: Adding Bolts to the LED Layout

Figure 67: Bolts in Rough Position

Artic Alumina Thermal Adhesive was also used in conjunction with the bolts to secure the LEDs, as well as to help conduct heat away from the LEDs (Figure 68).

Figure 68: Artic Alumina Thermal Adhesive

This adhesive is a two-part mixture. Each part (A and B) is added together in equal amounts (Figure 69) and a small drop is added to the back of each LED (Figure 70). When the LED is placed on the heat sink, the thermal adhesive will spread to coat the back LED surface.

Figure 69: Mixing Thermal Adhesive, Part A and B

Figure 70: Thermal Adhesive on LED Back

With the thermal adhesive on the back of the LED, it is placed into its proper position on the heatsink. Then, the bolts are moved into their final position and tightened down. The thermal adhesive should appear in a thin line around the LED if the correct amount was applied (Figure 71).

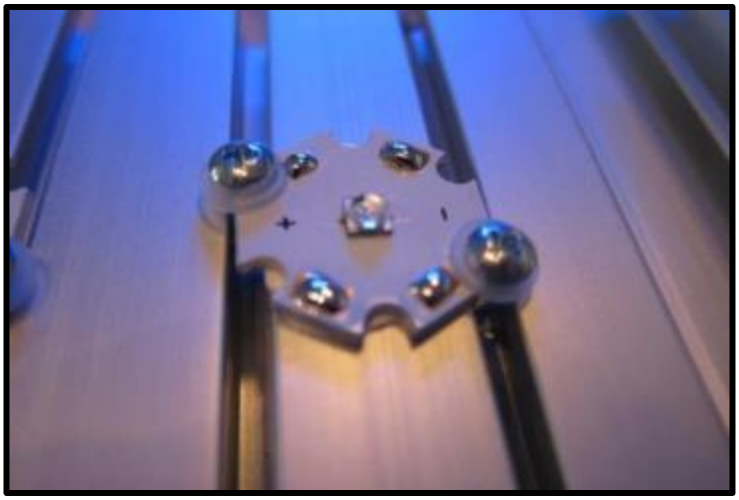


Figure 71: LED in Permanent Position

After all the LEDs are secured, wiring preparation was required. The wiring diagram was necessary, along with pre-tinned wire connections (Figure 72).

Figure 72: Wiring Preparation

Each wire was cut to the proper length for each connection, the ends were stripped, and the stranded wires were twisted together. The ends were pre-tinned with the soldering iron. To make the LED-to-wire connection, the soldering iron tip was touched to the LED solder pad until the solder melted. The pre-tinned wire was then inserted into the LED pad solder (Figure 73). Each joint was inspected and tested with a multi-meter for connectivity. Figure 74 shows the LEDs wired in series.

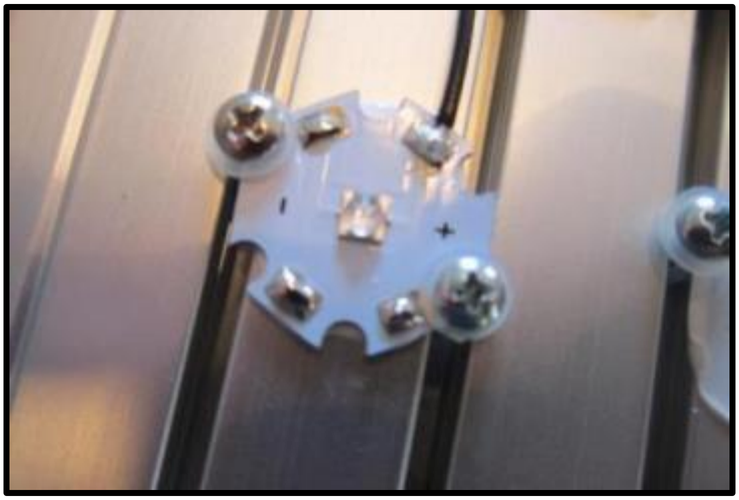


Figure 73: Adding Wire to the LEDs

Figure 74: Wiring Completed with Royal Blue Circuit Highlighted

Occasionally a mistake was made or an LED prematurely died (due to overheating with the soldering iron). These LEDs were removed by unscrewing the bolts, applying light heat with a heat gun (Figure 75), applying light pressure with a screwdriver to pop it up, and then scraping the thermal adhesive off with a razor blade (Figure 76). If the LED needed repositioning, it was retested with the multi-meter (to ensure it did not burn out during removal with the heat gun) and moved. If the LED was burnt out, it was replaced with a functional LED.

Figure 75: Heat Gun

Figure 76: Remnant Thermal Adhesive

Once all the LEDs were wired together (in series), the drivers were tuned. Each Meanwell driver was opened up (Figure 77), and the potentiometer was located. A small screwdriver was used to turn the driver current down as far as possible (turned the SVR2 potentiometer counterclockwise) (Figure 78). The current was measured with a multi-meter. This step was required to ensure excess current did not destroy the LEDs during testing. Additionally, the Meanwell drivers required the addition of an AC power cord (Figure 79). As with all wire connections, the ends were soldered together and heat shrink tape covered the connection. The RapidLED Nano drivers did not require the tuning or power cord steps.

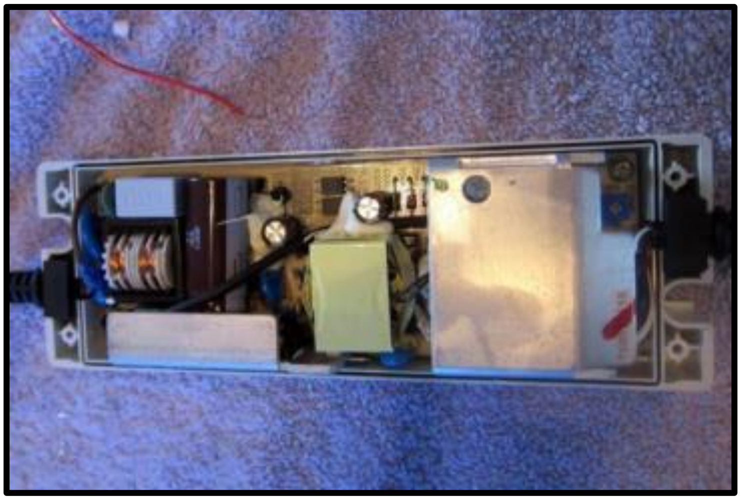


Figure 77: Meanwell Driver Internals

Figure 78: Turning down the Potentiometer

Figure 79: Adding the AC Power Cord to the Meanwell Drivers

In addition to the LED system build, a hanging fixture was designed and built. Figure 80 shows the base structure as viewed from above. It was built with drawer rails and rollers for easy installation and removal into the prebuilt aquarium canopy. The horizontal gaps were cut for the heat sink hangers, and the circular holes were for wires and some heat dissipation.

Figure 80: LED Light System Fixture

In order to tune the LED drivers, a secondary potentiometer was built (Figure 81 and Figure 82). It allows the voltage to vary from 0-10 volts. At 10 volts, the driver current is adjusted to 1.3 amps with the driver potentiometer (turning the potentiometer counterclockwise and monitoring the current with a multi-meter).

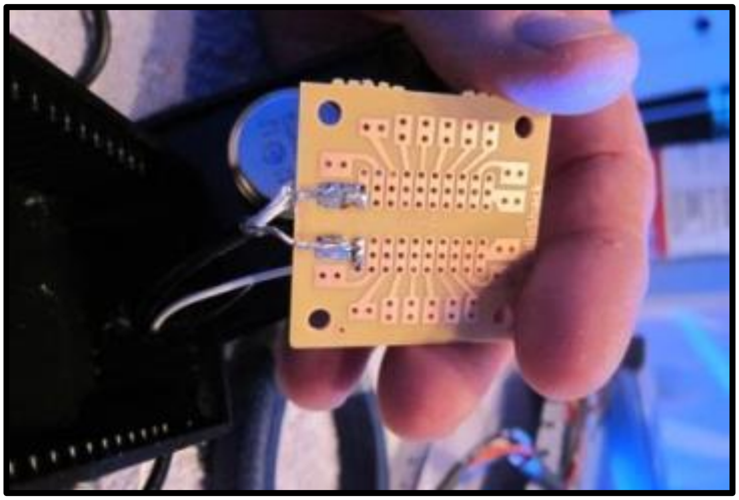


Figure 81: Potentiometer Circuit Board

Figure 82: Potentiometer Internals

The test drive circuit (Figure 83 and Figure 84) was set up with the Meanwell driver potentiometer turned down, the secondary potentiometer turned down to zero volts, and all power was off. The negative dimming wire (white) on the driver was connected to the negative (white) wire of the secondary potentiometer. The negative DC output wire from the driver (black) was connected to the negative (black) lead of the LED string under test. The positive secondary potentiometer wire (black) was connected to the positive driver dimming wire (blue). The driver positive DC wire (red) was connected to the positive multi-meter lead. Lastly, the negative multi-meter lead was connected to the positive (green) lead of the LED string under test. This setup tests the LED string in series and monitors the current through the system at a maximum of 10 volts.

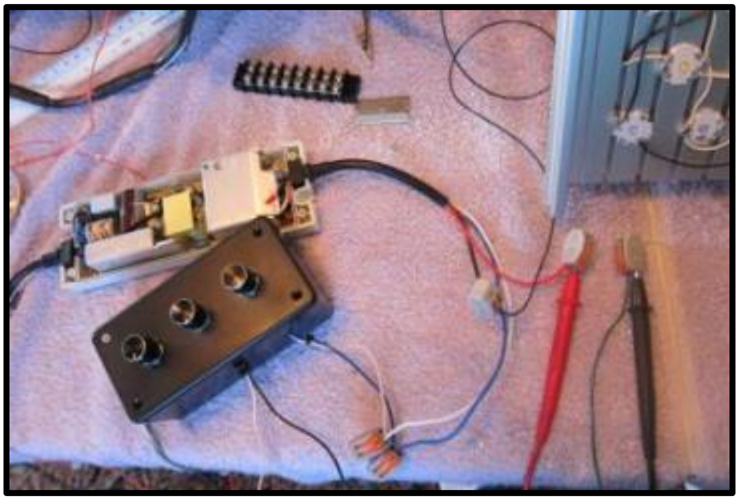


Figure 83: LED Test and Adjustment Circuit

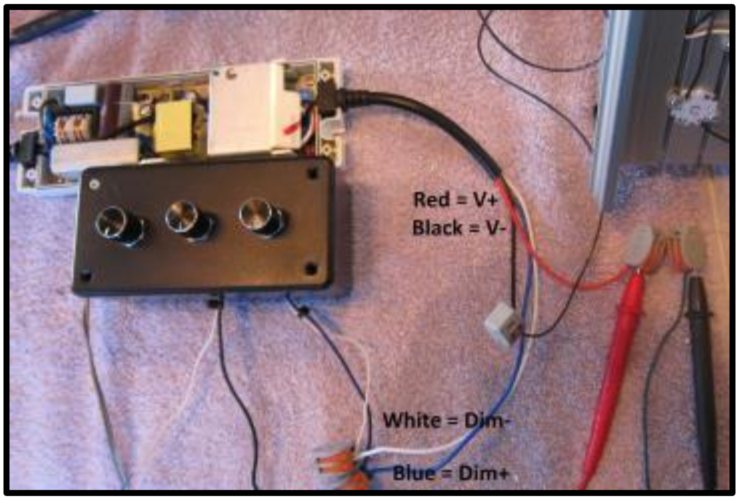


Figure 84: Test Circuit Detail

Unfortunately, even with a good design, not all projects go according to plan. At least there was encouragement within view (Figure 85). The LEDs would turn on, but they would only run at a maximum of 0.3 amps instead of 1.3 amps at 10 volts. Troubleshooting took several hours over several days, which nearly impacted the schedule. The problem was exacerbated by inconclusive test results from two secondary potentiometers. Eventually a 9-volt "wall wart" was used to eliminate the potentiometer variable. The root cause was a lower voltage driver capacity than marketed on the specification sheets. The initial LED design required each driver to run 16 LEDs, but the drivers could only handle 14 LEDs.

Figure 85: Troubleshooting the LED System

Once two LEDs were removed from each of the driver LED strings, the current reached 1.30 amps at 10 volts (Figure 86). Each driver was then re-tuned to run at 1.3 amps. Unfortunately, the violet LED driver was also accidentally tuned to run at 1.3 amps instead of the required 700 mA (violet LEDs cannot handle high current), so all of the violet LEDs burnt out and had to be replaced.

Figure 86: Correct Current Obtained

The royal blue LEDs were placed on two drivers. One driver controls the left side, and the other driver controls the right side. This allows a minimalistic sunrise-to-sunset movement if desired. Figure 87 shows the right side royal blue LED string with only 14 LEDs. Two LEDs were taken off the string in order to run the string at full current. The left side is identical.

Figure 87: Right Side Royal Blue LEDs

A single driver controls the 14 neutral white LEDs. Again, two LEDs were removed from the string in order to run at full current. Figure 88 shows the neutral white LED string. The intensity variation appearance is due to the LED optic directivity and relative heat sink and camera angles. The intensity output across each LED is the same, regardless of visual perception.

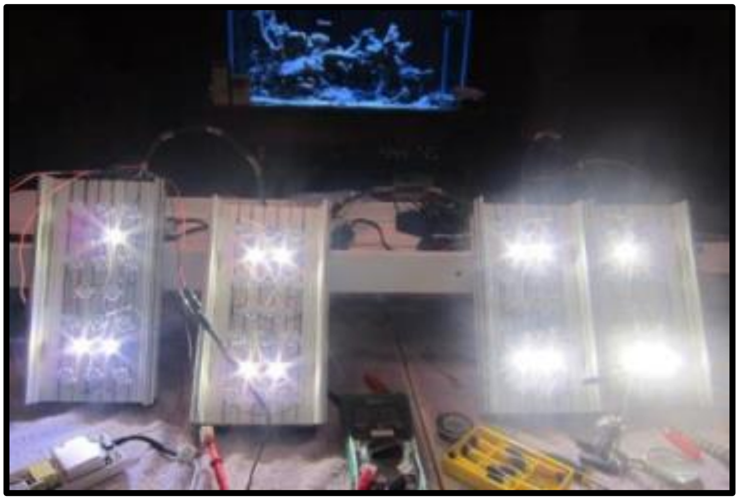


Figure 88: Neutral White LED String

Both the 405 nm and 430 nm violet LEDs were run on one driver. The 430 nm LEDs (eight) line the top and bottom while the 405 nm LEDs (four) line the center (Figure 89). Again, perceived intensity differences are not representative of actual LED output. Unfortunately, this LED string burnt out quickly after this photo was taken since the driver was accidentally set to 1.3 amps. The driver was re-tuned to 700 mA and the LEDs were replaced.

Figure 89: 405 and 430 nm Violet LED String

The cyan/turquoise, red, and cool blue strings all run on the RapidLED Nano drivers that do not require tuning. However, each string was tested regardless. Figure 90 shows the cyan/turquoise LED string, Figure 91 shows the red LED string, and Figure 92 shows the cool blue LED string.

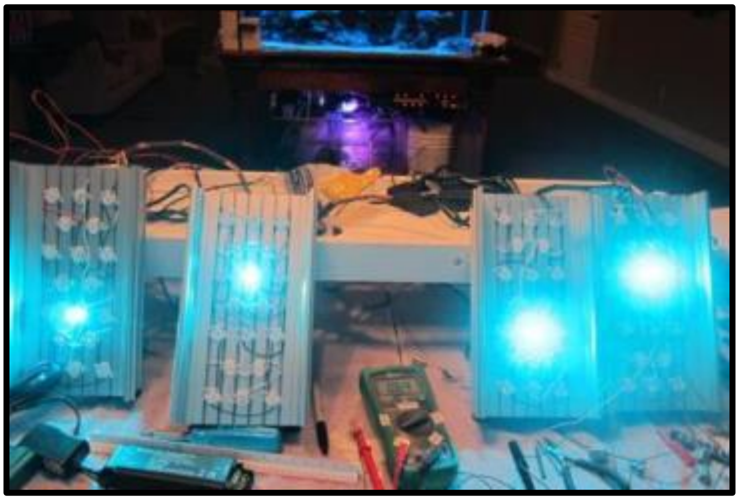


Figure 90: Cyan/Turquoise LED String

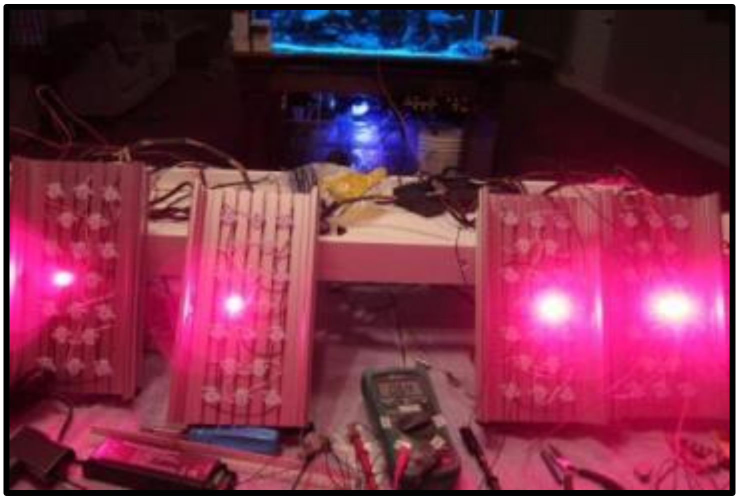


Figure 91: Red LED String

Figure 92: Cool Blue LED String

Next, each driver was mounted to the overall fixture, and the heat sink fixtures were hung under the fixture. Meanwell driver DC power was connected permanently to its corresponding LED string (positive-to-positive, negative-to-negative) in a screw terminal box (Figure 93 and Figure 94).

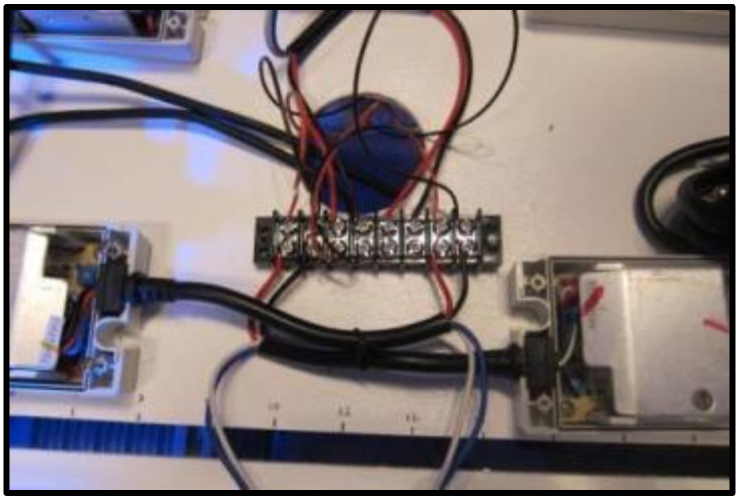


Figure 93: Meanwell Drivers-to-LEDs Connections

Figure 94: Meanwell Drivers-to-LEDs Connections Full View

Inside of a project box (Figure 95), the RapidLED Nano drivers were also connected to their LED strings on a screw terminal box. All dimming wires were fed into the project box as well and were soldered onto a pinned circuit board. A computer connector was salvaged and used in conjunction with the pins.

Figure 95: DC Power and Dimming Control

To run six fans (one on each heat sink and one on each side of the overall fixture) in parallel, the Molex connectors were cut off (Figure 96 and Figure 97). Additional lengths of wire were added and fed to a potentiometer. This potentiometer controls the fan speed (and therefore, noise level).

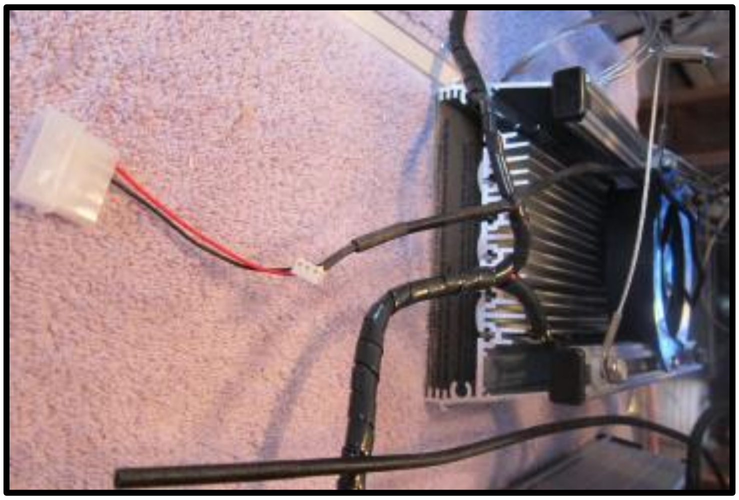


Figure 96: Fan with Molex Connectors

Figure 97: Fan with Molex Connectors Removed

After all the wiring connections were completed, the entire system was tested one last time before the final cleanup (Figure 98).

Figure 98: Final Developmental Test

Arguably the most frustrating part of the build was adding the optics. Super glue cannot be used to secure the optics since it will emit fumes at high temperatures, which will cloud the optics. So, room temperature vulcanizing (RTV) silicone is used to secure the optics (Figure 99). Needless to say, it is not the best adhesive.

Figure 99: RTV Silicone with Optic

A small amount of RTV was dabbed onto the backside of the optic and allowed to sit for several seconds to partially gel (Figure 100). Then, the optic was placed over the LED and held for approximately 30 seconds (Figure 101). It was not uncommon for the optics to fall off a few minutes later. Additionally, the Exotic LEDs have a slightly larger LED base, so the optics would not properly fit over them. Two tabs were clipped off the optics to make them fit (Figure 102). The entire process took several hours (Figure 103).

Figure 100: Optic Coated with RTV

Figure 101: Optics on LEDs

Figure 102: Optic with Two Tabs Clipped and Coated in RTV

Figure 103: LEDs Covered in Optics

To make the connection between the driver dimming wires (attached to the computer connector) and the Neptune AquaController Apex, three long CAT5e cables were cut in half to make six cables (for six dimming channels, one for each color). Shorter cables could have been used if one of the male ends was removed, but it was more economical to purchase three long ones in this design.

The Neptune AquaController Apex Base Module (and the Variable Dimming Module, VDM) have two ports with the ability to each control two channels (V1/V2 and V3/V4) (Figure 104). Subsequently, the CAT5e cable can be used instead of purchasing a proprietary cable. With the clip side up, the pins are, from left to right, 10-volt DC, ground, not used, not used, 10-volt DC, ground, not used, and not used (Figure 105).

Figure 104: Neptune AquaController Apex Base Module

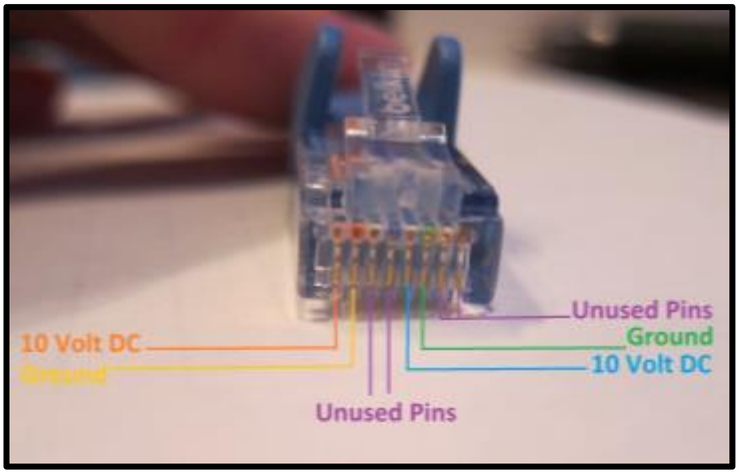
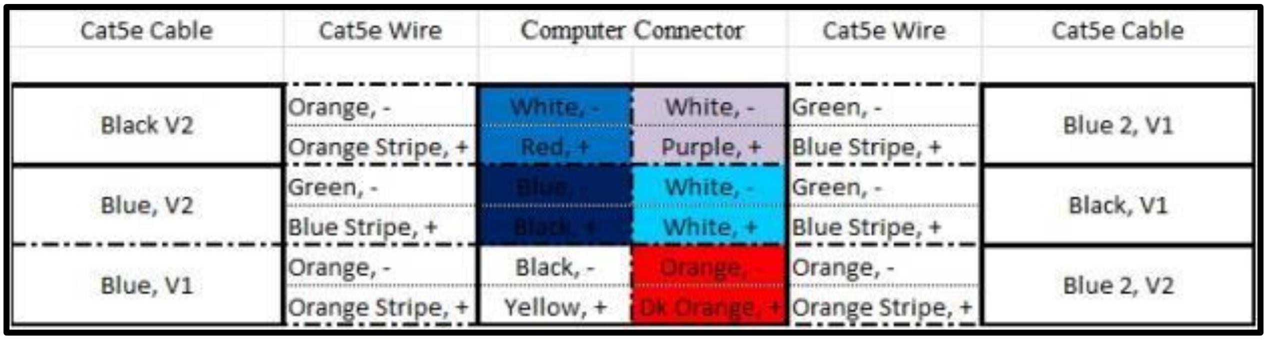


Figure 105: CAT5e Dimming Cable

As shown in Figure 106, the colored computer connectors (positive and negative pairs) were connected to each pair of the CAT5e cable. Two blue CAT5e cables were used along with one black cable. These cables were then plugged into the Neptune AquaController Apex variable dimming ports. Since the base module only has four dimming channels available, a secondary VDM was installed as well.



Cat5e Cable	Cat5e Wire	Computer Connector		Cat5e Wire	Cat5e Cable
Black V2	Orange, -	White, -	White, -	Green, -	Blue 2, V1
	Orange Stripe, +	Red, +	Purple, +	Blue Stripe, +	
Blue, V2	Green, -	Blue, -	White, -	Green, -	Black, V1
	Blue Stripe, +	Black, +	White, +	Blue Stripe, +	
Blue, V1	Orange, -	Black, -	Orange, -	Orange, -	Blue 2, V2
	Orange Stripe, +	Yellow, +	Dk Orange, +	Orange Stripe, +	

Figure 106: DimmingWire Connections

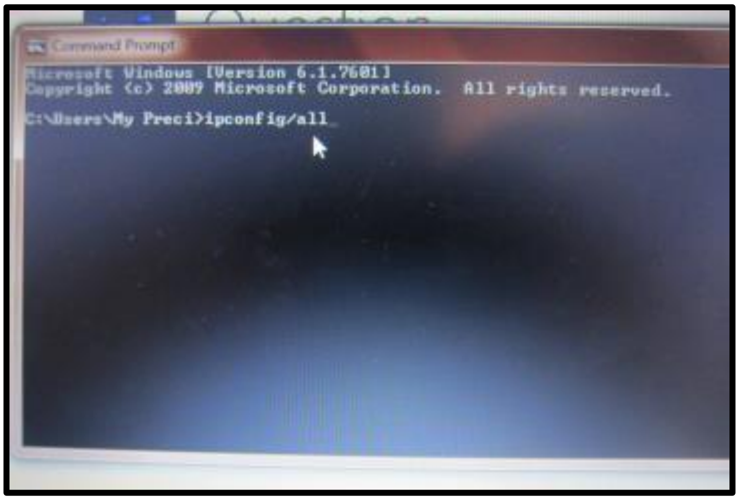
The finishing touches on the light system (Figure 107) included cleaning up the wiring with cable covers, cable ties, and securing all units with Velcro. The fans were permanently mounted onto the heat sinks, the acrylic heat sink covers were installed, and the heat sink end caps were also screwed on to prevent injury.

Figure 107: LED Light System Complete

With the light system complete, programming the Neptune AquaController Apex was next (Figure 108).

Figure 108: Neptune AquaController Apex

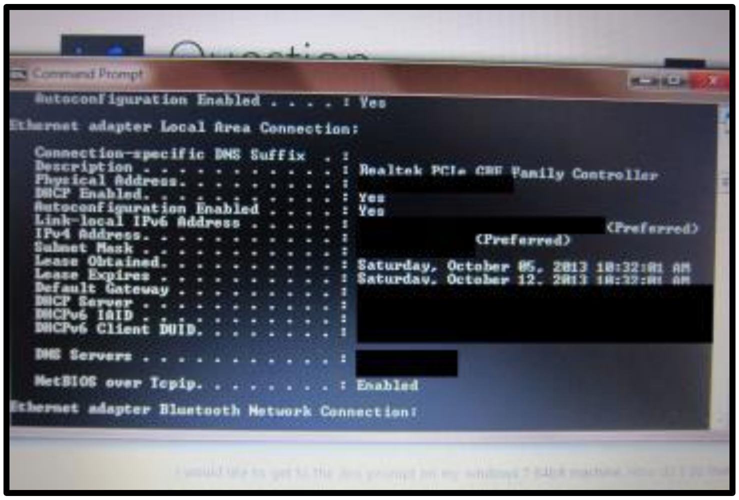
A network cable (also CAT5e) was connected directly between the network router and the Apex. To determine the internet protocol (IP) address of the network, the Disk Operating System (DOS) Command Prompt was used with “ipconfig/all” (Figure 109). This command returns adapter IP addresses (Figure 110).



```
Microsoft Windows [Version 6.1.7601]
Copyright (c) 2009 Microsoft Corporation.  All rights reserved.

C:\Users\My Preci>ipconfig/all_
```

Figure 109: DOS Command Prompt



```
   Autoconfiguration Enabled . . . . : Yes

Ethernet adapter Local Area Connection:

   Connection-specific DNS Suffix  . :
   Description . . . . . . . . . . . : Realtek PCIe GBE Family Controller
   Physical Address. . . . . . . . . : [redacted]
   DHCP Enabled. . . . . . . . . . . : Yes
   Autoconfiguration Enabled . . . . : Yes
   Link-local IPv6 Address . . . . . : [redacted](Preferred)
   IPv4 Address. . . . . . . . . . . : [redacted](Preferred)
   Subnet Mask . . . . . . . . . . . :
   Lease Obtained. . . . . . . . . . : Saturday, October 05, 2013 10:32:01 AM
   Lease Expires . . . . . . . . . . : Saturday, October 12, 2013 10:32:01 AM
   Default Gateway . . . . . . . . . : [redacted]
   DHCP Server . . . . . . . . . . . :
   DHCPv6 IAID . . . . . . . . . . . :
   DHCPv6 Client DUID. . . . . . . . :

   DNS Servers . . . . . . . . . . . : [redacted]

   NetBIOS over Tcpip. . . . . . . . : Enabled

Ethernet adapter Bluetooth Network Connection:
```

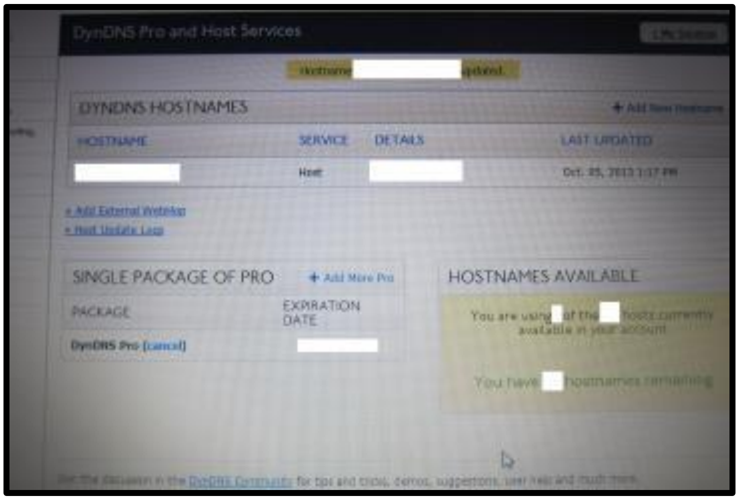
Figure 110: Adapter IP Addresses

The IP addresses in Figure 110 are used to setup the Apex Ethernet at http://apex (Figure 111). In order to keep the Apex connected to the wireless router, a static Dynamic Name Service (DNS) was required (Figure 112). DynDNS was used for the service that constantly monitors the external IP address and updates the server.

Apex Ethernet setup

DHCP	● Enabled ○ Disabled
Hostname	apex
AquaController IP address	[redacted]
Netmask	[redacted]
Gateway	[redacted]
Primary DNS server	[redacted]
Secondary DNS server	[redacted]
HTTP port (default 80)	80
Admin name	[redacted]
Admin password	[redacted]
Confirm admin password	[redacted]
Open XML Access	○ Enabled ● Disabled
Reboot system after update	☐

Figure 111: Apex Ethernet Setup



DynDNS Pro and Host Services

Hostname [redacted] updated.

DYNDNS HOSTNAMES

+ Add New Hostname

HOSTNAME	SERVICE	DETAILS	LAST UPDATED
[redacted]	Host	[redacted]	Oct. 25, 2013 1:37 PM

+ Add External WebHop
+ Host Update Logs

SINGLE PACKAGE OF PRO

+ Add More Pro

PACKAGE	EXPIRATION DATE
DynDNS Pro [cancel]	[redacted]

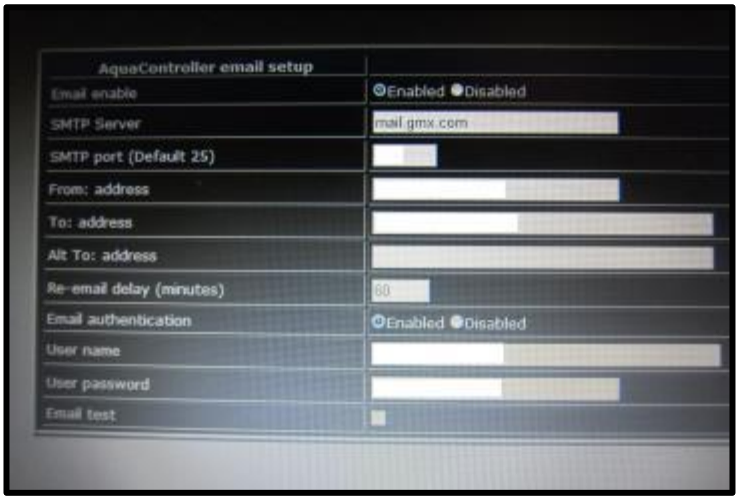
HOSTNAMES AVAILABLE

You are using [redacted] of the [redacted] hosts currently available in your account

You have [redacted] hostnames remaining

Figure 112: Dynamic Name Service

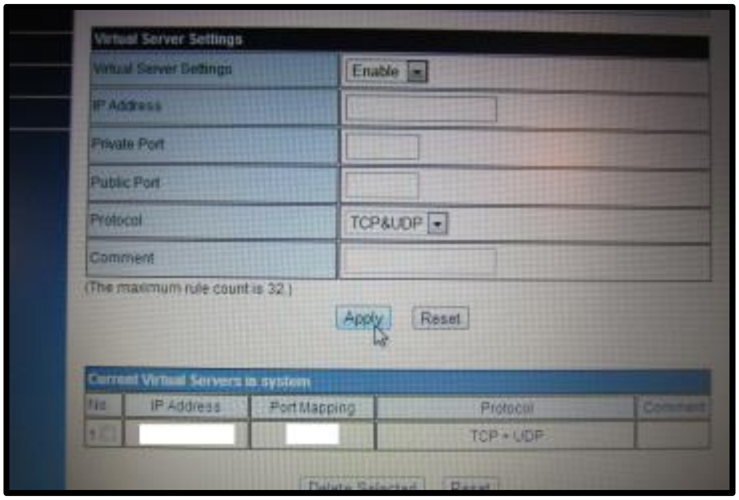
Email and text messaging alerts were setup in the AquaController Email Setup screen (Figure 113). This required setting up an email account without Secure Socket Layer (SSL). GMX was used for this service, as it was free. The "Alt To: address" line was filled in with the text messaging email address (for Sprint it is phonenumber@messaging.sprintpcs.com).



AquaController email setup	
Email enable	● Enabled ○ Disabled
SMTP Server	mail.gmx.com
SMTP port (Default 25)	[redacted]
From: address	[redacted]
To: address	[redacted]
Alt To: address	
Re-email delay (minutes)	60
Email authentication	● Enabled ○ Disabled
User name	[redacted]
User password	[redacted]
Email test	☐

Figure 113: AquaController Email Setup

Additional wireless internet settings were required for final configuration on the router (Figure 114 and Figure 115).



Virtual Server Settings

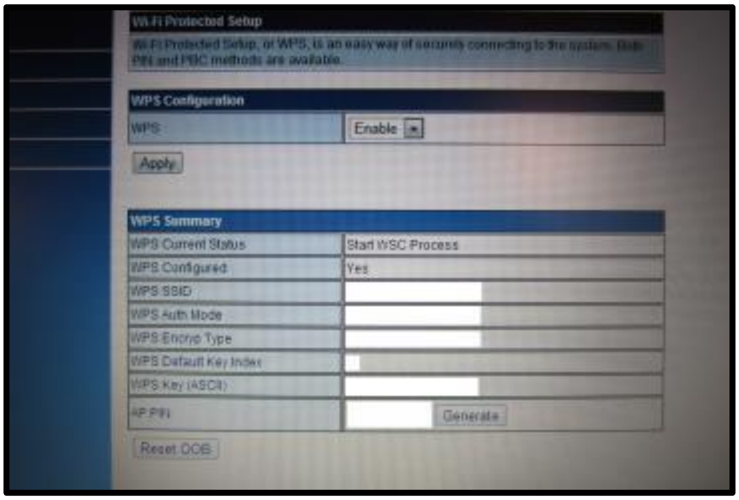
Virtual Server Settings	Enable
IP Address	
Private Port	
Public Port	
Protocol	TCP&UDP
Comment	

(The maximum rule count is 32.)

Current Virtual Servers in system

No.	IP Address	Port Mapping	Protocol	Comment
1	[redacted]	[redacted]	TCP + UDP	

Figure 114: Virtual Server Settings



Wi-Fi Protected Setup

Wi-Fi Protected Setup, or WPS, is an easy way of securely connecting to the system. Both PIN and PBC methods are available.

WPS Configuration

WPS	Enable

WPS Summary

WPS Current Status	Start WSC Process
WPS Configured	Yes
WPS SSID	[redacted]
WPS Auth Mode	[redacted]
WPS Encryp Type	[redacted]
WPS Default Key Index	[redacted]
WPS Key (ASCII)	[redacted]
AP PIN	[redacted]

Figure 115: Wi-Fi Security Setup

After all the Neptune AquaController Apex and home network setup, the Apex home screen is accessible from internet-ready devices (Figure 35). In other words, remote devices can be used to control the intensity, duration, and spectrum of the LEDs through programming. The basic program used to control this light fixture is located in APPENDIX F: Neptune Apex Code.

The lighting system was installed into the canopy and was connected to power and the dimming modules. There were no problems as the system ran correctly (Figure 116). Thus, operational test and evaluation started immediately.

Figure 116: LED Light System Installed and Functioning

APPENDIX F: NEPTUNE APEX CODE

```
<proglist software="4.20_1B13" hardware="1.0">
      <hostname>apex</hostname>
      <serial>AC4:06639</serial>
      <timezone>-7</timezone>
      <date>11/28/2013 15:27:21</date>
<outlets>
      <outlet>
            <name>V1</name>
            <icon>Light A</icon>
            <outputID>0</outputID>
            <outputType>Light</outputType>
            <program>
                  Fallback OFF Set OFF If Time 08:00 to 23:00 Then ON If Temp
                  > 82.0 Then OFF Min Time 030:00 Then OFF
            </program>
      </outlet>
      <outlet>
            <name>V2</name>
            <icon>Left/Right Arrows</icon>
            <outputID>1</outputID>
            <outputType>Light</outputType>
            <program>
                  Fallback OFF Set OFF If Time 08:00 to 23:00 Then ON If Temp
                  > 82.0 Then OFF Min Time 030:00 Then OFF
            </program>
      </outlet>
      <outlet>
            <name>V3</name>
            <icon>Light B</icon>
            <outputID>2</outputID>
            <outputType>Light</outputType>
            <program>
                  Fallback OFF Set OFF If Time 08:00 to 23:00 Then ON If Temp
                  > 82.0 Then OFF Min Time 030:00 Then OFF
            </program>
      </outlet>
      <outlet>
            <name>V4</name>
            <icon>Left/Right Arrows</icon>
            <outputID>3</outputID>
            <outputType>Light</outputType>
            <program>
                  Fallback OFF Set OFF If Time 08:00 to 23:00 Then ON If Temp
                  > 82.0 Then OFF Min Time 030:00 Then OFF
            </program>
      </outlet>
      <outlet>
            <name>SndAlm_I6</name>
            <icon>Sound B</icon>
            <outputID>4</outputID>
            <outputType>Advanced</outputType>
            <program>Set OFF</program>
      </outlet>
      <outlet>
```

```
      <name>SndWrn_I7</name>
      <icon>Sound A</icon>
      <outputID>5</outputID>
      <outputType>Advanced</outputType>
      <program>Set OFF</program>
</outlet>
<outlet>
      <name>EmailAlm_I5</name>
      <icon>Email</icon>
      <outputID>6</outputID>
      <outputType>Advanced</outputType>
      <program>
            Set OFF If Temp > 82.0 Then ON If Temp < 75.0 Then ON If pH
            < 07.80 Then ON If pH > 08.40 Then ON
      </program>
</outlet>
<outlet>
      <name>1</name>
      <icon>Light A</icon>
      <outputID>7</outputID>
      <outputType>Light</outputType>
      <program>
            Fallback OFF Set OFF If Time 13:00 to 22:00 Then ON If Temp
            > 82.0 Then OFF Min Time 030:00 Then OFF
      </program>
</outlet>
<outlet>
      <name>2</name>
      <icon>Light B</icon>
      <outputID>8</outputID>
      <outputType>Light</outputType>
      <program>
            Fallback OFF Set OFF If Time 08:00 to 22:00 Then ON If Temp
            > 82.0 Then OFF Min Time 030:00 Then OFF
      </program>
</outlet>
<outlet>
      <name>LEDFans</name>
      <icon>Fan</icon>
      <outputID>9</outputID>
      <outputType>Advanced</outputType>
      <program>
            Fallback OFF Set OFF If Time 10:00 to 22:00 Then ON If Temp
            > 80.5 Then OFF If Temp < 75.5 Then ON Min Time 030:00 Then
            OFF
      </program>
</outlet>
<outlet>
      <name>LEDsPower</name>
      <icon>Light A</icon>
      <outputID>10</outputID>
      <outputType>Advanced</outputType>
      <program>
            Fallback OFF Set OFF If Time 11:00 to 21:00 Then ON If Temp
            > 79.5 Then OFF If Temp < 75.0 Then ON Min Time 030:00 Then
            OFF
      </program>
```

```
</outlet>
<outlet>
      <name>Sump-5</name>
      <icon>Light B</icon>
      <outputID>11</outputID>
      <outputType>Advanced</outputType>
      <program>
            Fallback OFF Set OFF If Time 21:00 to 11:30 Then ON If Temp
            > 81.5 Then OFF If Temp < 75.0 Then ON Min Time 030:00 Then
            OFF
      </program>
</outlet>
<outlet>
      <name>Fan-6</name>
      <icon>Fan</icon>
      <outputID>12</outputID>
      <outputType>Chiller</outputType>
      <program>
            Fallback OFF If Temp > 76.9 Then ON If Temp < 76.6 Then OFF
      </program>
</outlet>
<outlet>
      <name>heater300W-7</name>
      <icon>Thermometer</icon>
      <outputID>13</outputID>
      <outputType>Advanced</outputType>
      <program>
            Fallback OFF If Temp < 76.8 Then ON If Temp > 77.0 Then OFF
            Min Time 010:00 Then OFF
      </program>
</outlet>
<outlet>
      <name>heater400W-8</name>
      <icon>Thermometer</icon>
      <outputID>14</outputID>
      <outputType>Advanced</outputType>
      <program>
            Fallback OFF If Temp < 76.6 Then ON If Temp > 76.9 Then OFF
            Min Time 010:00 Then OFF
      </program>
</outlet>
<outlet>
      <name>Lunar_A1</name>
      <icon>Moon</icon>
      <outputID>15</outputID>
      <outputType>Light</outputType>
      <program>
            Fallback OFF Set OFF If Time 08:00 to 23:00 Then ON If Temp
            > 82.0 Then OFF Min Time 030:00 Then OFF
      </program>
</outlet>
<outlet>
      <name>RoyalBlue</name>
      <icon>Up/Down Arrows</icon>
      <outputID>16</outputID>
      <outputType>Light</outputType>
      <program>
```

```
            Fallback OFF Set OFF If Time 10:00 to 21:00 Then ON If Temp
            > 80.0 Then OFF Min Time 010:00 Then OFF
        </program>
    </outlet>
    <outlet>
        <name>NeutWhite</name>
        <icon>Left/Right Arrows</icon>
        <outputID>17</outputID>
        <outputType>Light</outputType>
        <program>
            Fallback OFF Set OFF If Time 10:30 to 20:30 Then ON If Temp
            > 80.0 Then OFF Min Time 010:00 Then OFF
        </program>
    </outlet>
    <outlet>
        <name>Violet_V7</name>
        <icon>Up/Down Arrows</icon>
        <outputID>18</outputID>
        <outputType>Light</outputType>
        <program>
            Fallback OFF Set OFF If Time 10:00 to 21:00 Then ON If Temp
            > 80.0 Then OFF Min Time 010:00 Then OFF
        </program>
    </outlet>
    <outlet>
        <name>Red_V8</name>
        <icon>Left/Right Arrows</icon>
        <outputID>19</outputID>
        <outputType>Light</outputType>
        <program>
            Fallback OFF Set OFF If Time 10:00 to 21:00 Then ON If Temp
            > 80.0 Then OFF Min Time 010:00 Then OFF
        </program>
    </outlet>
    <outlet>
        <name>BluLED_9_5</name>
        <icon>Light A</icon>
        <outputID>20</outputID>
        <outputType>Light</outputType>
        <program>
            Fallback OFF Set OFF If Time 08:00 to 22:00 Then ON If Temp
            > 82.0 Then OFF Min Time 030:00 Then OFF
        </program>
    </outlet>
    <outlet>
        <name>WhtLED_9_6</name>
        <icon>Light B</icon>
        <outputID>21</outputID>
        <outputType>Light</outputType>
        <program>
            Fallback OFF Set OFF If Time 08:30 to 22:30 Then ON If Temp
            > 82.0 Then OFF Min Time 030:00 Then OFF
        </program>
    </outlet>
</outlets>
<profiles>
    <profile>
```

```
            <name>NW_Up</name>
            <type>ramp</type>
            <rampTime>30</rampTime>
            <startIntensity>0</startIntensity>
            <endIntensity>10</endIntensity>
      </profile>
      <profile>
            <name>NW_Day</name>
            <type>ramp</type>
            <rampTime>0</rampTime>
            <startIntensity>10</startIntensity>
            <endIntensity>10</endIntensity>
      </profile>
      <profile>
            <name>NW_Down</name>
            <type>ramp</type>
            <rampTime>30</rampTime>
            <startIntensity>10</startIntensity>
            <endIntensity>0</endIntensity>
      </profile>
      <profile>
            <name>RB_Up</name>
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            <rampTime>60</rampTime>
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